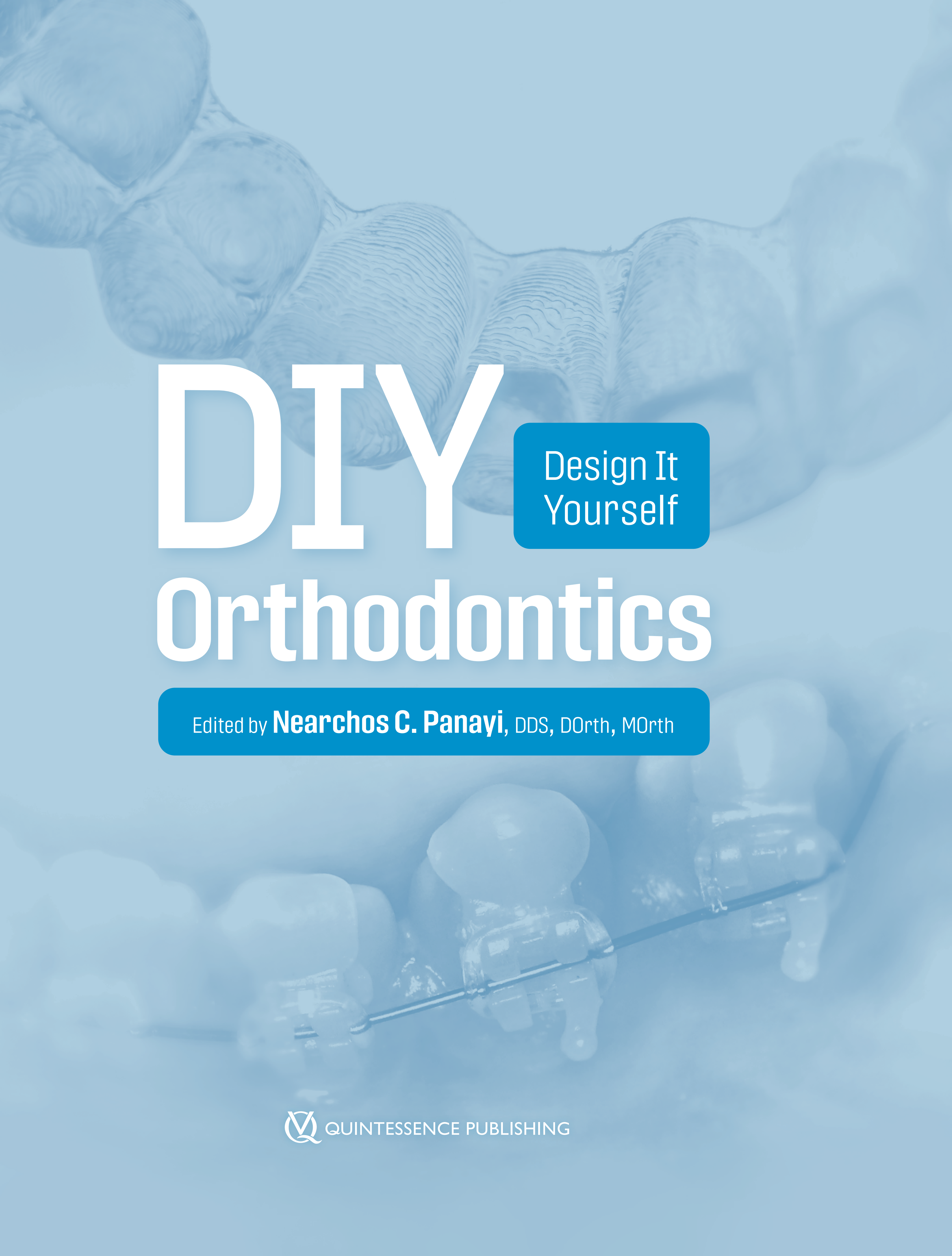


DIY

Design It Yourself

Orthodontics

Edited by **Nearchos C. Panayi**, DDS, DOrth, MOrth

QUINTESSENCE PUBLISHING

DIY Orthodontics:
Design It Yourself

Library of Congress Cataloging-in-Publication Data
Names: Panayi, Nearchos C., editor.
Title: DIY orthodontics : design it yourself / edited by Nearchos C. Panayi.
Description: Batavia, IL : Quintessence Publishing, [2021] | Includes bibliographical references and index. | Summary: "This book describes the current digital technology that is used in orthodontics, including volume and surface scanning, 3D printing, CAD software, and artificial intelligence, before delving into a "design it yourself" guide presenting the application of this technology in all aspects of orthodontic treatment"-- Provided by publisher.
Identifiers: LCCN 2021005696 | ISBN 9781647240516 (hardcover)
Subjects: MESH: Orthodontic Appliances | Equipment Design | Digital Technology | Computer-Aided Design | Orthodontics--methods
Classification: LCC RK521 | NLM WU 426 | DDC 617.6/43--dc23
LC record available at https://lccn.loc.gov/2021005696

A CIP record for this book is available from the British Library.
ISBN: 9781647240516

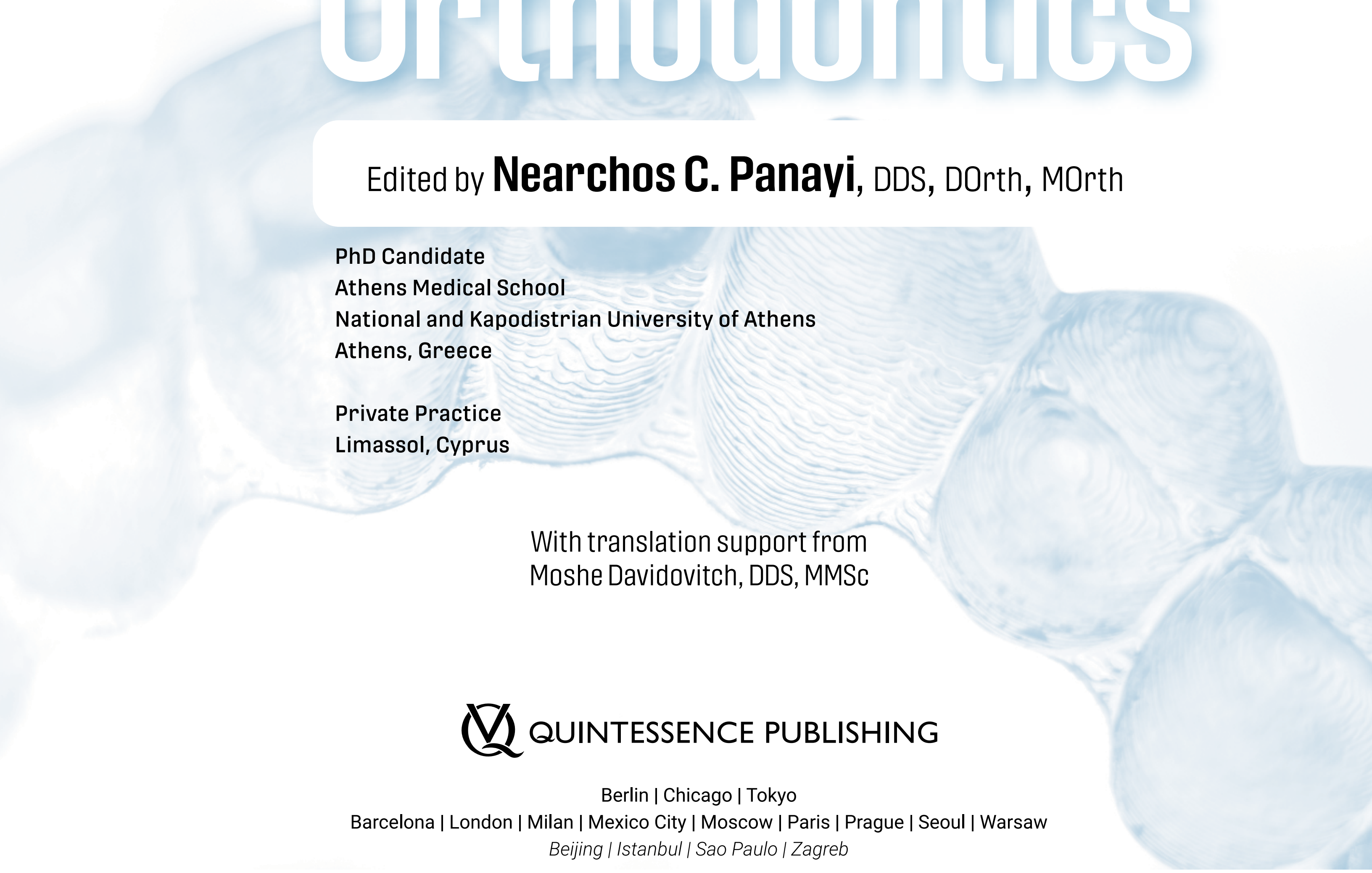
QUINTESSENCE PUBLISHING
USA

Quintessence Publishing Co, Inc
411 N Raddant Road
Batavia, IL 60510
www.quintpub.com

5 4 3 2 1

Editor: Leah Huffman
Design: Sue Zubek
Production: Sarah Minor

Printed in Croatia



DIY Orthodontics

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QUINTESSENCE PUBLISHING

Berlin | Chicago | Tokyo
Barcelona | London | Milan | Mexico City | Moscow | Paris | Prague | Seoul | Warsaw
Beijing | Istanbul | Sao Paulo | Zagreb

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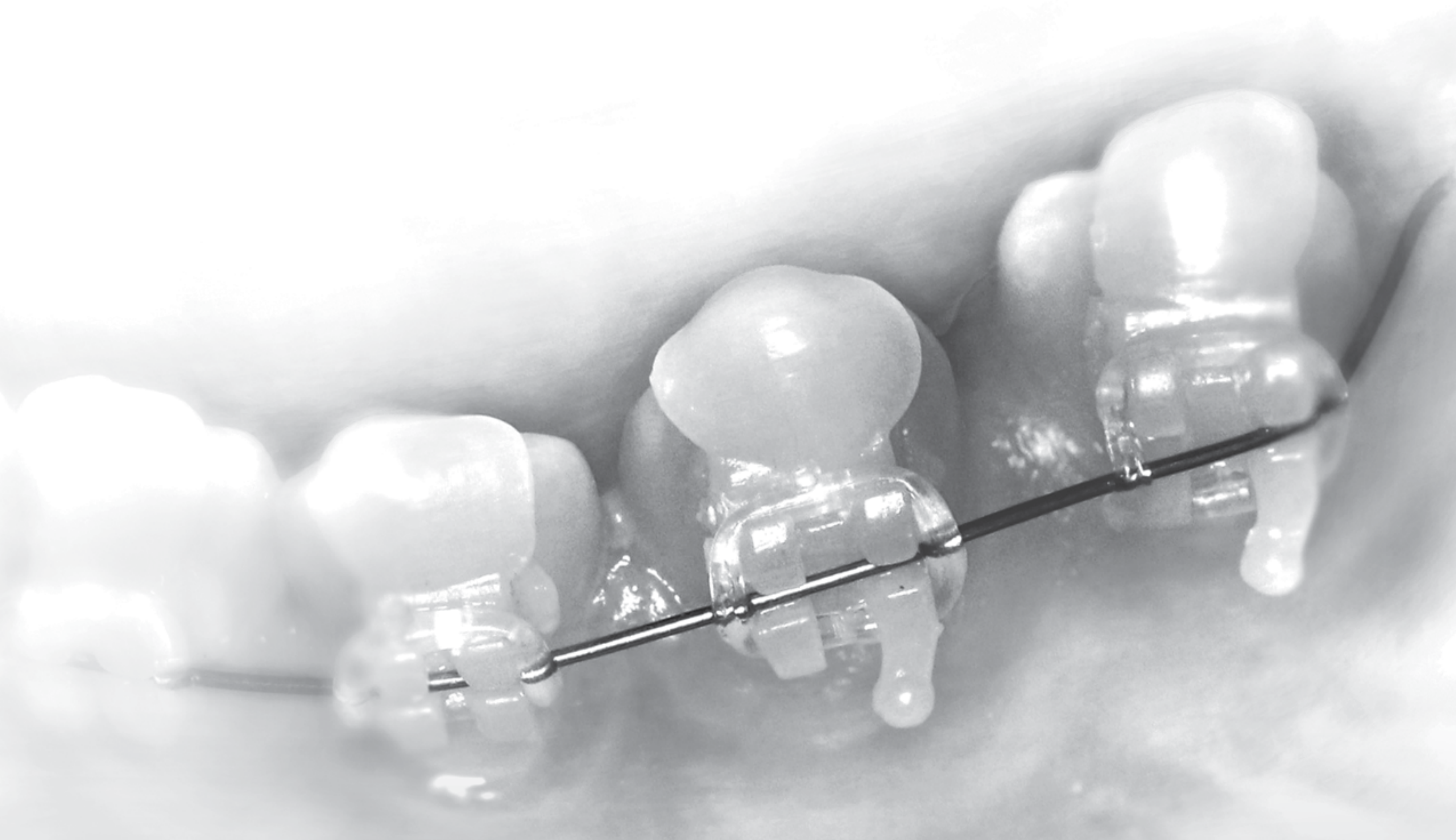

Foreword

with a glimpse into the analog past, the transforming present, and the digital future

This book opens the "digital pathway" to 3D success for the orthodontic clinical practice. It is a successful demonstration on how digitization of patient information and digitalization of clinical procedures can lead to a digital orthodontic transformation for the design and manufacturing of patient-specific devices—and in turn to considerable benefits for clinicians and patients.

Many years ago, I had the opportunity to propose the use of computer-aided engineering as a potential clinical tool for preoperative planning, surgical practice, and customization of medical devices. However, the efficient integration of medical imaging with design, simulation, and rapid manufacturing was a long, challenging, and demanding task. It could take weeks or even months to coordinate just the export of images from medical scanners. Specific knowledge and equipment were also necessary to transfer image data to a computer. Extra effort was required to decode and read the "native" formats utilized by those closed systems. Overall, too much effort, too many projects, extensive scientific work, and numerous clinical cases and patient stories have been required in order to prove the value of a digital engineering approach in clinical practice.

By the turn of the millennium, the underlying engineering technologies, as well as the relevant digital 3D workflow, were fully established. Computer-guided implantology was the first concrete example of a successful digital process in dentistry. During the following years, a considerable simplification and automatization of the procedures was achieved, mainly due to considerable software developments but also hardware improvements and increasing computer power. Nevertheless, it took decades to garner widespread recognition for the apparent benefits of engineering approaches in dentistry and medicine, as well as the potential of a generalized digital transformation in health care. Today, everyone wants to "go digital," even when it is often unclear what that even means.

Strictly, the term *digital* refers to the management of digital information. *Digitization* is the initial step to make all information available in a digital format. And *digitalization* is the next step to develop the appropriate tools to manage the digitized information. The "digital transformation" is the integration of digital data with digital tools into all aspects of any enterprise. The fact that many technologies, such as modern design and manufacturing, utilize digital information and rely on computational procedures leads us to consider ourselves under the "digital umbrella" as well. It is very important though to mention that a successful digital transformation is not just about the technology. It fundamentally changes how an organization operates in order to deliver the potential benefits. It requires a cultural change with new and different ways of thinking. It is a constantly evolving situation that requires experimentation for the implementation of novel processes that are frequently radical and challenge analog routines. In health care, the order always used to be disease, medicine, and then patient. However, a digital health care transformation puts the patient at the center of medical care, affecting how people access or even define health care.

What does a potential "digital health care transformation" really mean? It is estimated by IBM Watson that each person can generate enough health data in their lifetime to fill 300 million books. More medical data has been created in the past 2 years than in the entirety of human history, and this is predicted to double every 73 days. Most data though are unstructured and stored in hundreds of forms such as lab results, images, and medical transcripts. It is called Big Data because it is voluminous and complex. Traditional processing software was inadequate to deal with it, but now there are the technical capabilities to monitor, collect, and process this scale of information. Big Data can be analyzed by intelligent systems that can imitate human learning and reasoning, otherwise called *artificial intelligence* (AI). AI has the capability to sift through billions of pieces of unstructured information and "investigate" millions of patient cases in order to find patient-relevant information, sort its importance, make necessary connections, and summarize conclusions in a predictive way. In addition, such digital processes can employ "cognitive computing" techniques to simulate human thought by learning how to recognize and use the data. The relevant technology platforms can encompass reasoning, speech, and object recognition, language processing, and human-computer interaction. Doctors can interact directly through dialogue, discussing various proposals. Through "machine learning" (ML), digital systems can also be automatically trained and keep learning from any mistakes as well as successes to adapt and become "specialists" in a range of disciplines. As such, a potential digital health care transformation can help clinicians to make informed decisions regarding diagnosis and treatment options. It is also possible to obtain insights on outcomes of various treatment options, to better understand which therapy may be suitable for which patients, and in general to identify information for optimizing therapy approaches and improving clinical guidelines. It is important to note though that such intelligent systems are only assistants that support human experts. Doctors and nurses make decisions that are best for their patients, and they must always have the last word. Computers cannot replace the emotional and social side of people.

A key aspect for the success of a digital health care transformation is that humans remain in control. For that purpose, an interdisciplinary approach is necessary. Convergence among various disciplines such as mathematics, physics, chemistry, biology, engineering, and medicine is imperative. An appropriate understanding of the background technologies and training of medics for the ideal application of digital processes in clinical practice is also necessary. Certainly, the application of automated methods does not mean oversimplification of clinical procedures or reduced experience. Systematic clinical training as well continuous collaboration with experienced technology experts is mandatory. The development of relevant technical and clinical standards is a key element in establishing this digital health care transformation. "Certified" procedures and products are mandatory in order to protect public health, preserve quality, and promote safety for all concerned. For that purpose, developing and implementing regulatory strategies and policies for digital health technologies is imperative. The most important consideration in adapting digital procedures should be the optimal results for patient well-being. No one should forget that health care is about caring for people, and ethics should be a key aspect during any digital transformation.

A "digital future" presents possibilities for our life, but it depends on whether we can really embrace and make them happen. Twenty years ago, I was tasked to produce a "virtual human" model for the British MOD and NATO. It took a record time of a few months to generate a whole human anatomy for the first time in an STL format. Today, such a model could act as an input for AI and cognitive computing systems to analyze, study, and predict human anatomy physiologic functions and responses. In the future, such virtual patients or otherwise "digital human twins" will become a common practice for studying every pathology and treatment. From diagnosis to treatment, digital tools are about to change the way every health care professional works. Prior to embracing the forthcoming digital era, however, we should keep in mind that the success of "going digital" relies on the way we think, approach, and use the relevant technologies. As it is demonstrated by the prominent authors of this book, the future orthodontic practice is not that far away.

This book represents the future digital transformation of orthodontics. It is an illustration of future digital orthodontic workflows but also provides the reader the opportunity to adopt and apply this already today. A digital roadmap is provided for orthodontists who wish to provide care for their patients in a personalized 3D way. I would like to express my great appreciation to Dr Nearchos Panayi for his enthusiasm and commitment to adopt digital engineering in his daily orthodontic routine. His passion to share the digital knowledge and experience that he has accumulated during the last few years is admirable. I would also like to extend my gratitude to all the authors of *DIY Orthodontics*. This book is a significant recognition for all those pioneers, engineers, and clinicians who believed, developed, and introduced digital approaches in medicine. It proves that computer-aided engineering techniques are applicable to all clinical fields, as it was once thought and hoped. However, we are still in the beginning of exploring the many possibilities that 3D engineering technology can offer in medicine. We are entering a new universe in clinical practice, and it is a learning process for all involved. Knowledge, experience, as well as guidance and training on best practices are critical. Unrealistic expectations only lead to disappointment, but when we work together—researchers, scientists, engineers, and clinicians—we can get this right! Until then, by reading and applying *DIY Orthodontics: Design It Yourself*, you can already immerse yourself in tomorrow's 3D world.

Panos Diamantopoulos, DPhil, Dr Eng
President, Computer Aided Implantology Academy

Preface

Γηράσκω δ' αεί πολλά διδασκόμενος
I'm getting older while being taught all the time.
—Solon, 630–560 BC, Ancient Athenian legislator & philosopher

In 1957, the Canadian philosopher Marshall McLuhan stated that "As technology advances, it reverses the characteristics of every situation again and again. The age of automation is going to be the age of 'do it yourself.'" This proactive statement has come to be realized in our time.

The progressive nature of technology has given it a presence in modern orthodontics since its recognition as the first specialty of dentistry, as established by Dr Edward H. Angle. Its influence has been continuously evolving and altering the way orthodontics is practiced. The reality is that new materials, techniques, bracket designs and prescriptions, appliances, and software, together with advances in the field of biology, have influenced many aspects of orthodontic treatment. However, most of these advances have been within the confines of traditional clinical practice workflows, with a dependence on an orthodontic laboratory and orthodontic material companies for the necessary appliances and auxiliaries to be used for treatment. The advancement of automation, however, is a departure from that workflow entirely.

Automation implies self-regulation or acting independently with limited to no human intervention. This term is rooted in the Greek word *automatos*, which means acting by itself, or by its own will, or spontaneously. Automation, as alluded to by McLuhan, has been incorporated into medicine as a whole, and modern dentistry specifically, but to a lesser degree in orthodontics.

Automation can mean fully automatic or semiautomatic devices or systems where human input has a minor role. A modern CBCT, for instance, is a tomograph that can acquire images in three dimensions only by setting the necessary parameters in a semiautomatic configuration. An intraoral scanner delivers colored accurate surface 3D images by automatically matching different angle scans of points of interest (POIs). Recently, color matching for restorations is also available or even functions for caries detection. Automatic integration of a volume and a surface scan is also available with certain software. 3D printing or milling is another form of automation where 3D images are transferred to dedicated machines and output as real objects following several automation steps. Other such examples are CAD software that performs teeth segmentation and virtual bracket positioning for indirect bonding procedures, which are semiautomation processes. Furthermore, artificial intelligence is being developed to "trace" cephalograms with remarkable accuracy or convert DICOM files into an STL printable format.

Another example of automation in orthodontics is CAD software that performs automatic procedures to help the operator design almost all kinds of appliances, which are then printed or milled in special machines. Aligner 3D printing is in its initial steps but certainly will be the next big step in aligner treatment. Recently, in-house or laboratory wire-bending robots have been developed to manufacture patient-specific archwires. Artificial intelligence is also used by aligner companies to gather data from orthodontists in order to provide assistance for future aligner treatments. Blockchain, although initially developed for use with cryptocurrency (ie, Bitcoin), has also found use in medicine. The ability to automatically share medical data without any central server using only peripheral computers is a promising technology that could also be used between orthodontists for treatment and research purposes.

Customized orthodontic brackets manufactured by companies for individualized orthodontic treatments is an important recent step in the direction of personalized medicine within orthodontics, which has mainly occurred out of necessity in lingual orthodontics. Nevertheless, bracket customization manufacturing is currently available from a small number of companies also in labial orthodontics. Despite this customization evolution, the relatively high cost of such treatment currently deters the mass of patients from availing themselves to such systems. The present book describes a new CAD software called UBrackets, which may place fixed appliance customization within the grasp of the majority of orthodontists and their patients. This tool gives the orthodontist the ability to design the specific patient's tailor-made fixed orthodontic appliances. This has led to the start of a project to create the technology for in-house fixed appliance printing.

Creekmore, in his article "Straight wire: The next generation," lists five reasons why current preadjusted appliances cannot achieve ideal positions: inaccurate bracket placement, variations in tooth structure, variations in the vertical and anteroposterior jaw relationships, tissue rebound, and orthodontic appliance mechanical deficiencies. Moreover, he states that even with the preadjusted appliances, first-, second-, and third-order bends have to be made to move the teeth in the desired positions. Perhaps the use of digital technologies will satisfy these conditions.

It was the Greek philosopher Heraklitos (544–484 BC) who stated that "the only constant is change," or put differently, "nothing endures but change." Within the changes brought on by the digital revolution and the effect of automation processes is the continuous change of human roles. Thus, the whole complex of the contributing factors in practicing orthodontics is continuously changing due to technologic advancements driven by automation. The consequence of automation, as previously stated, is the "do it yourself" concept. It is evident that the concentration of all the digital records of a patient in a computer allows for a global view of the patient, or the *virtual patient*. Moreover, this facilitates in-house designing and printing of the majority of orthodontic appliances, as foretold by McLuhan. Thus, technologic advances directly influence the role of the orthodontist or orthodontic clinic by bestowing on its traditional laboratory tasks without the intermediary steps with their inherent lost time and material requirements. This now includes obtaining the patient-specific fixed appliance brackets as the result of an in-house customized bracket design and printing process.

Companies will strive to manufacture new 3D printers with higher capability for accurately printing small objects like brackets at an affordable cost. Moreover, they will turn their interest to creating reinforced resins or other materials that could be used for bracket printing and whose printing result will resemble the material quality and properties of the currently used metallic or ceramic brackets.

The goal of this book is to provide the modern orthodontic clinician a description of the current digital technology that is used in orthodontics, including volume and surface scanning, 3D printing, CAD software, and artificial intelligence, and to speculate as to the future developments that can be expected. The former will be summarized within a single chapter in an effort to indicate the directions expected of the latter to describe the future integration of digital technology and its use within the workflow of a completely digital orthodontic office. The second section of the book is a "design it yourself" guide presenting the application of this technology in all aspects of orthodontic treatment. Almost every chapter of this book is a separate subject that should be analyzed, studied, and evolved more by researchers and orthodontic companies in order to create a state-of-the-art orthodontic technology.

The book describes all the necessary technologic ingredients to be used in a self-sufficient digital orthodontic clinic. It focuses on the in-house design and production of tailor-made appliances by digitally diagnosing and evaluating the virtual patient and by creating an individualized treatment plan. Moreover, the book describes the concept of a future network connecting orthodontic offices (globally) to a central artificial intelligence server and to a noncorporate orthodontic blockchain network. This will connect all orthodontists in such a manner so as to create a "super study club" for case sharing and research purposes using cryptography.

Whenever we talk about technology and digital advancements, it is essential to understand that digital technology can make a good orthodontist better, but it will not transform a bad orthodontist into a good one. Furthermore, as it is described in these pages, automation is not to be the substitution of human error with mechanical error. Minimization of such errors is dependent on the changing but ever-present involvement of the human interlocutor. The symbiosis of human experience and knowledge, together with digitized technology, can be honed to better serve our patients and humanity.

Acknowledgments

I want to thank my parents for all the things they gave me since they brought me to life.

I want to thank my mentor, maxillofacial surgeon Dr Samaras Christos, Abbot Ephraim of Holy Great Monastery of Vatopediou in Mount Athos, and all the monks of the monastery for their valuable help and prayers, as well as Professor of Maxillofacial Surgery Iatrou Ioannis for his continuing support.

Huge thanks to Dr Moshe Davidovitch, who at my postgraduate studies in orthodontics at Tel Aviv University was my inspiration and role model because of his effective simplicity in orthodontic treatment, his devotion to the profession, his calmness, and for his continued pushing of me deeper into digital orthodontics with his phrase of "keep moving forward." In addition, he contributed to this book by "editing" the written English of the nonnative speakers and in so doing transformed the collection of chapters into a coherent scientific textbook of value to all modern orthodontists.

Special thanks to Associate Professor of Orthodontics Apostolos I. Tsolakis, who believed in me, helped me in any possible way, guided me through the field of research, and was my PhD supervisor in Athens Medical School as the eminent expert in animal studies that he is.

I must also thank Professor Panos Diamantopoulos, a world leader in 3D technology and the person who introduced me to 3D technology 6 years ago. Since then, he has become a valuable friend and partner in the amazing world of digital technology.

Many thanks to Professor of Orthodontics Athanasios Athanasiou for guiding me in writing scientific manuscripts and chapters.

My gratitude to all my friends, orthodontists or not, who helped me and encouraged me in compiling the current book.

Last, but certainly not least, I want to thank all the contributors for their efforts and commitment to write timely and practical chapters. This will significantly impact the integration of digital tools within orthodontics toward their inevitable merger culminating in the in-house design and manufacture of any conceptualized appliance. This actualization will not only enable the clinician but will also impact the specialty of orthodontics for the betterment of our patients. The future has arrived. Embrace it.

Dedication

This book is dedicated to my lovely wife, Marina, and to my six children: Christos, Theodora, Andreas, Maria, Nicolais, and Amalia. I want to thank my family, especially my wife, for their understanding and patience, but most of all for reminding me that there are more precious values in life apart from orthodontics.

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1

Introduction

Rafi Romano

"Do it yourself" (DIY) orthodontics is becoming requisite in modern orthodontic practice. Nevertheless, this book is titled *Design It Yourself Orthodontics* in order to differentiate it from the "doctorless" direct-to-patient appliances offered online or at shopping mall kiosks.

Technology and 3D software have irrevocably changed the way modern orthodontics is managed and administered. Printed models are eliminating poured plaster casts, appliances can be designed and printed with computer-assisted hardware and software, and tooth movements can be simulated and staged digitally to increase their accuracy and predictability.

Digitization converts real-world information into digital data that can be presented on a computer screen. Volume scanning and surface scanning of the dental arches and the face are transferred to dedicated orthodontic software to build the "virtual patient" for orthodontic diagnosis, tooth movement simulations, and treatment planning.

Artificial intelligence (AI), currently in its initial stages, holds promise in becoming a tool for orthodontic diagnosis and treatment outcome predictions. It also has the potential to assist in defining appropriate treatment options for a specific patient, as well as predicting tendencies of relapse. Furthermore, AI can be a valuable research tool. Blockchain assemblies are described herein that could be a digital tool to connect an infinite number of orthodontic clinicians without a centralized server as a network. This could become a window for participants to view treatment examples, digital appliances, radiographs, etc, without violating patient or doctor privacy.

Dentists and orthodontists can at times be intimidated by mathematics, physics, and technology, which are related to forces and appliance design. Technologic understanding is a time-consuming process with a learning curve that can deter the orthodontist from getting involved. A familiar work pattern and acceptance of a particular appliance serve to create a comfort zone for every clinician. The introduction of a disruptive technology may upset this pattern and disturb the established workflow. Nevertheless, avoidance of these technologies will be to the disadvantage of the practitioner. The longer the delay in integrating these technologies, the greater the learning curve in implementing them. As Darwin stated, it is not the strongest of the species that survives nor the most intelligent—it is the one that is most adaptable to change.

The versatility of digital applications has enabled increased control and greater independence within our clinical settings. This trend has justified the inception of many companies that recognize the need for tools to design and plan individualized appliances according to each clinician's vision for each case, and to enable modifications as needed during the treatment. These tools include multifunctional orthodontic software for virtual patient analysis, treatment simulation, patient education, treatment planning, and smile design. Other software offers the ability to design and create in-house orthodontic aligners, indirect bonding (IDB) trays, customized bands, appliances, and orthognathic surgical splints, etc. 3D printer companies have recognized the application of their technology in dentistry and orthodontics, and new biocompatible printing resins are continuously under development and being introduced in the market for use.

The younger generations of orthodontists and dentists, while certainly less clinically experienced, are naturally better informed as to these technologies because their emergence into the field parallel one another. Older, more experienced clinicians generally are slow to adopt new technologies due to the apprehension created by the disturbance in established principles and the apparent complexity new technology introduces. Young or old, inexperienced or experienced, all clinicians need sources that enable them to accept new technologies and overcome barriers so they can realize their own innovation.

It needs to be understood that technology is not a replacement for the process of coalescing the appropriate diagnostic information into a patient-specific treatment plan. Digital technology can only serve as an assistant, not the master in orthodontic treatments. Ironically, it is the more clinically experienced category of clinicians that can maximize the potential of these tools; however, their aversion to the changes brought by technology has left this potential unrealized. Also, knowledge of new technology should not give the impression in young dentists and orthodontists that it is sufficient for a satisfactory orthodontic treatment result.

This book, as stated in its title, covers the topic of DIY orthodontics from the simple design of expansion and cast/printed appliances using dedicated computer-aided design (CAD) orthodontic software to unique printed appliances designed by general CAD engineering software. As the reader will notice, such tools enable the orthodontist to directly design appliances that cannot be created with any other software. Indirect bonding with digital preparation is thoroughly described with the add-on of a special IDB process that is undertaken upon digital setup. In-house design of customized lingual braces is presented together with an in-house wire-bending robot, for both lingual and labial archwires.

In-house aligner design is presented using uncomplicated software, an aspiration that is currently central in orthodontics. Furthermore, industry efforts to produce a biocompatible material and technique to directly print clear aligners are discussed in these pages and, together with the applications for AI, are the frontiers in the integration of technology into clinical orthodontics.

One of the most revolutionary chapters of this book describes in-house custom bracket design and printing using a new software called UBrackets. This enables the operator-driven design and building of customized orthodontic bracket bases using composite resin on orthodontic brackets. In addition, as a second software option, the orthodontist can use the software's bracket library to print fully customized brackets. Volume scanning, surface scanning, 3D printing, and AI are covered in separate chapters. A full overview of the digital office workflow is also covered in detail.

To my knowledge, there is currently no similar compilation of these undeniably important aspects of the modern practice of orthodontics. This does not surprise me because the majority of what is described in this book was not in existence even 5 years ago. The importance of a book such as this is highlighted by the frequency at which new companies and products are popping up on the market, offering new ideas and tools to enable simplification of clinical tasks and broaden our professional lives with new and exciting opportunities.

The authors contained in this book are recognized clinicians and researchers whose reputations and contributions are highly regarded. Each presents their respective topic in a well-written, comprehensive, but very readable manner. All the material appearing in this book is not only topical but also extremely up to date with several items receiving initial exposure in these pages. The text and visual presentations complement each other and engender a flowing and enjoyable reading experience of a cutting-edge group of topics.

The biology of tooth movement and the biomechanics applied to do so are constants within orthodontics. Yet with simple DIY tools, the modern clinician can visualize and simulate treatment, and, most importantly, sustain maximum control of the progress of any given treatment. Furthermore, DIY tools facilitate the ability to modify treatment as and when needed without being limited or dependent on outsourced laboratories and/or commercial companies.

The highly innovative nature of this book is sure to make it standard for every orthodontic office. It will go a long way in helping today's clinicians immerse themselves in this fascinating era, which will certainly become the "new normal" in every clinic.

2

CBCT in Orthodontics

Apostolos I. Tsolakis
Christos Angelopoulos
Nearchos C. Panayi
Kostas Tsiklakis

CT and CBCT Historical Perspective

Cone beam computed tomography (CBCT) is undoubtedly the most significant diagnostic imaging advancement in maxillofacial imaging in the last 25 years.[1,2] Sir Godfrey N. Hounsfield invented computed tomography (CT) in 1972, for which he received the Nobel Prize in Medicine in 1979; however, the principles of tomosynthesis were described in 1934 and provided the theoretical basis of the integration of multiple planar images.[3–6]

The first patent application for a maxillofacial CBCT was submitted in Italy in 1995 by Attilio Tacconi and Piero Mozzo. This led to the commercial development of the first available CBCT—NewTom DVT 9000. Presently, more than 60 CBCT brands are available, the majority of which offer multiple options to the practitioner, including hybrid panoramic units to a full maxillofacial unit with or without a cephalometric unit.

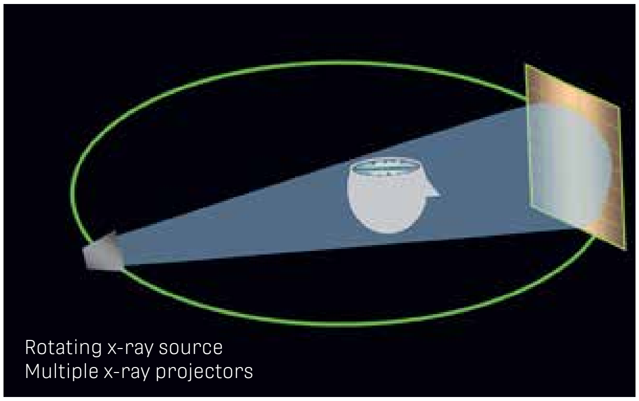

Fig 2-1 A rotating x-ray source, a flat panel detector, and a conical beam are the key components of the CBCT image acquisition process. The x-ray tube completes a full rotation around the patient's head, producing multiple exposures.

Basics of CBCT

CBCT imaging is accomplished by rotating an x-ray source and a detector around the region of interest (ie, the patient; Fig 2-1). Radiation is emitted by the x-ray source passing through the patient in a cone-shaped beam to the x-ray detector on the opposite side, with the range of the arc employed being 180 to 360 degrees. During the exposure, hundreds of sequential planar projection images are acquired. In contrast, the CT machine consists of a fan-shaped x-ray beam with a simultaneous translation of the patient table and rotation of the x-ray source and detector, resulting in a helical trajectory (Fig 2-2).

The basic parts of a CBCT are the following[7,8]:

- An x-ray generator
- An x-ray detector that must be able to capture multiple basic images
- A powerful computer and software able to process all the acquired image data
- Appropriate image acquisition and integration algorithms

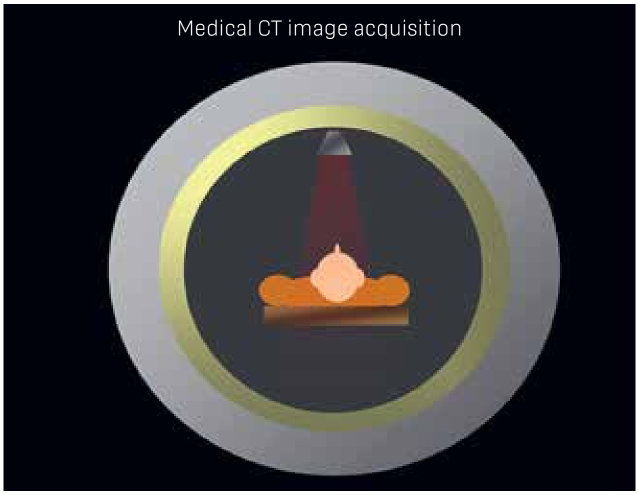

Fig 2-2 Medical CT image acquisition involves a thin fan-shaped rotating beam, a ringlike array of detectors *(yellow ring)*, and a supine patient. The x-ray source scans the area of interest with multiple rotations, collecting x-ray attenuation data.

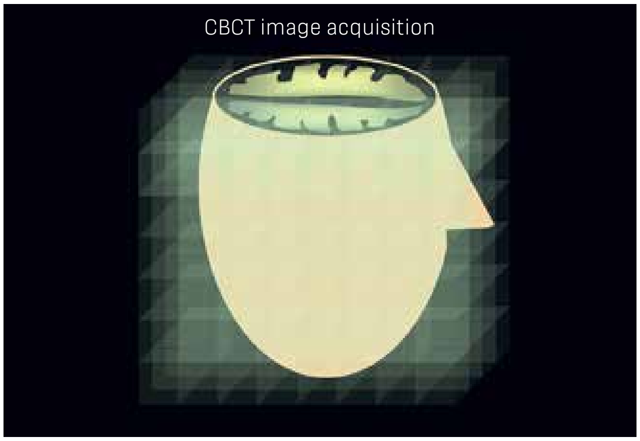

Fig 2-3 The moment a region of interest is determined, this area is "split" in numerous small fictional cubes from which the detector of the scanner will collect attenuation data; these cubes, known as *voxels*, are of a known spatial location and are assigned a shade of gray after the data are processed. This composite of voxels forms the 3D volume.

In order to transform a series of 2D multiple planar images (which are captured by the 2D x-ray area detector) to a 3D volume image, a cone beam reconstruction image procedure must be performed. In other words, 3D volume reconstruction software turns a series of 2D acquired images into a 3D volume image. The most popular reconstruction scheme for cone beam projections is the FDK (Feldkamp-Davis-Kress). CBCT provides an alternate method of volume scanning, allowing a fast acquisition of data in an in-office mode. CBCT units use an image intensifier or a flat panel detector as the image detector. The larger the detector, the bigger the field of view (FOV), and as a result the better the imaging; however, this increases the cost of the CBCT unit.

An important factor in the quality of the x-ray detector is the pixel size it detects, because this determines radiographic resolution and subsequently the CBCT image quality. A detector with a small pixel size increases the resolution of the acquired image but captures fewer photons, the consequence of which is increased image noise. In order to increase the resolution and decrease the image noise, detectors are usually grouped together and considered as one element; otherwise, the radiation dose has to be increased to achieve the same goal. While the detector captures 2D images consisting of pixels, the 3D volume data output is composed of cubical elements called *voxels* (Fig 2-3). This transformation, from the 2D image to a 3D volume image, is performed by a sequence of software algorithms. CBCT images are reconstructed from pixels to voxels and presented as gray values depending on the media through which the radiation is passed (air, bone, soft tissue, teeth, etc).

Originally, the use of CT in the maxillofacial area was a rarely used diagnostic tool limited to suspected tumors, fractures, or craniofacial syndromes—not for dental implant placement. The amount of radiation required, together with the unit costs and size, made the early use of this diagnostic tool prohibitive for dentistry. Resolution of these parameters and what is now almost routine use of CBCT images has facilitated the transition from 2D to 3D imaging in dentistry and maxillofacial imaging, allowing the use of a fast, inexpensive, and reliable imaging tool.

Field of view (FOV)

The FOV in CBCT is the maximum diameter of the scanned object in the horizontal and vertical dimensions that is represented in the reconstructed image. In other words, FOV refers to the anatomical area that will be included in the data volume and the area of the patient that will be irradiated[9,10] (Fig 2-4). Although a wide range of FOVs is available, generally, four categories exist:

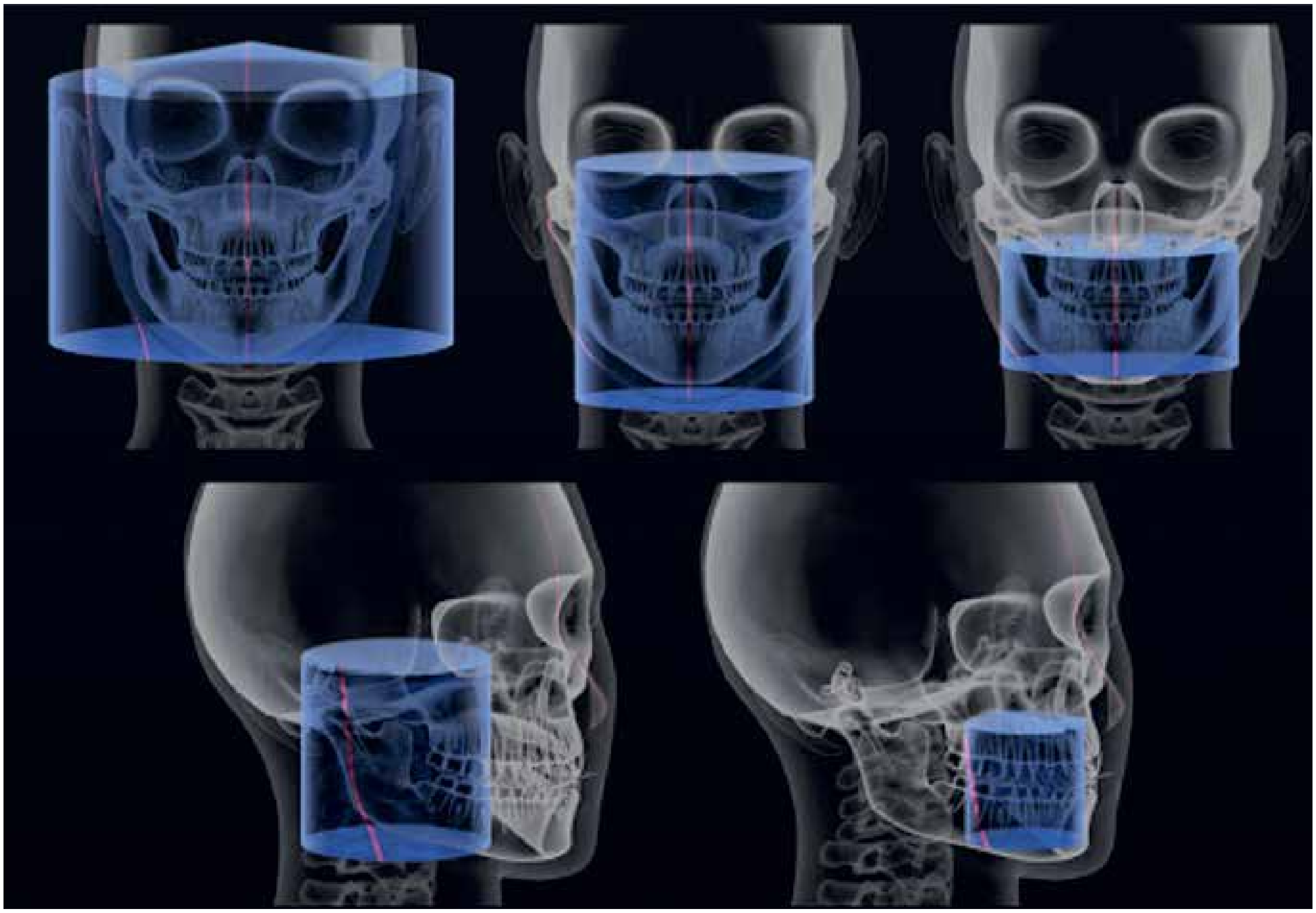

Fig 2-4 There are a variety of available FOVs in modern CBCT machines; these range from very small (40 × 40 mm) to very large to include almost the entire head of the patient (230 × 230 mm).

1. **Large FOV:** Covers most of the craniofacial skeleton and is more than 15 cm in both dimensions
2. **Medium FOV:** Covers both jaws and is 8 cm or more in vertical and horizontal dimensions
3. **Small FOV:** Covers a single jaw and is wide in diameter (about 10 cm or more) but limited in height (4–6 cm)
4. **Very small FOV:** Covers between 4 and 6 cm in both dimensions

In most CBCT units, there are options of increasing or decreasing the FOV depending on the specific diagnostic needs and variability in patient anatomy. Furthermore, the quality of the image is also affected by the FOV size. A large FOV increases the amount of scattering per detector area, which in turn reduces the image quality.[11] Image quality is also decreased in large FOVs by the higher beam divergence at the edge of the FOV.

Image quality

The quality of the image is dependent on four parameters:

1. **Spatial resolution:** The ability to distinguish small details in an image. It is a factor that depends on the voxel size, the pixel size, and the fill factor (Fig 2-5).
2. **Contrast resolution:** The ability to discriminate objects of different density. Compared to medical CT, CBCT cannot reveal with accuracy differences between soft tissues or structures that have similar anatomical contrast. Nevertheless, structures with different density can be visualized very well (Fig 2-6).
3. **Image noise:** The variability of the projected gray values in a homogenous tissue. There are various causes of this noise in a CBCT. These include the basic nature of random x-ray interactions resulting in a nonuniform

Fig 2-5 *(a)* Coronal section of the maxillary bone (0.3-mm voxel size scan acquisition) vs *(b)* a coronal section of another scan of the maxilla (0.15-mm voxel size). There is an obvious difference in the image resolution attributed to the smaller voxel size.

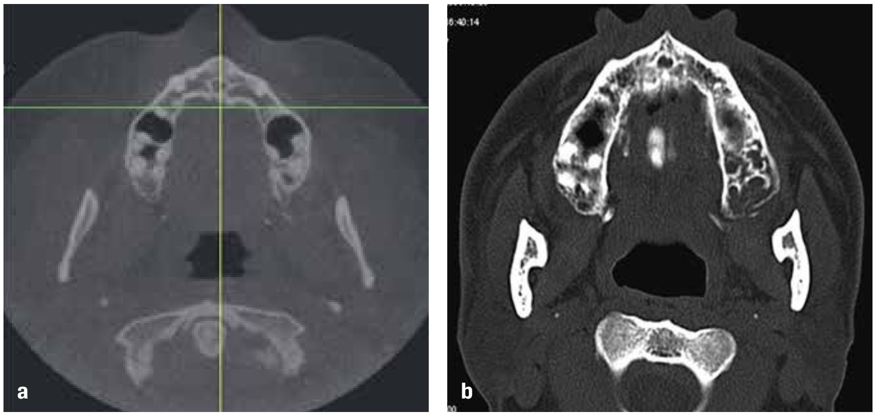

Fig 2-6 *(a)* A CBCT axial section at the level of the maxilla compared to *(b)* a medical CT axial section at the same level. Note the difference in the soft tissue contrast (much higher in the medical CT scan) because of the higher contrast resolution (many more shades of gray).

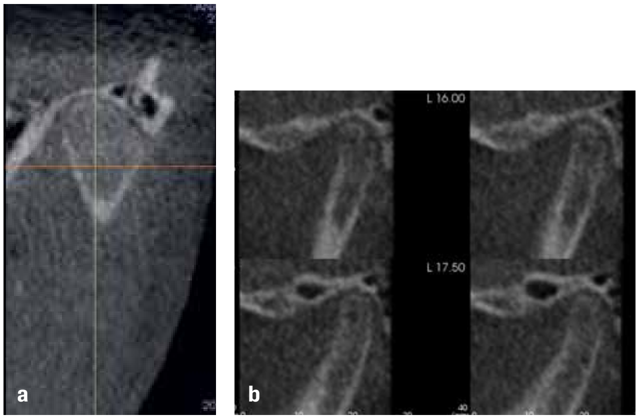

Fig 2-7 *(a)* Coronal CBCT section and *(b)* a series of sagittal CBCT sections of the left temporomandibular joint (TMJ) in a young patient. Note the diffuse “graininess” seen in all images; this is attributed to the noise in the scan (ie, the heterogeneous distribution of the x-rays onto the detector).

signal at the detector, as well as x-ray scatter. Filtering during image reconstruction can improve the resolution of signal detection (ie, separate useful diagnostic information from noise; Fig 2-7).

4. **Artifacts:** An image artifact is a visualized structure in the 3D volume image that is not present in the object under investigation. In the maxillofacial region, this most frequently occurs due to the presence of a metallic structure (ie, restorations) and can be seen as dark/bright streaks most often in the axial plane. Patient movement during the CBCT scanning will also result in artifacts proportional to the extent of the motion.[11] Ring artifacts can also occur when the detector has not been properly calibrated. Unfortunately, when such a 3D volume image is taken, such unwanted structures are frequently detected; however, they are usually discernible from normal structures and are only problematic if they obscure an area of interest.

Scanning time is another variable that can alter image quality. In general, longer scanning times lead to a larger

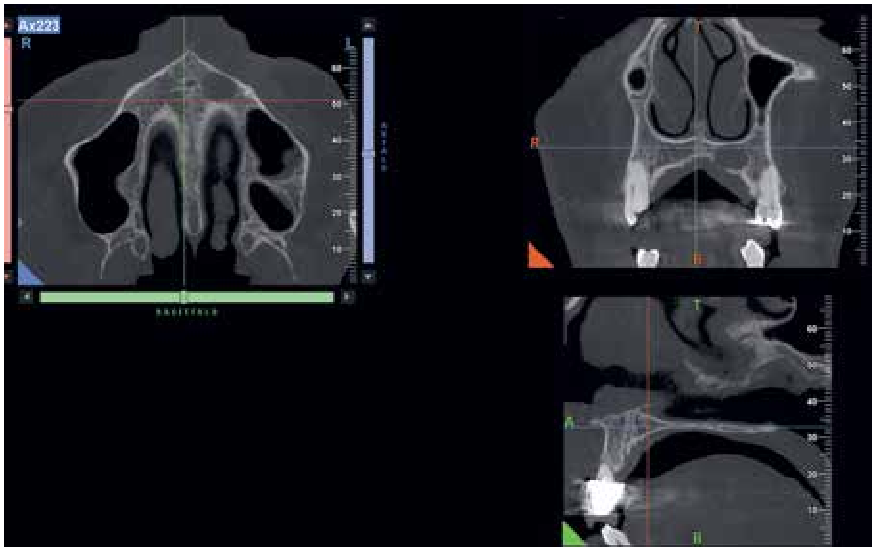

Fig 2-8 Standard multiplanar view of a CBCT volume of the maxilla with *(clockwise from left)* axial, coronal, and sagittal sections.

number of base images, higher radiation dose, more data, greater contrast resolution, smoother images, and fewer metallic artifacts. On the other hand, longer scanning times could lead to motion artifacts due to an increased chance of patient movement.[12]

Exposure parameters

There is the need to adjust the exposure parameters before we proceed to CBCT image acquisition:

- **Milliamperage (mA):** This determines the number of x-rays emitted by the generator per unit time; it is coupled with the kilovoltage (kV) and exposure time to create an acceptable image. This parameter should be set according to the patient's size and age. A high mA reduces image noise by increasing the radiation dose, which leads to an increased detector signal.
- **Kilovoltage (kV):** This proportionately determines the quantity of x-rays produced per unit time. Moreover, it also increases the mean and maximum energy of each x-ray. In general, an increase in kV increases the quantity of x-rays produced while reducing the image noise and beam hardening and improving contrast.

In most CBCT machines, the kV and mA settings are predetermined or fixed; however, there are also units where some level of adjustment is possible. "As low as reasonably achievable" (ALARA) is a technical concept that should be taken into account in order to decrease the dose of radiation without lowering the image quality. In cases where image quality is not crucial, mA could be reduced without compromising diagnostic quality.[13] An appropriate example of decreased radiation is the CBCT imaging for presurgical implant planning or for orthodontic diagnosis.[14,15]

Image display

From the time that the data from the detectors enters the computer, there are four distinct operations involved[16]:

1. **Reconstruction:** The 2D sequential planar imaging data derived by the detector undergo reconstruction to generate a 3D volume dataset.
2. **Visualization:** The reconstructed images from the CBCT are optimized and finalized to be visualized by rendition techniques.
3. **Postprocessing:** The operator uses software tools to change the presentation of the image. The tools are usually based on specific image enhancement techniques.
4. **Analysis:** The image characteristics are assessed to provide the necessary quantitative information from the data.

Almost all CBCT computer visualization software displays images in the standard three planes of section (axial, sagittal, coronal) as well as different reformatted images (panoramic and cross-sectional; Figs 2-8 and 2-9). A multitude of image reconstructions can be performed by

Fig 2-9 Very popular reconstruction layout for CBCT data visualization: Axial section *(left)* with a curved line indicating the panoramic reconstruction *(top right)* and a series of cross-sectional images *(bottom right)* perpendicular to the panoramic curved line.

"reshuffling" the volumetric data. Image enhancements can also be performed in order to improve diagnostic image quality.

Orthodontics and CBCT

Traditionally, radiographic imaging in orthodontics was performed using 2D extraoral radiography, namely panoramic and cephalometric radiographs, combined with analyses using manual tracing of the latter and 2D photographs. The main purpose of such imaging in orthodontics is to provide diagnostic information to corroborate the clinical orthodontic diagnosis of skeletal, dental, and soft tissue conditions. Moreover, cephalometric radiography is used as an adjunct to treatment planning, evaluation of growth, treatment progress follow-up, and research purposes.

It needs to be emphasized that this entails the assessment of a 3D object on a 2D basis. Traditionally, the only 3D tool that has been used for diagnosis, treatment planning, and progress evaluation is the plaster dental casts. The task of merging 3D information from plaster casts into 2D radiographic or photographic images is a difficult one. Thus, the result could be an inaccurate diagnosis due to the inability of the diagnostic tools to be combined and reflect the true nature of the malocclusion in 3D.[17] According to DiFranco et al, the process of recording a 3D object into 2D data can cause significant data loss and could result in an incomplete diagnosis or even misdiagnosis.[18] Although there are problems related to the 2D imaging of 3D subjects, attempts have been made to obtain the necessary information by stereometrics. Nevertheless, this approach was never universally adopted as part of standard acceptable clinical procedure.[19,20]

It has been demonstrated that deficiencies are revealed where a thorough 3D evaluation of the patient was needed but not performed or cases where 2D radiographic imaging was found to be lacking in differentiating important information. Moreover, complications can arise when information derived from 2D images was misleading, which is common given the projection of intervening anatomical structures. According to Tsolakis et al, conventional radiographic methods demonstrate a more subjective diagnostic procedure compared with CBCT images. Furthermore, CBCT is a more accurate and precise examination method compared with conventional radiography for the localization of impacted teeth and for the identification of root resorption of the adjacent teeth.[21]

The comparative information presented above begs the question as to whether it is obligatory to perform a CBCT scan without exception on all patients based on the concern of not discovering vital imaging/orthodontic information. In resolving this query, it is recommended to apply the same criteria as in treatment planning, meaning that each patient's treatment plan should be individualized and based on careful examination leading to the appropriate selection of an imaging modality based on anatomical and functional requirements. Factored into this decision is the added value of 3D imaging and analysis (ie, skeleton, airway, temporomandibular joint [TMJ], impacted teeth, etc), with the principle of ALARA being the golden rule that should always be followed in every orthodontic case.

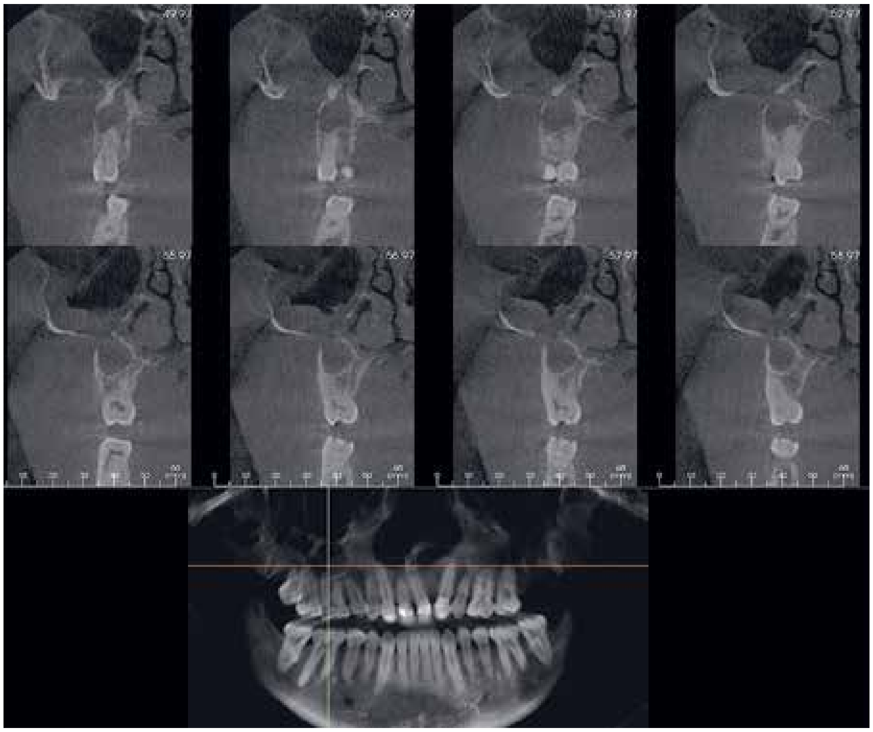

Fig 2-10 A CBCT panoramic reconstruction *(bottom)* and a series of cross-sectional images *(top)* of the maxilla for the assessment of postsurgical changes in the midface after orthognathic surgery (LeFort 1 osteotomy).

CBCT in orthodontic treatment stages

Similar to traditional 2D radiographic imaging indications, a CBCT could be performed in the following three stages of orthodontic treatment: *(1)* diagnosis, *(2)* treatment, and *(3)* posttreatment.

Diagnosis stage

CBCT scanning usually is used as a supplemental diagnostic tool for pretreatment assessment of the orthodontic patient. A CBCT can be easily reconstructed into a panoramic, lateral, or posteroanterior cephalometric image. Volume scanning can reveal the contribution of the dental and skeletal elements to the malocclusion or the craniofacial anomaly. Soft tissue can also be assessed and combined with the dental and skeletal elements in order to formulate a treatment plan. In a fully digital orthodontic office where an intraoral scanner and orthodontic diagnostic software (ie, Dolphin Imaging) are present, a CBCT scan can serve as the core of data integration to form the "virtual patient." In this way, the orthodontist can combine all the data fragments (puzzlelike format) into a single central image (3D dental cast, CBCT image, 3D face photography), evaluating the totality of a given orthodontic problem from a single unified perspective rather than from disjointed fragments.

Treatment stage

A CBCT should not be performed without profound justification. During treatment it is done mostly to monitor changes that have occurred and to investigate possible problems that were not assessed before treatment, or to evaluate issues that appeared during treatment. An example that justifies this procedure is in preparation for orthognathic surgery, where it has implications for surgical preparation analysis and surgical splint fabrication. Another possible justification is to aid in TAD (temporary anchorage device) placement.

Midtreatment CBCT scans are also appropriate to facilitate clear aligner fabrication as well as to direct orthodontic fixed appliance orientation. In both these instances, a CBCT scan could be fused with the 3D virtual dental cast to evaluate crown and root position in relation to peridental structures. Surface and volume scanning integration are desirable when there is a risk of root recession, fenestration, or dehiscence.

Posttreatment stage

A CBCT is rarely needed after orthodontic treatment. However, it is routinely performed for postsurgical assessment in orthognathic cases, craniofacial deformities, assessment of root resorption, or for TMJ periodic evaluation (Fig 2-10).

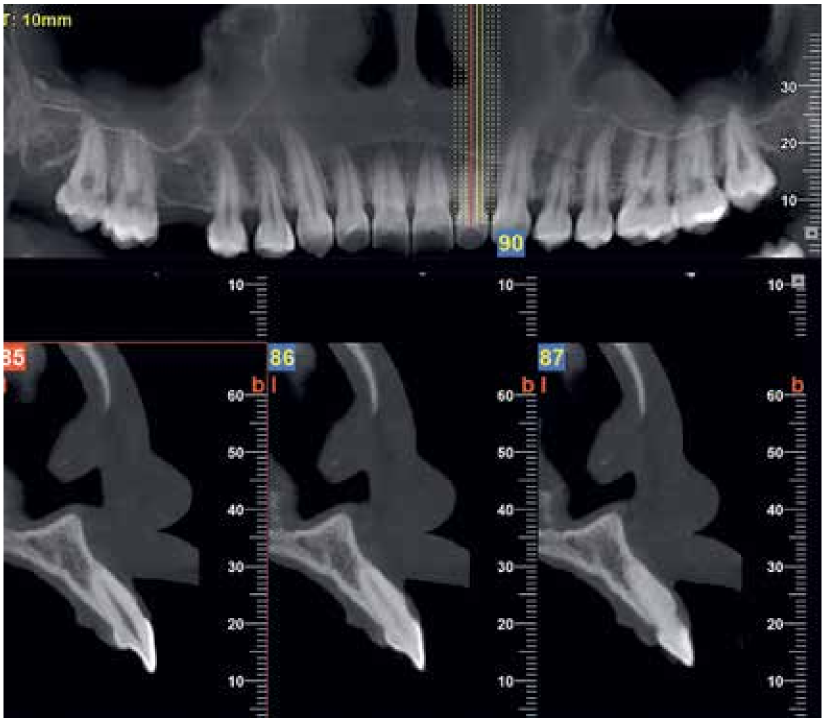

Fig 2-11 A CBCT panoramic reconstruction *(top)* and a series of cross-sectional images *(bottom)* of the anterior maxilla for the assessment of the integrity of the cortical plates and incisor root position inside the alveolar ridge.

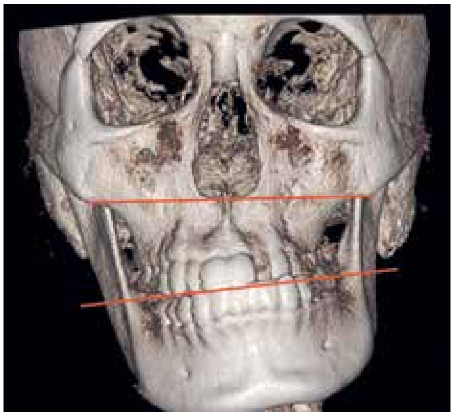

Fig 2-12 A CBCT 3D reconstruction illustrating a marked asymmetry between the right and left mandible due to hemimandibular hyperplasia (right side); note the deviated mandibular midline to the left.

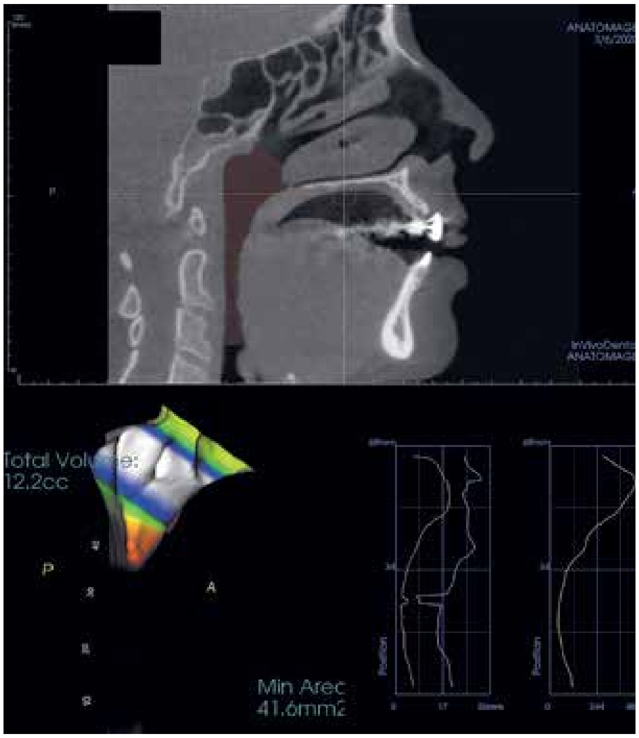

Fig 2-13 A CBCT midsagittal section with the airway highlighted *(red)*; this is a special software application that provides volumetric measurements of the airway *(bottom)*, a crucial tool in airway analysis.

CBCT indications in orthodontics

Although some authors mention several general indications for CBCT imaging in orthodontics,[22–24] there is no true consensus in the field regarding its appropriate indications.[25,26] CBCT scans may be used for the following reasons:

- 3D patient analysis at diagnosis
- Evaluation of buccolingual root position (Fig 2-11)
- Analysis of craniofacial deformities (Fig 2-12)[27,28]
- Imaging of clefts
- Airway volume analysis for patients with sleep apnea (with the disadvantage that the image is acquired in a vertical position instead of in a horizontal position; Fig 2-13)
- Assessment of dentoalveolar bone loss
- TMJ evaluation (Fig 2-14)
- Localization of dental impaction(s), root dilacerations, transposed teeth, supernumerary teeth, external resorption, root fusion, germination, fenestrations, or dehiscence (Figs 2-15 and 2-16)
- Computer-aided surgical simulation (CASS)

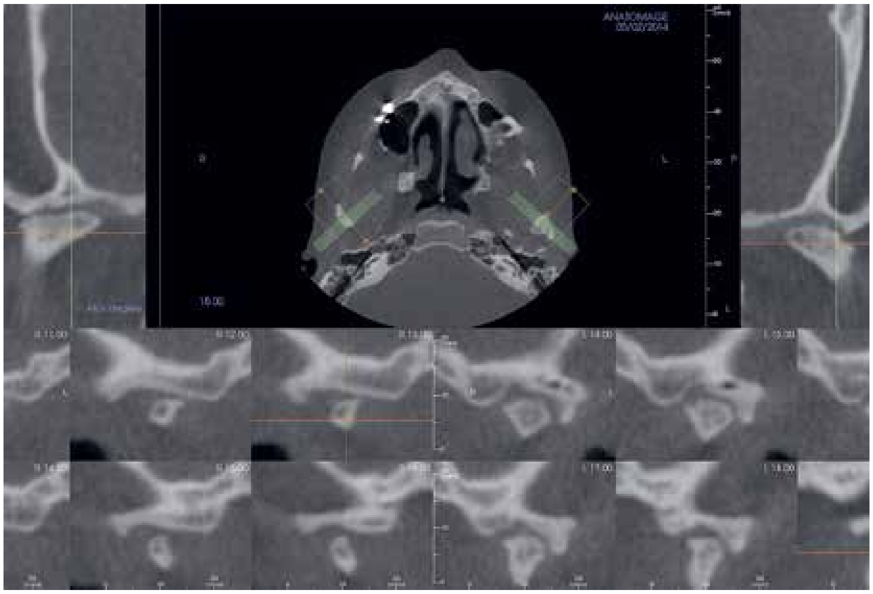

Fig 2-14 Coronal section *(top)* and a series of sagittal cross sections *(bottom)* of the right and left TMJs acquired for the periodic evaluation of the TMJ after extensive orthognathic surgery; note the marked degenerative changes in both TMJs.

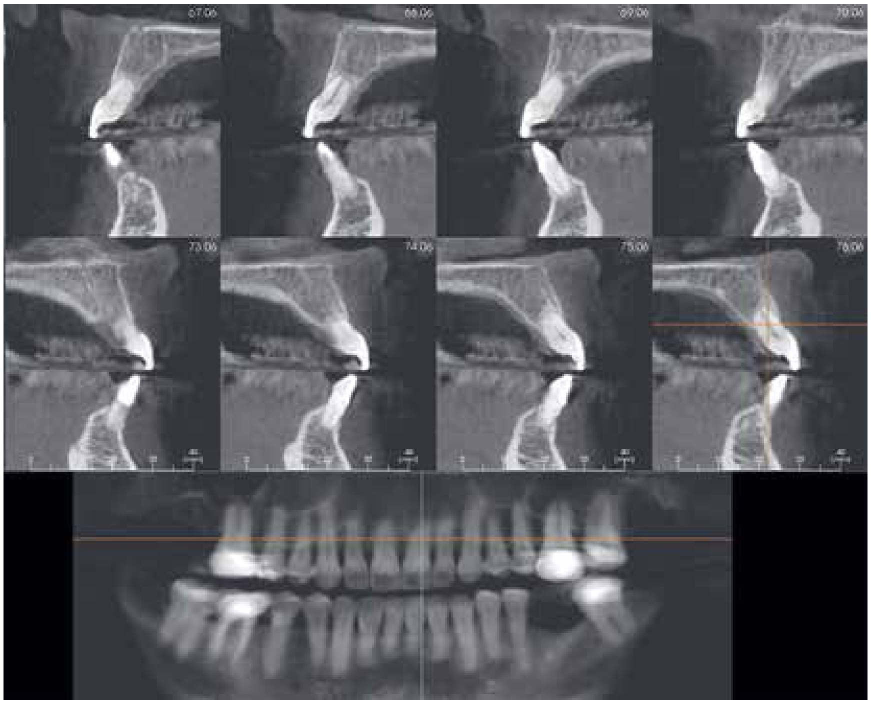

Fig 2-15 A CBCT panoramic reconstruction *(bottom)* and a series of cross-sectional images *(top)* of the maxilla and mandible showing extensive root resorption on the maxillary and mandibular incisors after orthodontic treatment.

- Computer-aided orthognathic surgery (CAOS)
- Orthognathic surgical splint design
- 3D cephalometry (Fig 2-17)
- TAD and miniplate placement planning
- Corroboration of panoramic radiographic findings
- Integration of volume and surface scanning in a virtual setup for aligner design
- In cases of impacted teeth, where the planning of the dental movements has to be performed (once these are defined in 3D) through the design of a force system[29]

According to Tsolakis et al, CBCT seems to be the only reliable and accurate diagnostic method for the exact 3D localization of impacted maxillary canines and root resorption of the adjacent teeth.[21,30,31]

Fig 2-16 Root fenestrations in the apical third *(a)* and middle third *(b)* in two different patients; these were anatomical variants revealed prior to orthodontic treatment.

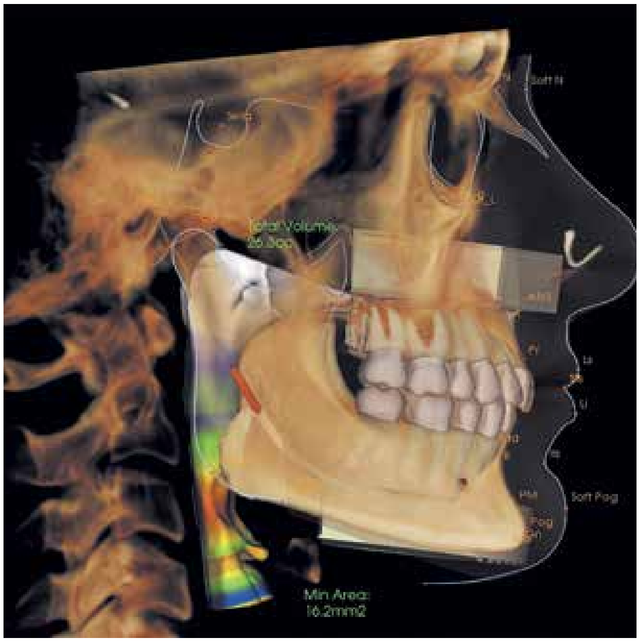

Fig 2-17 3D volume rendering of the skull, airway, and soft tissue outline with major anatomical landmarks identified; this is an application of contemporary software (courtesy of Anatomage Inc).

Advantages of CBCT imaging in orthodontics

Traditional panoramic and cephalometric radiographs have some advantages over CBCT. For example, they carry lower radiation exposure, they are relatively easy to obtain, and they are comparatively inexpensive. On the other hand, 3D imaging affords the clinician several diagnostic refinements over conventional 2D images[32]:

- Anatomical accuracy
- More precise information
- Structures are visible in their exact position with their exact shape
- No radiographic projection errors
- No enlargement and no distortion
- Ease of landmark identification, with no duplication of measurements (cephalometry) and no significant variations in the position of reference points
- 3D facial photo superimposition
- No misleading findings like panoramic radiography due to reflection of other anatomical structures
- Accurate comparison between CBCTs of the same patient
- Ability to reformat panoramic and cephalometric radiographs from a CBCT; those images compared to the conventional 2D images represent the "anatomical truth" of the morphology, teeth-to-teeth, and teeth-to-bone relations
- Ability to integrate surface scanning with the CBCT in dedicated orthodontic software to create the virtual patient
- Ability to visualize depth information by using stereoscopic binocular vision with the aid of special 3D glasses
- Excellent tool for research

CBCT image integration with other 3D images

One of the disadvantages of CBCT imaging is the difficulty in creating smooth surfaces, for instance, dental crowns, in 3D reconstructions. The real anatomy cannot be presented adequately, especially where we need to distinguish between different adjacent tissues, which speaks to the aspect of contrast resolution. In addition, artifacts could also inhibit a clear view of a given anatomical structure. Furthermore, noise is unpredictable and could also create problems. A possible solution could be the integration of different 3D imaging modalities to enhance the outcome image quality.[33]

Two 3D imaging modalities exist that could be fused with a CBCT: digital dental casts and 3D photographs. Some CBCT units like Carestream 9600 provide the option of simultaneous volume scanning and 3D photography (Fig 2-18). CBCT and digital dental casts can be fused in cases of orthognathic surgical planning and surgical splint design. In the virtual patient image, CBCT serves to visualize the bony structures for orthodontic diagnosis, surgical planning, and splint fabrication. 3D dental casts serve as the main tool for occlusion simulation and precise splint fabrication. The CBCT image and 3D dental cast could also be fused with 3D photography taken separately using 3D face scanners (ie, Bellus3D ARC). The two images are usually superimposed in the area between the eyebrows and the bridge of the nose. In cases where the intraoral scanner and the CBCT are manufactured by the same company (ie, Carestream), fusion of the 3D dental casts, CBCT, and 3D facial photography is done under the same software platform almost automatically. Specialized software exists for orthognathic surgical planning that can fuse the CBCT with the 3D dental casts using the same reference points (ie, Viewbox dHAL).

The fusion of the CBCT with the 3D dental casts is not limited to orthognathic surgical planning. As mentioned previously, in CAD orthodontic software for in-house aligner fabrication, there is an option to fuse the 3D dental casts with the CBCT images. This is helpful for the orthodontist to visualize the position of the roots while planning the necessary tooth movements in order to maintain their roots in the alveolar bony envelope. In this procedure, there is a limit because the movement of the dental crown does not have any effect on the position of the roots shown in the CBCT image. In order to move both crowns and roots (derived from the CBCT) at the same time, a tooth-by-tooth segmentation is needed in the CBCT image and fusion with the 3D dental cast tooth by tooth. This procedure would be useful for visualizing not only the crown movement in the setup procedure but also to assess the bony structure around the roots to be moved for biologic and biomechanical reasons. Such a process would be time-consuming, and the computer needs to be powerful enough to handle so much information.

Perhaps in the near future, artificial intelligence software could perform the segmentation and fusion automatically. In a 2D diagnosis data environment derived from a 3D subject, the separate data elements that are gathered are independent of each other, and a virtual patient cannot be created. This condition does not fulfill the principle of starting an orthodontic treatment with the end in mind.[34]

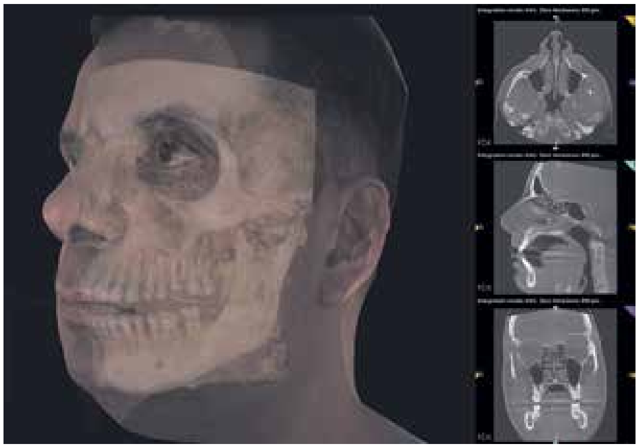

Fig 2-18 3D volume rendering of the skull with 3D photography.

3D Cephalometry

Cephalometric radiography was introduced by Broadbent in the United States and by Hofrath in Germany in 1931. This diagnostic radiograph has been the basis for multiple standardized 2D analyses (eg, Downs, Steiner, Tweed, Ricketts, McNamara, etc) for evaluating dental, skeletal, and soft tissue relationships. A detailed description of these analyses are provided elsewhere in several textbooks.

Notwithstanding the contribution made by the use of this type of diagnostic and clinical research tool, 2D conventional cephalometric analysis has inherent weaknesses. First of all, this method projects a 3D subject onto a 2D format. This invariably creates confounding anatomical superimpositions, which leads to a loss of information that is irrecoverable. Secondly, landmark identification is subject to measurement error due to magnification, distortion, superimposition of other structures, patient positioning, and/or duplication of landmarks.[35–37]

The availability of software to construct diagnostic images from CBCTs has catalyzed a 3D revolution in craniofacial radiology including analyses analogous to the above. Examples of such products include 3dMD (Vultus), Invivo Dental (Anatomage), Dolphin 3D, and MIMICS (Materialize), among others. These programs typically require moderate computer skills from the orthodontist, which somewhat explains the reluctance many clinicians exhibit to switch to a 3D cephalometric analysis mode. Nevertheless, it is also possible to combine 2D and 3D approaches where the 3D data could be reformatted into a 2D cephalogram so that a conventional analysis could be performed. Furthermore, the orthodontist could identify landmarks on the 3D rendering image and have this information transferred to the 2D reconstruction. This would tend to increase the accuracy of the 2D cephalometric analysis.

The literature contains few articles on the subject of 3D cephalometrics.[38–43] Some of these studies confirmed the accuracy and precision of linear and angular measurements between anatomical landmarks using 3D software in CBCT. Nevertheless, the accuracy and reliability of a 3D cephalometric analysis depends on the choice of landmarks studied, as well as the establishment of a protocol for operator training and calibration. The latter provides uniform exposure and operator experience, which have also been shown to determine accuracy and reliability.[44,45] These studies have demonstrated a linear percentage accuracy of 1% to 2% for hard tissue and 2% for soft tissue, and an accuracy of angular measurements to be within 3.2 and 1.18 degrees.[42,46,47] These studies also illuminate that decreased radiation exposure does not reduce landmark identification accuracy and that accuracy and reliability in 3D landmark identification is highest when a combination of 3D virtual rendering and cross-sectional slices in the three planes of space are used.[44,48]

Prediction in CBCT: A 3D VTO

Ricketts et al described the use of 2D lateral cephalometric information to construct a growth- and/or treatment-influenced outcome for a given patient referred to by the term *VTO (visual treatment objective)*. An analogous construct has also been proposed creating a virtual 3D VTO using predictive computer-assisted simulation software.[49] Its advantage is that it increases the patient's understanding of the proposed treatment by enabling visualization of the possible outcome and helps to design a more precise treatment plan. Soft tissue response to these skeletal and dental movements is not easily predicted because it is multifactorial; however, it has been demonstrated that fusion of 3D photography provides an accurate simulation with differences that are smaller than 0.5 mm.[50,51]

MRI in orthodontics

Although magnetic resonance imaging (MRI) is an entirely different way of acquiring images compared to CBCT, it is interesting that some researchers designed studies to evaluate the use of MRI in the field of 3D cephalometry with comparison to CBCT. Such a study was reported by Juerchott et al, where MRI- and CBCT-based cephalometric analyses were compared in order to investigate the possibility of using MRI as an alternative imaging tool in 3D cephalometric analysis.[52] It was concluded that MRI is an excellent tool that could be used for 3D cephalometric analysis with remarkable correlation to corresponding measurements on CBCT, although it was acknowledged that the sample size was small.

It has to be stated that MRI images of patients with metallic orthodontic brackets, osteosynthesis materials, or dental restorations are more prone to lower image quality, especially with MRI. For this reason, the monitoring of treatment progress using MRI in orthodontic patients is not advisable. In addition, the current cost of an MRI is very high compared to that of a CBCT, and the space required to house an MRI unit is too large to be considered for placement into a typical orthodontic clinic. Furthermore, the long scan time required to produce an MRI increases the chance that a given subject will shift in place, with these unwanted movements producing low image quality.

Conclusion

CBCT is a promising, valuable supplemental diagnostic tool for the diagnosis, treatment planning, and follow-up of orthodontic patients. It is the responsibility of the orthodontist to decide what imaging modality is best for the specific patient taking into account the concept of ALARA and discussing the advantages and disadvantages with the patient and/or family. Currently, there is no consensus to provide guidelines as to which instances warrant a CBCT scan. Confounding this lack of scientific recommendation for the orthodontist is the fact that many of these patients are in different stages of growth. It has been stated by the US Food and Drug Administration that pediatric patients (aged 21 or younger) are more radiosensitive than adults with a higher risk of cancer per unit dose of ionizing radiation.[53] Hence, it is incumbent on the specialist to properly temper the elective exposure to radiation with the understanding of the significance this presents.

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3

Surface Scanning

George Michelinakis

Introduction to Intraoral Scanning

The origins of intraoral scanning (IOS) technology can be traced back to the early 1970s when Dr François Duret and coworkers pioneered the first dental intraoral digitizer to obtain an optical impression.[1] Digitized data was reconstructed as a 3D graphic, and then the optimal morphology of the crown was virtually designed on the monitor. The final crown was fabricated by milling a block using a CNC (computer numerically controlled) machine. Duret and colleagues later developed the commercial Sopha system, but this system was not widely used mainly because it was designed too soon to be applied in dentistry.[2] The lack of accuracy in digitizing, low computing power, and materials with insufficient mechanical properties would delay the onset of intraoral digitizing until the mid 1980s when Mörmann and Brandestini first introduced the CEREC (Chairside Economical Restoration of Esthetic Ceramics) system.[3] The original concept was similar to that of Duret's—the digital impression taking of an inlay cavity and the subsequent production of a chairside ceramic inlay restoration. This was the first introduction of the concept of chairside in-office restoration fabrication.

Two decades later, in late 2006, Cadent developed and launched the iTero digital impression scanning system followed by the launch of the E4D dentist system by D4D Technologies in 2008 and TRIOS IOS by 3Shape in December 2010.[4] 3M developed the True Definition IOS system and launched it onto the dental market in late 2012 as a replacement of their Lava COS intraoral scanner first introduced in 2008.[5] Numerous other IOS systems were launched in the following years as clinical interest in the field of digital impression taking grew and artificial intelligence applications developed. Lythos IOS was launched in May 2013 by Ormco, and PlanScan IOS was unveiled in the United States in early 2014 by Planmeca. Carestream Dental released the CS3500 IOS system also in 2014, and Dental Wings unveiled the DWOS at the International Dental Show in 2015. Medit officially launched their i500 IOS in 2018, and Biotech Dental marketed their WOW IOS in 2019. In addition to the older hardware versions of the existing IOS devices, newer hardware and software versions are constantly being introduced by the manufacturers that claim improved accuracy, improved user interface, and better patient experience (Fig 3-1).

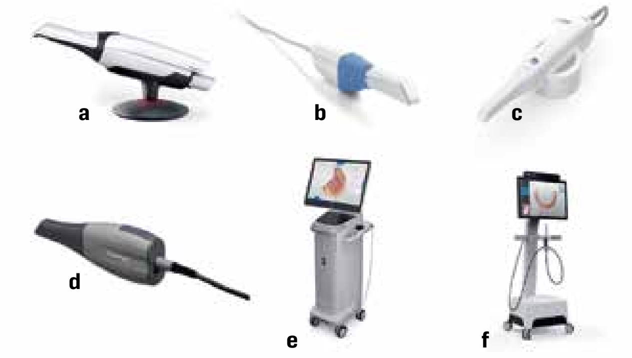

Fig 3-1 Latest-generation IOS devices currently available on the dental market. *(a)* TRIOS 4 (3Shape), *(b)* Emerald S (Planmeca), *(c)* i500 (Medit), *(d)* CS3700 (Carestream), *(e)* Primescan (Dentsply Sirona), and *(f)* Virtuo Vivo (Dental Wings).

Table 3-1 Main technologies employed by IOS devices[9,10]

Data acquisition technology	Data capture principle	Intraoral scanner	Technology	Manufacturer	Use of powder
Active triangulation	Estimation of the position of a point of a triangle from the positions and angles of two points of view	CEREC Bluecam	Video	Dentsply Sirona	Yes
		CEREC Omnicam	Video	Dentsply Sirona	No
		CEREC Primescan	Video	Dentsply Sirona	No
		CS3500	Photo	Carestream	No
		CS3600, CS3700	Video	Carestream	No
		Emerald/ Emerald S	Video	Planmeca	No
Pattern triangulation		PlanScan	Video	Planmeca	No
Optical triangulation		i500	Video	Medit	No
Confocal microscopy	Acquisition of focused and defocused images from selected depths of field	TRIOS 2/3/4	Video	3Shape	No
		Zfx IntraScan	Photo	MHT	No
Parallel confocal imaging	Image capture through a color wheel	iTero Element 1/2	Video	Align Technologies	No
Active wavefront sampling	Camera and an off-axis aperture module rotating around the optical axis	Lava COS/ True Definition	Video	3M	Yes
Stereophotogrammetry	Determination of the 3D geometric properties of objects from photographic images and object reflectance signatures	WOW scanner	Video	Biotech Dental	No
		Aoralscan	Video	Shining 3D	No
Optical coherence tomography	Use of low-coherence light with relatively long wavelength capturing 2D/3D images from within optical scattering media	E4D	Video	D4D Technologies	No
Multiscan imaging 3D technology	Use of multiple 3D scanners that work simultaneously to capture details from multiple orientations	DWOS	Video	Dental Wings	No

Image Acquisition Technology in Intraoral Scanners

Modern-day IOS devices are composed of a handheld camera, a computer, and a proprietary software. Their goal is to accurately record the 3D geometry of an object. In order to achieve this, they project structured light onto the scanning object that is then reflected back and recorded as individual images or video. The distance to points on the scanned object—and therefore the shape of the object itself—can be measured using different technologies depending on the specific scanner used. The main technologies employed by different contemporary intraoral scanners are shown in Table 3-1.[6–10]

Acquisition of the point cloud

Irrespective of the intraoral scanner used, the process of digitization of the hard and soft oral tissues creates a point cloud (Fig 3-2a). This cloud is a raw set of data points acquired by the intraoral scanner device and expressed in 3D with x-y-z coordinates. These data points are representative of the external surface of the scanned object. The points that form the point cloud often overlap and cannot always be placed on the same plane. Using system-proprietary algorithms, the point cloud is processed into a mesh model—a polygonal representation of the object with vertices, edges, and faces to produce a network of triangles and polygons (Fig 3-2b). Different intraoral scanners acquire point clouds with variable density and therefore produce variable mesh representations of the physical objects. Denser point clouds generally lead to higher resolution and larger-output digital files, but recent evidence suggests that this does not necessarily translate into higher scanning accuracy.[6,11,12] Possible explanations for this include differences in the scanners' hardware (camera and light projector) and software.

Types of mesh file formats

There are different mesh file formats available. Among them, the STL (standard tessellation language) file is the most widely used digital format and was created in 1987 by 3D Systems. This file type only conveys information on the geometry of the object being scanned without any additional data on surface texture, color, or any other common computer-aided design (CAD) attributes (Fig 3-2c). It describes a surface with a number of interconnected triangles defined by their vertices and by the unit normal on each triangle.[8]

Other popular formats include PLY (polygon file format or Stanford triangle format), OBJ (object), DCM/3OXZ, and RST/DXD file formats. Some are manufacturers' proprietary system formats that can only be used with the corresponding software (closed type), and others can be used with multiple systems (open type). The main advantage of these file formats over the STL format is that they can additionally convey information on color, transparency, or texture (Fig 3-2d). An additional advantage of the "open type" digital file formats is that they can be used by any CAD and computer-assisted manufacturing (CAM) software without the need for file conversion that can lead to a dimensional error of up to 20 to 40 μm.[13,14]

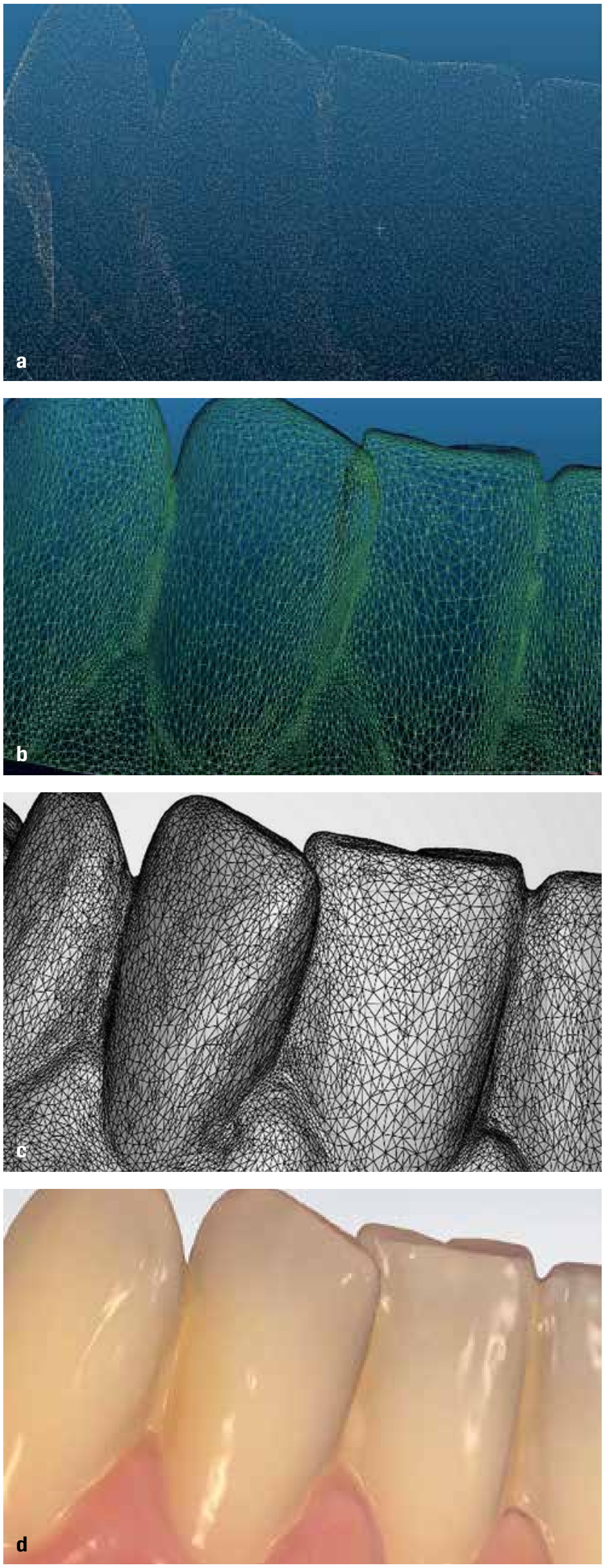

Fig 3-2 *(a)* Point cloud acquired from the intraoral scanner generated in CloudCompare software. *(b)* Mesh file of triangles. *(c)* STL digital file format. *(d)* TRIOS 3 (3Shape) proprietary DCM file format.

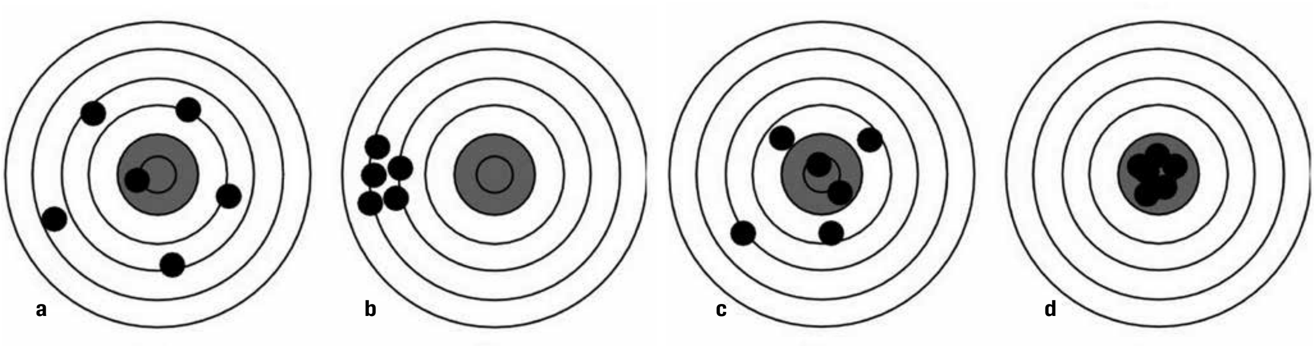

Fig 3-3 Correlation between trueness and precision. *(a)* Low trueness and low precision. *(b)* Low trueness but high precision. *(c)* High trueness but low precision. *(d)* High trueness and high precision. (Reprinted with permission from Mutwalli et al.[16])

Accuracy of Intraoral Scanners

Trueness and precision

Although the terms *trueness* and *precision* are often used to describe the general accuracy of a scanning device or technique, there are significant differences between them. According to the ISO 5725, *trueness* is described as the ability of a measurement or measuring device to match the actual value of the quantity being measured, whereas *precision* is the ability of the measurement or measuring device to consistently repeat a particular measurement. Therefore, general accuracy is trueness and precision combined and is determined as the agreement between the experimental and the reference data sets.[15]

Trueness and precision are depicted schematically in Fig 3-3.[16]

Technical factors influencing IOS accuracy

Various studies have reported on partial and complete arch accuracy of intraoral scanners with conflicting results. There are several factors contributing to this discrepancy, with the method of measurement being one of them. IOS accuracy in vivo is usually established by comparing an intraoral scan against an in vitro scan of a relevant plaster cast using a high-accuracy laboratory scanner as the reference. Nevertheless, the process of obtaining a conventional impression and producing a plaster cast for reference purposes has also been shown to result in dimensional inaccuracies of up to 97 μm due to the dimensional changes of the impression material and plaster during setting.[17] These deviations from the actual dental arch size can influence the final measurements. Further on in the process, the plaster cast is digitized using a laboratory scanner, a step that has been shown to introduce further deviation ranging from 7 to 31 μm depending on the laboratory scanner used.[18] Finally, the IOS digital file is compared with the extraoral plaster cast scan using a best-fit least-squares algorithm. Nevertheless, through this global registration process, if a large discrepancy in one part of the arch is autocorrected, errors can result in other parts leading to local differences' misinterpretation.[19] Therefore, the actual trueness of an IOS can only be established indirectly, because a high-reference scanning device cannot be used directly in the oral cavity to capture the complete arch.[20]

The data capture technology employed by each IOS device has also been shown to contribute to dimensional discrepancy, with active triangulation and confocal microscopy IOS devices exhibiting higher general accuracy compared to other available technologies.[6] The refractive index of different intraoral and extraoral substrates such as enamel, dentin, gypsum, and polymeric materials has also been shown to influence scanning accuracy due to their optical properties such as translucency, with enamel being less accurate than dentin.[21] Recent evidence suggests that active triangulation IOS devices might be more sensitive to substrate differences compared to confocal microscopy IOS devices.[22] The presence of saliva or moisture on the scanned tooth surface can also introduce inaccuracies due to alterations in the reflective properties of dental tissues.[23]

Full-arch scan accuracy is also negatively influenced by the image stitching process. Due to the small field of view (FOV) of the IOS devices as opposed to the laboratory scanners, a large number of consecutively acquired images is

Table 3-2 In vitro and in vivo studies on full-arch dentate IOS accuracy (3D surface measurement values)

Reference (year)	TRIOS 2/3	Omnicam	Bluecam	Prime-scan	CS3500	CS3600	PlanScan	Lava COS	True Def	iTero Element 1/2	Medit i500	Emerald/ Emerald S
In vitro studies												
Ender and Mehl[29] (2013)			58 µm									
Patzelt et al[7] (2014)			333 µm					38 µm		49 µm		
Su and Sun[35] (2015)	88 µm											
Ender and Mehl[36] (2015)		37 µm	29 µm					44 µm		32 µm		
Jeong et al[37] (2016)		192 µm	375 µm									
Anh et al[38] (2016)	22 µm									29 µm		
Wesemann et al[27] (2017)	27–50 µm[a]											
Renne et al[39] (2017)	69 µm[b]	101 µm	140 µm		76 µm		96 µm			56 µm		
Malik et al[40] (2018)	87 µm	80 µm										

[a] Distance measurements; [b] maxillary/mandibular values; [c] generation of scanner.

→

needed in order to scan the complete arch. The successive images are then matched together by the software using identical reference points on each image to produce the complete arch scan. Literature suggests that the longer the scanning scope is, the greater the error from the stitching process will be, with the deviations accumulating toward the posterior segments of a full-arch scan.[19,24–29]

Clinical factors influencing IOS accuracy

Several other clinical factors have been investigated relative to their influence on the accuracy of IOS devices. Operator experience has been associated with scanning accuracy, with the latter increasing exponentially as the operator progresses along his or her learning curve.[30,31] Scanning strategy or scan path is another clinical factor that influences accuracy, especially in the full-arch clinical scenario. Each IOS device has a unique scanning strategy recommended by the manufacturer for optimal trueness and precision results that is directly correlated to the data capture technology and image stitching algorithms employed by the specific IOS device.[13,32,33]

Partial edentulism and its extent in the arch is another factor that has been shown to influence full-arch scanning accuracy. Partially edentulous arches may present great clinical variations depending on the number and site(s) of missing teeth. IOS accuracy is reduced due to the lack of reference points in these edentulous sites, and surface scan deviations accumulate as edentulous spaces become longer.[34]

Average full-arch IOS accuracy

Full-arch dentate accuracy from recent in vitro and in vivo studies for the major IOS systems is presented in Table 3-2.[7,13,19,22,24,25,27–29,31,34–50] Note that an in vitro study on IOS accuracy is easier to execute mainly because many of the confounding factors discussed earlier can be controlled more readily. The lack of saliva or moisture, the lack of movement, the uniformity of the refractive index across the plaster or plastic models used for test scanning, and the accessibility of posterior sites by the scanner tip as opposed to the difficulty in accessing them intraorally are all factors that significantly affect IOS accuracy results between in

Table 3-2 ***(cont)*** **In vitro and in vivo studies on full-arch dentate IOS accuracy (3D surface measurement values)**

Reference (year)	TRIOS 2/3	Omnicam	Bluecam	Prime-scan	CS3500	CS3600	PlanScan	Lava COS	True Def	iTero Element 1/2	Medit i500	Emerald/ Emerald S
Park et al[19] (2019)	25–47 µm[a]				25–47 µm[a]							
Treesh et al[25] (2018)	46 µm	49 µm	37 µm		84 µm							
Sim et al[41] (2018)					29 µm							
Medina-Sotomayor et al[13] (2018)	55 µm	98 µm							32 µm	94 µm		
Mennito et al[42] (2019)	78 µm	32 µm				46 µm	119 µm			25 µm		90 µm
Ender et al[43] (2019)	51 µm	50 µm		34 µm		61 µm				60 µm	93 µm	
Lee et al[34] (2019)						44 µm					52 µm	
Michelinakis et al[44] (2020)	17 µm										16 µm	56 µm
Dutton et al[22] (2020)	22 µm	58 µm		17 µm						36/21 µm[c]	29 µm	53µm/ 40 µm[c]
Kang et al[45] (2020)	93 µm/ 44 µm[c]				62 µm	49 µm					143 µm	
In vivo studies												
Flügge et al[46] (2013)										57 µm/ 43 µm[a]		
Ender et al[28] (2016)	43 µm	48 µm	56 µm					82 µm	59 µm[a]			
Gan et al[47] (2016)	80 µm									68 µm		
Kuhr et al[48] (2016)	37 µm	214 µm							23 µm			
Lee et al[49] (2018)	10–150 µm[a]											
Lim et al[31] (2018)	52 µm									10–150 µm[a]		
Sfondrini et al[50] (2018)	29 µm/ 28 µm[b]									60 µm		
Michelinakis et al[24] (2019)	38 µm											

[a] Distance measurements; [b] maxillary/mandibular values; [c] generation of scanner.

vivo and in vitro studies. Nevertheless, newer IOS devices with updated software and hardware versions perform exceptionally well both intraorally and extraorally, yielding full-arch mean accuracy values below the 100-µm threshold value accepted for restorative purposes or the 140-µm threshold value accepted for orthodontic purposes.[40,44,51]

Digital bite registration and virtual articulation

The virtual registration of the actual static interocclusal relationship between the maxillary and mandibular arch is made possible through the process of scanning of the buccal surfaces of the arches in maximum intercuspation. One great benefit of this procedure is that there is no need to place a bite registration medium (wax or silicone) between the arches. Literature suggests that digital bite registration is more accurate compared to analog bite registration using wax and equally accurate to hand articulation of stone casts when no registration medium is used.[52,53] Nevertheless, clinical parameters such as region of bite scan, number of missing teeth, and range of digital bite scan have been shown to influence the accuracy of the virtual bite registration process. Digital interocclusal registration in the molar and premolar region has been shown to be as accurate as analog bite registered using a pressure-sensitive articulating paper, but the authors suggest that digital anterior bite is overestimated, perhaps due to the algorithm involved in the registration of the 3D images of a confocal microscopy–based IOS system.[49] In another in vitro study, the number and location of missing teeth has been found to influence the virtual bite accuracy. Single missing posterior teeth did not affect bite scanning accuracy, but when three or more posterior or anterior teeth were missing unilaterally or bilaterally, the bite registration using a desktop laboratory scanner was inherently affected.[54] Finally, when full-arch scans are made, single-sided digital bite registration has been shown to produce a tilting effect of the virtual articulation toward the registered quadrants; therefore, scanning the bite on both sides for maximum accuracy is recommended.[55]

The next step in the process is the articulation of the directly or indirectly digitized dental arches in their intercuspal or centric relation on a virtual articulator (Fig 3-4). The purpose of this tool is to replace mechanical articulators and their inherent inaccuracies and help reproduce static and dynamic patient occlusion more accurately.[56] Different virtual articulators are available for use within the various CAD systems. There is scarce evidence in the literature reporting on the accuracy of dynamic virtual articulators compared to their analog counterparts, but the results are promising, and the reported deviations may not be clinically relevant.[57]

Fig 3-4 Digitized dental arches mounted on a virtual articulator.

Advantages and Disadvantages of Intraoral Scanners

The use of intraoral scanners has been implemented into daily practice for almost a decade now, and their potential advantages and shortcomings have been studied extensively in the literature. Their main advantage is increased digital impression accuracy leading to improved fit accuracy of short- to medium-span fixed partial dentures (FPDs).[58] Reduced patient discomfort and increased patient acceptance for the digital as opposed to the conventional impression procedure has also been documented in the literature. Patients with a strong gag reflex and periodontally compromised patients can be treated successfully, especially with the newer-generation IOS systems that are faster and more comfortable to both adults and children.[50,59–64] Digital archiving and reduced physical storage space is another potential advantage of the IOS systems combined with improved communication with the laboratory technician.[65]

The main limitation of IOS is the requirement for a training period that is directly connected to the operator's learning curve. The latter has been documented in the literature to significantly affect scanning accuracy and therefore strongly impact on the performance of the clinical workflow.[31,66,67] Another potential limitation is the purchase and maintenance costs associated with this technology and also the fact that not all systems in the market are "open type" systems.

Table 3-3 In vitro studies on full-arch dentate desktop scanner accuracy (3D surface measurement values)

Desktop scanner	Flügge et al[46] (2013)	Hayashi et al[68] (2013)	Su and Sun[35] (2015)	Jeong et al[37] (2016)	Wesemann et al[27] (2017)	Renne et al[39] (2017)	Nowak et al[18] (2017)	Park et al[19] (2019)	Oh et al[69] (2019)	Mennito et al[42] (2019)
D250	11 µm/ 9 µm[b]									
D640										
D710										
D800			12 µm			43 µm				37 µm
D810										
D2000										
R500							23 µm[a]			
R700		50 µm			21–50 µm[a]		15 µm[a]			
R900					12–17 µm[a]					
R1000							36 µm[a]			
R2000							44 µm[a]			
IMETRIC D104i							8 µm[a]			
IDENTICA BLUE				165 µm					66 µm	
VIVID 900		55 µm								
GC AADVA LAB SCAN							9 µm[a]			
FREEDOM HD								47 µm		
DW 7SERIES										
DENTACORE CS ULTRA							41 µm[a]			
DENTAURIUM ORTHOX							15 µm[a]			
MAESTRO 3D							55 µm[a]			
MEDIANETX COLORI							55 µm[a]			
MEDIEANETX GRANDE							48 µm[a]			
E1										
ACTIVITY 102										
TIZIAN SMARTSCAN										
NEWAY										
InEOS X5										

[a] Distance measurements; [b] maxillary/mandibular values.

Keul and Güth[70] (2020)	Michelinakis et al[44] (2020)	Kang et al[45] (2020)	Emir and Ayyıldız[71] (2019)
			31 µm
			27 µm
42 µm			
			17 µm
		24 µm	
	16 µm		27 µm
		14 µm	
			33 µm
			32 µm
			21 µm
			26 µm

Extraoral Digitization

Extraoral or indirect digitization can be accomplished using either a laboratory scanner or a CBCT device. Both plaster casts and conventional impressions can be digitized in this manner.

Extraoral laboratory scanners can be tactile or optical. Tactile or contact scanners employ a probe constructed by wear-resistant materials that is dragged over the surface to be registered. This is a slow process that is not influenced by the optical characteristics of the scanned surface but can be affected by its physical characteristics such as surface hardness. Therefore, scanning an elastomeric impression with a contact scanner would lead to probe impingement into the material and therefore produce inaccuracies. Tactile scanners can be either a coordinate measuring machine (CMM) or an articulated arm type. Their use is presently limited to dental implant impression accuracy research.

Optical or noncontact scanners, on the other hand, emit structured light or laser light (in the form of single or multiple beams) that is then reflected onto the surface of the object being scanned and registered by a sensor inside the scanner. Compared to tactile scanning, extraoral optical scanning is considerably faster and does not distort the scanned surface, but it can also be affected by surface characteristics such as reflection and refractive index and translucency, similarly to an IOS device.

Extraoral digitization using an optical laboratory scanner device

Laboratory scanning of plaster casts has been the standard of care due to the high average accuracy of these devices. Laboratory scanners employ the principle of triangulation for acquiring their data. Their main advantage compared to the IOS devices is their large FOV—almost tenfold that of IOS devices—which allows them to capture images of the scanned object with considerably less registration (stitching) and thereby producing less dimensional error. Full-arch mean accuracy for the laboratory scanners varies according to the specific device and has been reported in the range of 10 to 55 µm.[18,19,27,35,39,42,46] Recent in vitro studies on desktop scanners' accuracy are listed in Table 3-3.[18,19,27,35,37,39,42,44–46,68–71] Literature supports the superiority of desktop scanners in dentate full-arch scanning in vitro compared to some IOS devices,[35,37,47,48,46,72] but there are also available studies that do not advocate this finding.[28,39,41,50,73]

Literature regarding digitization of conventional impressions using a desktop laboratory scanner is inconclusive. There are studies supporting the superior accuracy of IOS devices compared to impression scanning, but there is also available research postulating the opposite.[28,36,74,75]

Extraoral digitization using a CBCT device

Concerning the digitization of dentate plaster casts by a CBCT device, recent data suggests the inferiority of this technique compared to both IOS and laboratory desktop scanning.[24,27,76] Using a CBCT device to digitize a conventional dentate impression also mandates the use of a nonmetallic impression tray, and the resulting accuracy has been reported to be low.[27,77]

The Virtual Patient

The oral cavity, the underlying bone structures, and the facial structures consist of hard and soft tissue with differing optical qualities, and currently there is no technology available that can accurately depict all of them in a single data set. Dentition and oral soft tissues are accurately digitized with IOS and desktop scanners, bone is digitized using CBCT technology, and facial soft tissues are captured through scanning and 3D imaging. Average accuracy for the intraoral scanners and the laboratory desktop scanners is shown in Tables 3-2 and 3-3.

For facial scanning, digital images can be obtained through stereophotogrammetry or laser light scanners. Stereophotogrammetry and white-light scanning have shown superior accuracy compared to magnetic resonance imaging (MRI) and infrared laser scanners, although the deviation values range between 140 and 1330 µm, with an average value close to 500 µm.[78,79] White-light scanners are also less dangerous to the eye as they project a safer white light instead of a laser beam. Single-camera structured white-light and laser scanners are prone to inaccuracies because the facial image is not captured all at once, allowing facial muscle movement to introduce motion errors. Multiple-camera systems are becoming available, which instantly capture the face across an angle of almost 180 degrees, thus eliminating the need for multiple acquisitions. Simultaneously, high-resolution texture 2D photographs can also be captured and integrated onto the mapped 3D surface in order to generate a full-color 3D model of the face. Table 3-4 depicts commonly used stereophotogrammetry and structured light scanners for extraoral facial scan use.

For the CBCT devices, accuracy has been shown to be influenced by the exposure parameters such as voxel size, kVp and mA values, and exposure time, with a range between 106 and 760 µm.[79–81]

The crucial step in connecting the language of different digital technologies in order to create the virtual patient is finding the common landmarks between the data sets. This is accomplished by using the patient's existing dentition, typically the visual facial aspects of anterior teeth, which need to be depicted in all three data sets. Loading the data sets onto a powerful visualization and planning software and superimposing them using constant landmarks creates a complete digital representation of the virtual patient.[82] In completely edentulous patients, the challenge of integrating facial scanning into the workflow is greater. Other relatively immobile landmarks such as the labial surface of the edentulous alveolar ridge, the forehead, the root of the nose, and zygoma have to be employed in order to register facial scans with intraoral scans and CBCT scans, respectively.[83]

The objective of successfully combining the acquired data sets from intraoral and extraoral soft and hard tissues is the creation of the virtual patient. This step will greatly enhance preoperative diagnostics, aid in orthognathic surgery, and also allow the planning of the patient's smile through digital smile design tools. After completion of treatment, it can also provide a valuable tool for postoperative assessment and follow-up in plastic surgery and maxillofacial rehabilitation. Nevertheless, variation in the image quality and accuracy between the data sets to be merged and technical difficulties regarding the precise selection of identical landmarks for superimposition still pose a considerable challenge to the creation of the virtual patient. Moreover, an accurate virtual patient representation will only be a static one, as dynamic facial scanning capturing facial expressions is still under research. In an effort to overcome these technical shortcomings, facial scanning has been recently introduced as a modular function of some CBCT devices. Manufacturers of both IOS and CBCT devices such as 3Shape, Planmeca, and Carestream have developed dedicated software platforms that can integrate data sets from different sources in a single digital ecosystem and thus better facilitate the merging process.

Table 3-4 Commonly used stereophotogrammetry and structured light scanners

Extraoral scanner	Scanning technology	Indication for use	Accuracy	Portable	Output formats	Manufacturer
ATOS Core 80	Structured light (blue light)	Extraoral (model)	Up to 30 μm	Yes	STL	GOM
Precise Implants Capture (PIC)	Active stereophotogrammetry (structured light)	Intraoral (dental implant fixture scanning)	10 μm	Yes	STL	PIC Dental
iCam 4D	Active stereophotogrammetry (structured light)	Intraoral (dental implant fixture scanning)	Up to 30 μm	Yes	STL	Imetric 4D
EinScan Pro 2X Plus	Structured light (blue LED)	Facial scanning	Up to 100 μm	Yes	OBJ, STL, ASC, PLY, P3, 3MF	Shining 3D
Artec Space Spider	Structured light (blue LED)	Facial scanning	Up to 50 μm	Yes	OBJ, PLY, WRL, STL, AOP, ASCII, PTX, E57, XYZRGB	Artec 3D
3dMDflex	Active stereophotogrammetry (structured light)	Facial scanning	200–400 μm	No	OBJ, PLY, STL	3dMD
Di3D FTP-001	Passive stereophotogrammetry (digital cameras)	Facial scanning	200–600 μm	No	STL, OBJ, PLY	Dimensional Imaging Ltd
Face Camera Pro Bellus	Dual-structured light	Facial scanning	Up to 900 μm	Yes	STL, OBJ, MTL, JPEG, YML	Bellus3D
InstaRisa 3.0	Dual-structured light	Facial scanning	Up to 40 μm	Yes	PLY, STL	InstaRisa Technologies LLC

Future Developments in Surface Scanning

Acquiring intraoral digital impressions by means of an intraoral scanner is a well-established technique featuring significant advantages, as described earlier in this chapter. Nevertheless, in restorative dentistry, digital optical scanning has one limitation that is difficult to overcome due to the nature of this technology. Subgingival marginal identification is difficult to achieve and requires tissue retraction to gain direct optical contact. High-frequency ultrasound scanning (HFUS) technology has been tested to address this particular shortcoming of the optical IOS device, as ultrasonic waves can travel through soft tissue and moisture. The literature reports statistically significant lower accuracy for an HFUS device compared to optical scanners for single prepared teeth.[84,85] Limitations of this approach regarding full-arch scanning accuracy, increased scanning time, and complexity of technology and technique need to be addressed before it can be considered a valid alternative to optical IOS.

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4

Additive Manufacturing

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Introduction to Additive Manufacturing

In contrast to conventional manufacturing methods, such as drilling, cutting, and milling, that form objects by mechanically removing material, additive manufacturing technologies build physical objects directly from computer-aided design (CAD) data sources by adding and bonding materials in layer-by-layer fashion[1] (Fig 4-1).

Rapid prototyping (RP) is the original name given to a host of such technologies that emerged in the early 1980s with the aim of accelerating the product-development process as well as allowing product customization.[2–4] The key concept has been the rapid production of illustrative or functional prototypes of virtually any complexity in hours instead of days, weeks, or months.

RP has come to be known by the names of *freeform fabrication*, *layered manufacturing*, *automated fabrication*, or simply *rapid manufacturing*. As the systems have evolved and the effort has been gradually focused on the production of final parts rather than prototypes, the original term has become outdated and misleading; thus, the terms *additive manufacturing* (AM) and the more common *3D printing* (3DP) are now increasingly used for industrial and consumer applications, respectively.[1]

Nonetheless, *RP*, *AM*, and *3DP* are terms that are often used interchangeably as synonyms. All of them refer to the general process whereby a physical object is constructed by progressively applying and building up very thin horizontal layers of material.

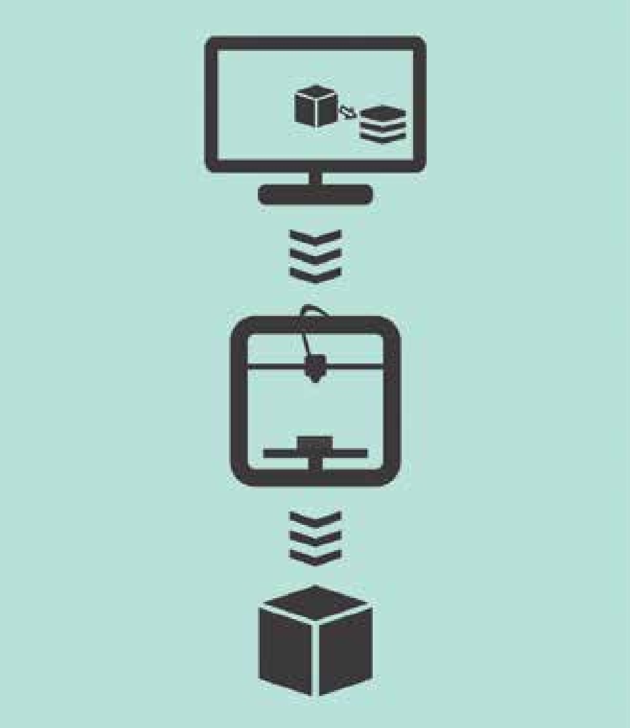


Fig 4-1 General concept of additive manufacturing, whereby CAD data is used to add and bond materials layer by layer.

The aim of this chapter is to provide a general summary of the AM process and its technologies, materials, and applications and then relate them to orthodontics, speculating potential benefits for the doctor, the clinical practice, and the patient.

The AM Process

AM is a design-driven process, and all methods use a 3D model as an input. The approach relies on the existence of a data file that describes the geometry of the object surfaces. This object is designed virtually within a CAD environment using appropriate software. However, the object can also originate by reverse engineering techniques and by scanning its geometry with a 3D scanner. All design modifications take place within a CAD environment. Once the design is complete, the 3D file containing the object's geometry is exported in an appropriate format readable by manufacturing devices. The most common representation of 3D geometry for 3DP is triangulated models in an STL format.[5] Prior to fabrication, the STL file containing the 3D model is checked, prepared, and "sliced" in layers of data, containing 2D cross-sectional information of the object's geometry. This task can sometimes be done within the same CAD environment, but it is usually completed by other dedicated software packages that can also accompany the 3D printer. Each "slice" of data provides the instructions to the 3D printer to move along specific coordinates and apply a thin layer of material. The process is repeated layer by layer, and the actual object is physically constructed according to the original design[1] (see Fig 4-1).

Each 3DP technology can process different materials in different ways. The available materials vary, with polymers and plastics being the most common, but metals, ceramics, and various other composites are also emerging.[6–16] The produced parts can also have a wide range of physical properties depending on the AM process, parameters, and application.

All 3DP materials require proper handling and maintenance. For example, most of the resins are provided in special containers that protect the material from light, humidity, and oxygen. Most of the metal powders are also provided in special packaging and require specially trained technical personnel to handle. After the printing process, all powder should be removed from the build volume and be sieved, filtered, and recycled for later use.

3D-printed parts are rarely ready-to-use out of the machine. The part is built on a component called the *workspace* or the *platform*. Once the object is complete, post-processing is almost always required, including UV curing, cleaning, smoothing, polishing, and painting, according to the specific requirements of each piece. These steps take additional time and usually involve manual effort. It is also worth mentioning that most 3DP methods are not necessarily very rapid regarding the production itself. Depending on the size of the object to "print," it can take many hours.

AM Technologies

The origins of 3DP date back to the 19th century. In 1860, François Willème captured an object in 3D using cameras surrounding the subject, and in 1892 Joseph E. Blanther proposed a layering method to produce 3D topographic maps.[17]

Much later, in 1972, Matsubara of Mitsubishi Motors proposed to use photohardened layers of materials (photopolymers) to form a casting mold. Nevertheless, it was in 1980 that AM was practically invented by Hideo Kodama of Nagoya Municipal Industrial Research Institute, Japan, who first demonstrated the process for creating 3D plastic parts by photohardening polymers with ultraviolet (UV) exposure.[2,3,18]

In 1983, Charles (Chuck) Hull developed a prototype system referred to as *stereolithography* in which layers were added by curing photopolymers with UV lasers. He defined the process as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed."[19] Mr Hull obtained patent no. 4,575,330 (filed August 8, 1984) for an "apparatus for production of three-dimensional objects by stereolithography."[19] In 1986, he cofounded 3D Systems, Inc to commercialize the technology, and the first-ever 3D printer, the SLA-1, was introduced in November 1987.

Since then, 3DP technologies have shown enormous progress. Manufacturing in layers by adding material is a considerable advantage compared to traditional machining methods. 3DP has been used to create objects of detailed, intricate geometry or complex parts that can avoid assembly (Fig 4-2). In the past, such features were thought impossible to create by conventional methods or required too much effort, time, and cost. Advances over the years have accelerated the speed, increased the accuracy, and decreased the costs of this method. 3D printers have been used in the automotive, aerospace, healthcare, architectural, clothing, jewelry, and many more industries. In recent years, 3D printers have also become available for consumers.

Presently, a wide range of 3DP technologies are available, each one employing a different method and different materials but all aiming to accelerate the product-development process, facilitate the design-to-manufacturing process, and revolutionize the way the world thinks and creates.[1]

In 2009, ASTM created the F42 Technical Committee to develop the first AM standards that established 3DP as an industrial manufacturing technology.[20] According to the ISO/ASTM 52900 standard, there are seven general types of 3D printing:

1. **Vat polymerization:** Utilizes UV light to selectively cure liquid photopolymer in a vat.
2. **Powder bed fusion:** Uses a high-energy source to selectively fuse material powder particles.
3. **Material extrusion:** Selectively dispenses material through a nozzle.
4. **Binder jetting:** Selectively binds powder using a liquid bonding agent.
5. **Material jetting:** Selectively deposits and cures droplets of material.
6. **Direct energy deposition:** Uses a high-energy source to fuse material as it is deposited.
7. **Sheet lamination:** Bonds and forms sheets of material layer by layer.

As mentioned earlier, 3DP is growing quickly in popularity, and the technology is developing rapidly. AM technologies are changing at such a quick pace that the information contained herein may become outdated very quickly. It is also impossible to cover all aspects of AM processes within a few pages without being brief at times. For the purpose of this book, it is not important that all technologies are described in detail but that the reader becomes acquainted and intrigued by the possibilities in order to search further for his or her own application. As such, of all the technologies that are available and of many others that are still under development, the representative methods that are briefly discussed next are well-proven and mature examples to demonstrate principles and possibilities.

Vat polymerization: Stereolithography

Vat polymerization utilizes UV light to selectively cure liquid photopolymer in a vat.[21] Stereolithography (SLA) is the first and original 3DP process initially commercialized by 3D Systems[19] (Fig 4-3). In this process, a UV light source (laser) is directed in the xy axis by mirrors (called *galvanometers*) to cure photosensitive liquid resin. The laser beam hits the resin, which is cured, and a thin layer of solid material is produced. At the beginning of the process, the platform is just below the surface of the resin, so that the first layer attaches to the platform. After each layer is completed, the platform lowers by a small amount, thus exposing another thin layer of resin that can also be cured. In this way a solid model slowly builds up.

Fig 4-2 Part of an artificial tibia made with complex structure printing.

To prevent collapse of the structure, most of the time supports must be provided for the resin layers[1] (Fig 4-4). The position of the supports and the position that the object is built on the platform are also set at the preprocessing "slicing" level. Once complete, the model is carefully removed from the bath, cleaned of excess resin, and placed in a UV oven for further curing and to achieve its final material properties. Any supports must then be removed from the model, and the object can be further processed (eg, smoothed) according to the specific requirements for that piece. This is especially the case regarding the removal of certain marks that are created by support structures. A large range of photopolymer resin materials are available, such as transparent, flexible, castable, high-temperature, as well as biocompatible and application-specific.

In general, SLA is used to develop parts with very high accuracy, fine details, and smooth surfaces. It is a very useful process for producing high-quality visual prototypes. However, due to the brittle nature of resins, this process is generally is not recommended for functional parts. Attention should also be given to light exposure because the mechanical properties and color can be affected.[22,23]

Recently, a similar process has emerged that is called *digital light processing* (DLP).[24] Instead of curing one point at a time, DLP uses a digital light projector to "flash" an image of the cross-sectional layer and cure a whole layer

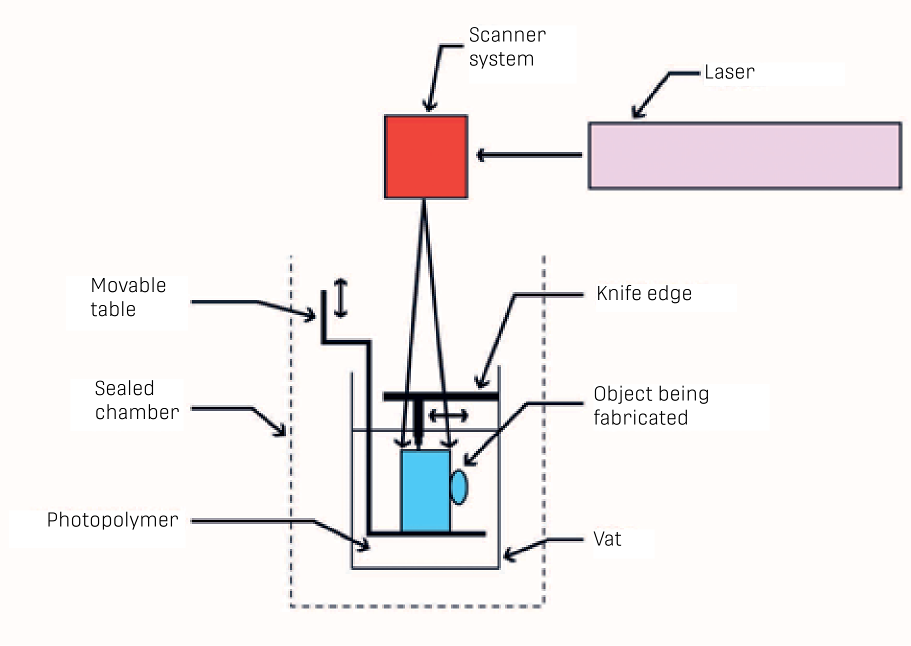


Fig 4-3 Illustration of the SLA process.

Fig 4-4 3D-printed object showing printing supports in place.

at once. The digital projector is comprised of pixels, so the material curing is done in the form of voxels. The utilized source light is a light-emitting diode (LED) or UV light lamp. The light pattern is directed onto the resin using an array of micromirrors called a *digital micromirror device*.

A more recent SLA method is masked stereolithography (MSLA).[23,25] Like DLP, it flashes UV light as an image of the cross-sectional layer and cures a whole layer at once. However, instead of using a single-point UV light source, it utilizes an array of individual UV light emitters. In addition, instead of using micromirrors to direct the light pattern, it emits the UV light and projects the layer as a mask through an LCD (liquid-crystal display) screen. While it is also a faster method than SLA, the other advantage is that the xy accuracy does not depend on any mirrors but is fixed. Due to the low cost of LCD screens, MSLA is a significant development for the emerging low-cost desktop resin printer market, aimed toward professionals as well as consumers.

Powder bed fusion: Selective laser sintering

Powder bed fusion uses a thermal energy source to selectively induce fusion of powder particles to create a solid object. The first method was patented by C. Deckard in 1989 and developed by DTM in 1992 (later acquired by 3D Systems).[26] Selective laser sintering (SLS) employs powder instead of a resin that can be fused by heat (Fig 4-5). The process begins with heating the powder material just below its melting point. A roller deposits a very thin layer of powder material onto the platform. A laser beam selectively “sinters” the shape of a cross-sectional layer, and the powder particles are fused and solidify (Fig 4-6). The laser is directed to the correct location by xy mirrors (galvanometers). The platform moves down by one layer, the roller spreads some more powder, the laser hits the surface of the next cross section, and the process is repeated until the part is completed (Fig 4-7). There is generally no need for overhang supports to be provided in this process because the unfused powder fulfills this function. The part is removed after the bed has cooled down and is cleaned of the nonsintered powder.[1] Usually, no other process is required. However, SLS parts present certain internal porosity, and the surface is grainy.

SLS is often used for functional prototypes due to the almost-isotropic mechanical properties of the printed parts. The development of complex geometries is also facilitated because there is no need for support structures that can damage the part at removal. Moreover, the SLS build volume is quite large and can accommodate the production of multiple parts in a single print. Thus, SLS is usually utilized by industry for small-to-medium production of

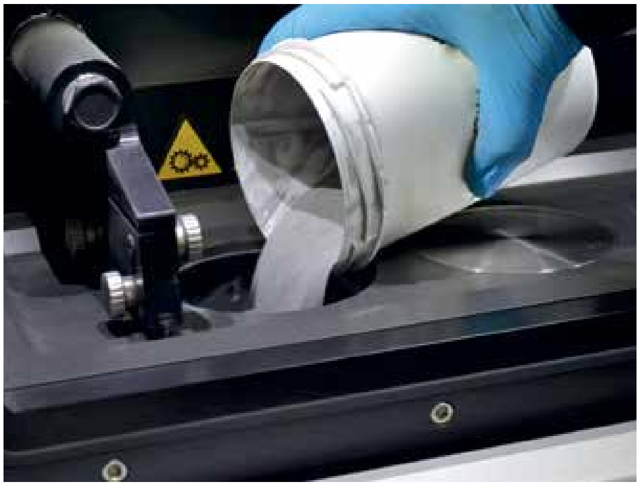


Fig 4-5 Powder used for SLS.

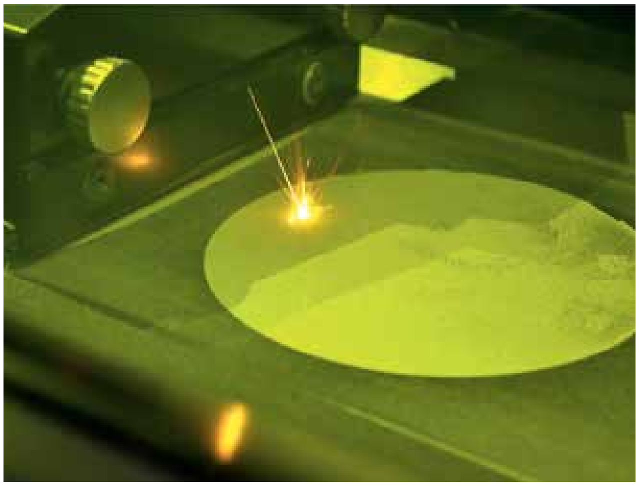
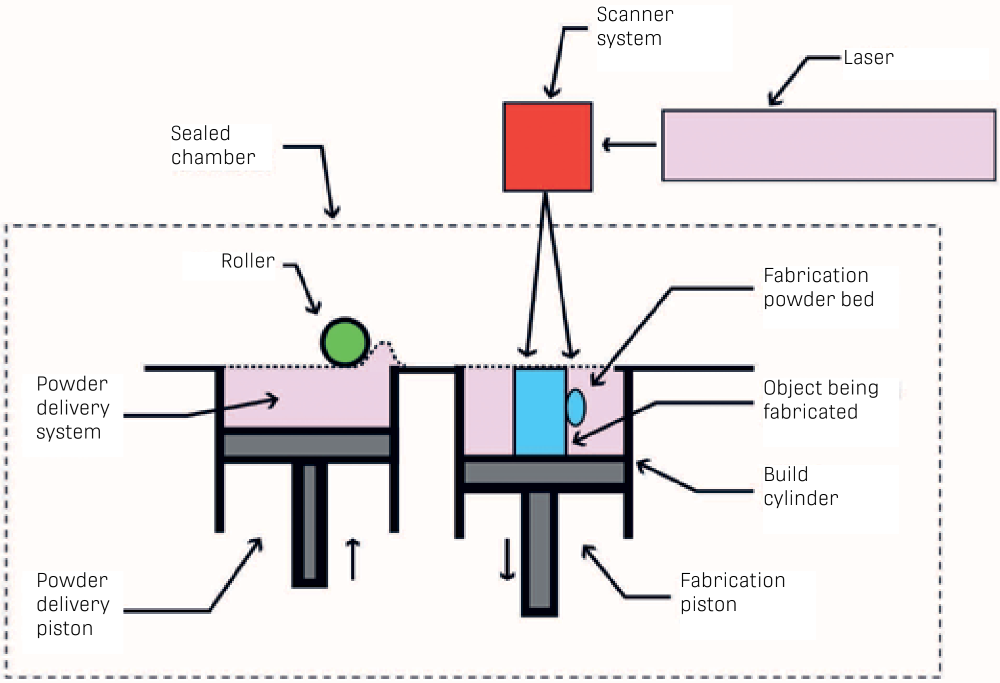


Fig 4-6 Laser beam used in the SLS process.

Fig 4-7 Illustration of the SLS process.



end products. The cost of SLS technology is quite high and not easily accessible. Available materials include thermoplastic polymer powders, like polyamide based powders (PA6, PA11, PA12).[27] Other materials include polystyrene, polypropylene, polyethylene, thermoplastic polyurethane (TPU), and polyether ether ketone (PEEK).[28–30]

In recent years, SLS methods have been developed to produce metal parts. Direct metal laser sintering (DMLS) heats the metal powder at the appropriate temperature to fuse particles at a molecular level and can produce parts of metal alloys.[31] Selective laser melting (SLM) heats and fully melts metal particles in order to build single-material parts.[32] Both methods are ideal for building metal parts of complex geometries. In addition, it is possible to control the way that the metal is fused, which affects the internal structure of the built part, its mechanical properties, and in turn its performance. This can be used to maximize the performance of the manufactured part while minimizing the material amount and weight. The possibility to manipulate but also surpass the physical properties of

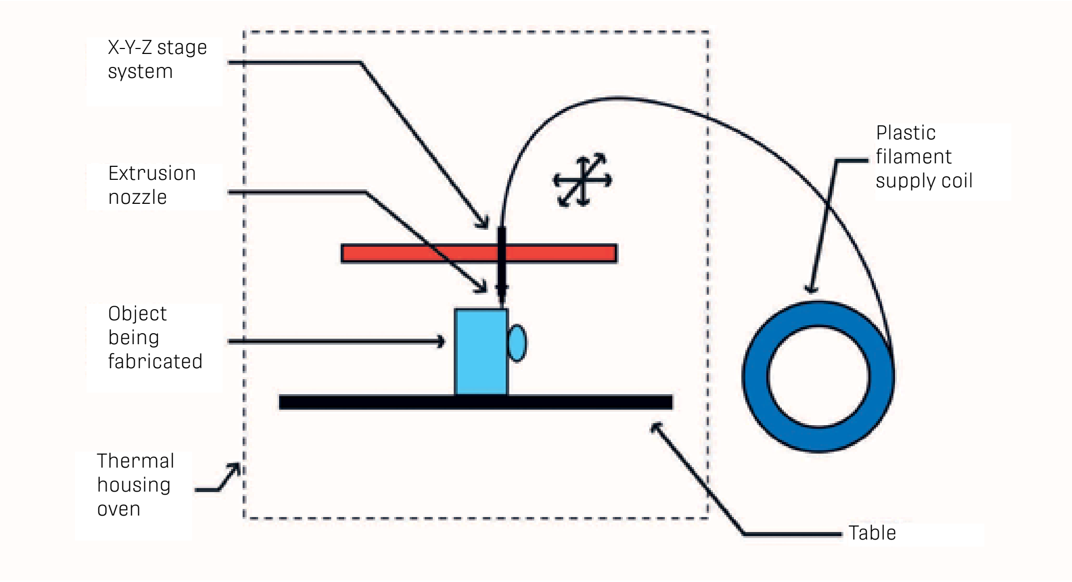


Fig 4-8 Illustration of the FDM process.

Fig 4-9 Example of FDM printing.

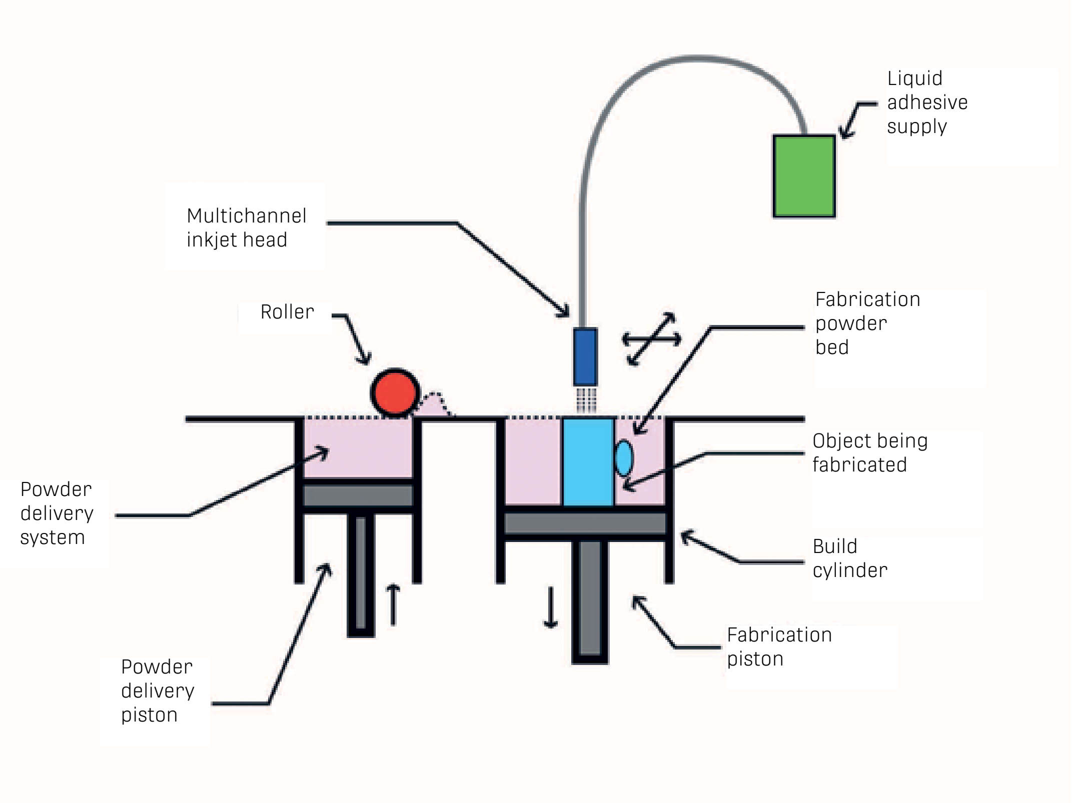
rough metals, as well as process expensive alloys, is a great advantage. However, DMLS and SLM are overall complex and very expensive processes. They are generally difficult methods to retain and maintain, they require specific manufacturing conditions, and the build size is limited for optimal control. Support structures are also necessary because high temperatures can lead to part distortion. However, removing metal supports is not an easy task, and manual removal may not be enough. CNC machining can also be required for removing metal supports as well as for improving important features (eg, holes). Final parts must also be treated thermally to eliminate any residual stresses. For all the above reasons, they are mainly used to manufacture parts that other methods cannot and thus are utilized for specialized automotive, aerospace, and medical applications. Available metal powders are stainless steel, titanium, aluminum, and cobalt-chrome.

The electron beam melting (EBM) technique is a proprietary process developed by Swedish company Arcam.[33] It is a method similar to DMLS, but the heat source is an electron beam instead of a laser to induce fusion between the particles of metal powder. It is necessary to print within a vacuum using conductive materials. EBM is a faster process than DMLS and SLM because of the higher energy, but the feature size, powder particle size, layer thickness, and surface finish are typically larger. An advantage of EBM is that it can build strong and fully dense parts in a variety of metals and alloys at a faster speed and at lower cost. It has been particularly used in the medical industry for producing implants.

Material extrusion: Fused deposition modeling

Material extrusion, or fused deposition modeling (FDM), is the most common 3DP method.[25] In this process developed by the company Stratasys Inc in 1991, a filament of thermoplastic material is supplied to a heated extrusion head (Figs 4-8 and 4-9). Once the right temperature is reached, the heated nozzle moves across the building platform, dispensing melting material that quickly cools and solidifies. Once a layer is applied, the platform moves down, the extrusion head applies more material, and the process repeats until the complete object is built. Usually, no further processing

Fig 4-10 Illustration of binder jetting.



is required, other than removing any support structures. Surface smoothing may also be necessary because often there are visible layer lines. Material options include polymers and thermoplastics such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), polyethylene terephthalate glycol (PETG), TPU, and many relevant composites that are continuously developed (eg, PEEK).

FDM, also known as *fused filament fabrication*, is the least expensive process regarding material and printing cost. It is used for visual and functional prototypes as well as simple end parts and applications. Accuracy is low compared to the other 3DP technologies. However, FDM remains a very interesting process with very high potential.

3DP: Binder jetting

3DP used to be itself one of the RP technologies, based on an MIT patent (Massachusetts Institute of Technology) and commercialized by Z Corporation (3D Systems), concerning the application of special powder-binder systems.[34] The original process used starch or plaster-ceramics material powder and a water-based binder liquid (Fig 4-10). The machine contains three spaces: *(1)* the entire build space with a movable piston at its bottom, *(2)* the powder feeder, and *(3)* the powder overflow space. A roller system traverses over the build space in order to spread the powder. Then an inkjet-type printhead is traversed, ejecting a colored water-based liquid binder on the surface of the powder bed. The powder surface solidifies when it comes in contact with the binder. The unaffected powder remains in the build space, supporting the model. After the build of one layer, the piston is lowered by one-layer thickness, and the next layer is made. After the last layer is finished, the model is elevated within the powder bed, the loose powder is removed, and the model is further infiltrated with wax or with epoxy resin.

The relevant modern process and utilized term is *binder jetting*, and it is a flexible technology with a wide spectrum of materials and applications, including multicolor and metal possibilities.[27] The available materials are sand, polymer, ceramic, and metal powders. The process has also evolved. A thin layer of powder material is spread onto the platform, and then droplets of adhesive are selectively ejected by an inkjet printhead. The droplets bind the powder particles. The part is built layer by layer; the object is then removed from within the powder material and cleaned. Postprocessing is required because the initial build is brittle as well as porous. As with the original 3DP process, the object is infiltrated but using common liquid adhesive. In the case of metal parts, postprocessing is more demanding, requiring infiltration with a polymer binding agent, metal material, or even thermal sintering.

The advantage of binder jetting is that it can produce full-color plastic prototypes as well as metal parts at a much lower cost than DMLS and SLM. It is a stable process, not affected by thermal effects and warping, and can also build very large parts in sand, such as casting molds. It does not require support structures, can produce complex geometries, and has a considerable build volume so that it can be used for low-to-medium series production. However, the porosity and internal gaps of the produced parts leads to lower mechanical properties than the actual raw material. The material properties of manufactured metal parts are lower than those manufactured with DMLS and SLM. Attention should also be given to small and fine details because the resulting parts are very brittle and can easily be damaged during postprocessing. Metal parts should be handled carefully, as they may deform during the infiltration or postprocessing sintering.

3DP: Material jetting

An even more recent but similar process is material jetting (MJ).[35,36] Instead of printing single layers of binder, MJ prints layers of material. In order to achieve this, multiple printheads are utilized to selectively deposit material droplets onto the platform. The material is cured and solidifies using a UV light source. The process is repeated layer by layer, much like the other AM methods. It is possible to use different materials for the same object, in a similar way that ink is used to print different colors on a piece of paper. It is necessary to use support structures, which are printed in parallel to the actual object using a water-soluble material. This facilitates postprocessing, as the supports can easily be dissolved.

MJ is considered a very precise method, similar to or better than SLA. The advantage of the process is that it allows printing of multimaterial and multicolor objects with very smooth surfaces and very high accuracy. As such, it is an ideal AM method for illustrative prototypes with the highest possible finish and appearance. However, it is an expensive process, restricting certain applications. The produced parts are relatively brittle with mechanical properties that can be affected by light, similar to SLA. MJ utilizes photopolymer and generally plastic resins such as polypropylene, high-density polyethylene (HDPE), polystyrene, polymethyl methacrylate (PMMA), polycarbonate, ABS, high-impact polystyrene (HIPS), and environmentally degradable plastics (EDPs) that can be found as solid, transparent, temperature-resistant, and castable.

Direct energy deposition

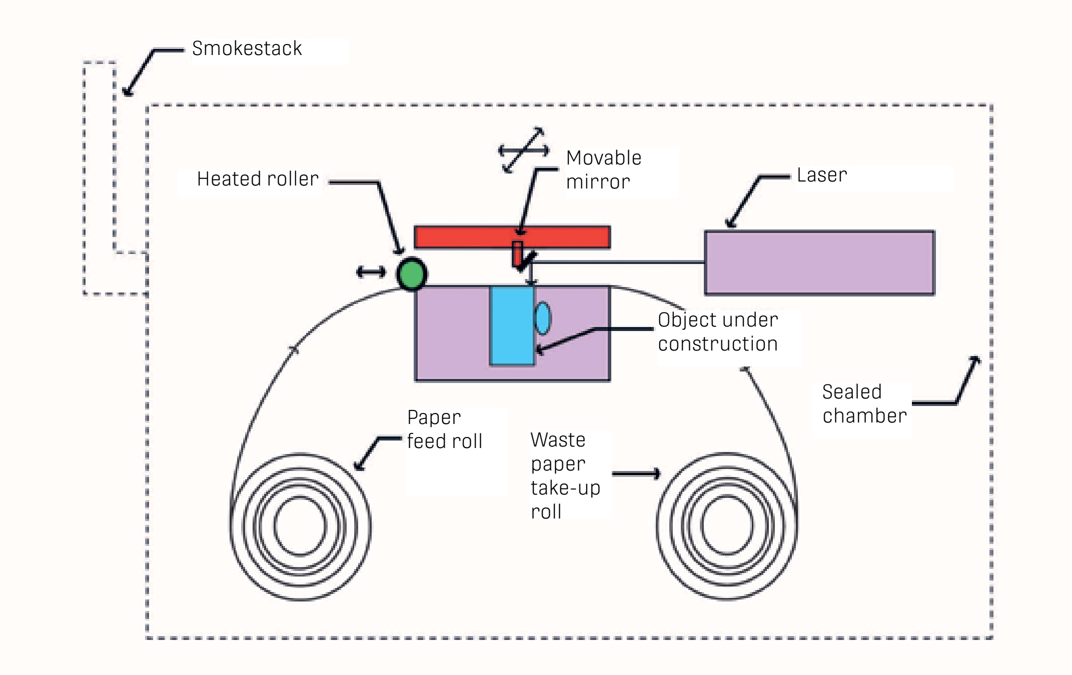
In comparison to other AM technologies, directed energy deposition (DED) does not build layer by layer.[37] The method utilizes a nozzle that is mounted on a multiaxis arm and deposits material. In principle, it is very similar to material extrusion. However, the nozzle can move in multiple directions and apply material at any angle due to four- and five-axis machines. The material melts upon deposition with a laser or electron beam. DED is usually used to maintain or repair existing parts, and materials include polymers, ceramics, and mainly metals in the form of either powder or wire.

Sheet lamination: Laminar object manufacturing

Laminar object manufacturing (LOM) is one of the first AM methods and utilizes plain paper (Fig 4-11).[38] The laser simply cuts the slices from a sheet of paper, which is attached to previously cut layers. Unlike other processes, only the external pattern of the shape needs to be cut. Once lamination is complete, the model feels like (and effectively is) wood. It can then be treated like wood, but care must be taken to avoid delamination. The significant advantage is the use of readily available and inexpensive A4 paper as well as the relatively simple setup and use, compared to all other AM methods.

An alternative, more recent method is ultrasonic additive manufacturing (UAM), which utilizes sheets of metal bound together using ultrasonic welding.[39] The process requires additional machining for the removal of the unbound metal during the welding process. The process can bond different materials with low temperature and energy. It is also possible to create internal geometries. UAM metal materials include stainless steel, copper, aluminum, and titanium.

Fig 4-11 Illustration of the LOM process.



AM Potential

AM and 3D printing represent a considerable expansion to the subtractive manufacturing represented by computer-aided manufacturing (CAM). However, all such technologies represent a continuous and ongoing development effort toward digital manufacturing and the integration of intelligent production systems with information technologies. In the context of digitization, AM represents the future of manufacturing and a key element of the 4th Industrial Revolution.

One of the main 3DP limitations regarding methods, materials, and applications is that there is no single solution for all applications. From the user's point of view, the major aspects to take into consideration in choosing an AM method are time, cost, and functionality. None of the processes is perfect in all respects. Each process has its only particular characteristics and restrictions imposed by price, material, geometry, size, and accuracy. In addition, any method chosen requires considerable "tuning" until it can achieve the required results. That is a fact for systems and applications aimed to industry or individuals.

Nevertheless, AM presents a considerable advantage compared to conventional manufacturing for product customization. Since the early days, it was made evident that these technologies, when applied correctly, can bring benefits in the form of better products in shorter lead times and at reduced costs. Building an object by adding material allows the construction of complex shapes and features that would otherwise impose considerable obstacles (Fig 4-12). Constructing intricate geometries with conventional methods means serious constraints on tools, materials, and labor and therefore investment of time and money. On the contrary, AM introduces an almost automated digital model-to-print approach, which promotes design imagination and limits manufacturing problems. In addition, it promotes a design-for-manufacturing philosophy, allowing the possibility to foresee and avoid fabrication issues, thus accelerating further the overall development process.

Fig 4-12 Example of complex structure printing.

In general, AM can substantially reduce product-development time, manufacturing costs, and material waste. It can provide independent manufacturing, sustainability, greater efficiency, shorter lead times, and optimal procedures. Today the accuracy has improved significantly, and the choice of materials is quite large, from sand to paper, polymers, plastics, metals, ceramics, alloys, and composites. Object sizes range from microns to entire buildings. The parts developed by AM are frequently being used for functional testing, preproduction parts, and, increasingly, fully functional end products. As such, 3DP has seen rapid growth across many industries for various applications that range from toys to fashion, from aerospace to construction, from medicine to bioprinting, including numerous dental and orthodontic applications, as also discussed later in this book.

AM is indeed a rather promising technology and rightly is considered an industrial revolution. While it was initially developed as a method to provide prototypes and shorten the industrial product-development process, AM is growing to a general, customizable 3D manufacturing method, accessible to small companies, designers, makers, students, consumers, and anyone else who wishes to be considered a "manufacturer." As the technology is adopted by a much wider audience, there will be a continuous development of new systems and materials that can ignite even further applications. As such, it seems that even if it has already taken decades to prove the value of AM technologies, the actual full potential of 3DP is still to be realized, and another scientific term may again be inevitable.

It is a logical progression that the digital nature of AM can also integrate upcoming machine learning, artificial intelligence, and robot technologies, leading to even more sophisticated possibilities and applications. The digital manipulation of data in collaboration with a network of interconnected distributed fabrication sites not only can revolutionize design and manufacturing but also can have a serious economic, social, environmental, and political impact. As presented in subsequent chapters, it is also the aim of this book to discuss potential orthodontic applications and how AM will affect the future of orthodontic clinical practice.

AM in Orthodontics

It is evident that many aspects of our everyday life are changing due to digital technology. Dentistry and orthodontics are no exception to this evolution. 3DP has been for many years a procedure almost unknown to orthodontics. However, the need for customized treatment, the evolving technology, and the interest of many companies in new markets encourage and promote a digital "in-house" concept that is fast emerging in the orthodontic profession.

The main advantage offered by AM/3DP in orthodontics is customization: customization to simplify clinical processes, satisfy patient-specific requirements, lower costs, and above all, optimize the clinical results.

In general, the materials used in orthodontic applications are polymers, metals, metal alloys, ceramics, and composites. 3DP technologies can handle almost all of these materials, thus presenting an important potential in the orthodontic domain, as with many other industries. 3DP methods can be employed for the development of any orthodontic appliance, such as customized bands, lingual holding arches, space maintainers, mini-implant–supported molar anchorage appliances, fixed tooth retainers, and many others. AM technologies have already been used to "print" dental casts, indirect bonding trays, aligners, occlusal splints, temporary anchorage device (TAD) surgical splints, palatal plates for cleft lip, fixed retainers, as well as anatomical models and surgical guides for orthognathic surgery.[40–45] A novel application of 3DP, discussed in chapter 8, is in-house printing of hybrid ceramic customized orthodontic brackets.

It is important to remember that 3DP is bringing virtual models into real life; thus, many factors contribute to an accurate and precise result. 3DP is considered the most demanding part of the design-to-manufacturing workflow chain. However, many limitations of the general process, such as dedicated knowledge, complicated technical procedures, unsatisfying accuracy, lack of appropriate materials, and high costs, seem to be gradually surpassed. Growing interest is encouraging companies to turn their interest to creating CAD software, materials, and desktop 3D printers dedicated to orthodontic applications. In turn, orthodontists around the world are gradually climbing the necessary learning curve successfully and becoming acquainted with the forthcoming digital change. More and more dental schools are also increasingly including digital technology in their educational program. Therefore, it is almost inevitable that in a new digital era, orthodontics will be practiced in an entirely different way for the benefit of the patient, the orthodontist, and the orthodontic profession. In the future, 3D printing will undoubtedly be a part of orthodontic offices and clinical practice, helping the orthodontist to manufacture his or her own customized orthodontic appliances with minimal dependence on outsourced laboratories or auxiliary selling companies. The intention of this book is also to highlight this future path, and subsequent chapters will explain various specific applications.

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5

Orthodontic Office Digital Workflow

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The word *digital* is derived from the Latin *digitus*, meaning finger, and this term was first used by the mathematician George Stibitz in 1942.[1] However, the modern usage of this term has shifted to electronics and computing, where real-world information is converted to binary (0, 1) numeric form. *Analog* is the opposite of digital, and it refers to any technology that does not convert data into binary code.

Digitization is the process of converting text, images, sound, and objects into a digital (binary) form to be processed by a computer. At this juncture, we are proposing the use of the term *undigitization* to describe the reverse process where a digital form of any kind is converted to a real-world form—for example, when a digital dental cast is exported from a computerized database and printed as a physical form (Fig 5-1).

Digitalization is another word that is not common in the medical literature. As defined by Gartner, it is the use of digital technologies to change a business model to provide new revenue and value-producing opportunities; in other words, it is the process of moving to a digital business.[2] If digitization is a conversion of data and processes, digitalization is a transformation. Digitization in an orthodontic office is the first step, followed by digitalization.

Today, nearly all human endeavors are processed in digits and are becoming digitized, with massive amounts of digital data being stored in or processed by computers. All branches of medicine, including dentistry, have incorporated these tools. Orthodontics has done so in every aspect of patient diagnosis, treatment, and record management.[3–6] In addition, appliance design and fabrication, once performed manually, are also increasingly being done with the use of these tools.[7–11] Furthermore, artificial intelligence (AI) is also a promising technology starting to find pertinence in orthodontics.[12–15] It will take time for all orthodontic offices to become digitized, but this tide cannot be turned back. Each new group of graduating orthodontic residents has been exposed to these promising

Fig 5-1 Digitization and undigitization.

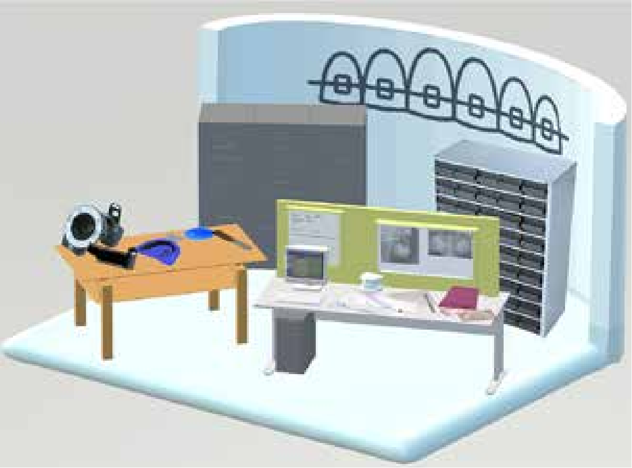


Fig 5-2 The analog orthodontic office.

technologies, and they will provide the driving force for its further advancement.

The Analog Orthodontic Office

Currently, many orthodontic clinics are analog environments (Fig 5-2). In some instances, the only digitized aspect is the front office/receptionist's computer, where appointments are booked and patient medical records are kept with the possibility of providing electronic bookkeeping services as well. This common working model requires that all appliances, dental casts, examination forms, x-ray films, cephalometric analysis, photographs, treatment plans, and treatment simulation (ie, setup) be outsourced or processed manually. All this information, analog or digital, is very important to gather and analyze for the following reasons[16]:

- To analyze the specific problems of the patient
- To visualize the patient's orthodontic and orthognathic profile
- To set the goals of orthodontic treatment
- To be able to plan a treatment for the patient
- To be able to simulate possible treatment plans
- To present to the patient the problem and the treatment plan
- To be able to communicate with the dental laboratory and other dental specialties
- To be able to compare posttreatment results with the initial presentation
- To be able to compare the specific patient's problem with similar problems
- To be able to provide patient medical data upon request
- To be able to develop/design patient-specific orthodontic appliances
- For outcome assessment and research purposes
- For AI purposes

"Analog" clinics gather diagnostic records without the use of digital methods. For example, dental casts are made from alginate impressions, clinical examinations are recorded on paper forms, and radiographs are provided and read from chemically developed film or printed onto photosensitive paper and analyzed manually using acetate sheets. (It was not until recently that students enrolled in orthodontic postgraduate studies are no longer intimately familiar with slide projectors and passing around of plaster casts.) In addition, 3D facial features are recorded on 2D film, and 2D photographs are taken using analog film-based cameras or, in recent years, digital cameras.

"Analog" dental laboratories perform multiple tasks using poured stone dental casts derived from dental impressions that must be transported to the facility and returned upon completion. These can be mounted on articulators, manipulated to create "setups," or used to manufacture orthodontic appliances or simulate orthognathic surgeries. In reality, these analog orthodontic clinics have the analog dental laboratory as an extension to their workflow.

Unavoidably, all data accumulated in this manner is dispersed in different disassociated files and in fragments that necessarily deconstruct a 3D human being into 2D pieces of information. This 3D to 2D conversion causes significant data loss.[17]

Nonetheless, this traditional workflow, when in the hands of an experienced orthodontist, can work in a reasonably satisfactory manner. Difficulties can often be anticipated when severe orthodontic problems are encountered, for example when dental and skeletal disharmony is merged in the same patient. However, communicating diagnosis, treatment plan, and expected outcomes to the patient or parents is much more difficult with the analog approach, and analog 2D information does not facilitate the principle of initiating an orthodontic treatment with the end in mind.[18]

The Semi-analog or Semi-digital Orthodontic Office

The current level of penetration of digital technology into the clinical orthodontic setting is such that it is used only to partial capacity, meaning that certain aspects such as photography and the filling out of forms have moved into the digital realm (Fig 5-3). The ability to accurately reproduce both resolution and chroma digitally has replaced the need for chemical processing of film. In addition, many clinics have become paperless. Furthermore, software such as Microsoft Office PowerPoint has enabled the clinician to present general and patient-specific material to active or prospective patients as well as educational material for instruction purposes, if not equipped with presentation software such as Dolphin Imaging or Orthomation (Dentsply Sirona).

The development of digital sensors has replaced the conventional x-ray film (and thereby reduced radiation exposure). Images fabricated with the digital technique can be delivered via the Internet or on external memory, while the analog variety must be chemically processed and then manually delivered. Digital tools to analyze diagnostic radiographs in use currently require manual registration of reference points with the derived angular and millimetric measurements available at the press of a button. AI will soon render this interaction unnecessary. Presently, Ceph X (ORCA Dental AI) is harnessing AI to register the standardized anatomical points delineated on a cephalometric radiograph in order to automatically trace the cephalogram and provide linear and angular measurements.[19]

This period of technologic advancement in medicine and dentistry has impacted orthodontics significantly in clinic and patient management and in diagnosis and treatment planning/delivery. The current model of a semi-digital orthodontic clinic consists most commonly of a digital camera, necessary software for clinical examination and data gathering, some digital panoramic and cephalometric radiography, a presentation software (eg, Orthomation), and sometimes (thought rarely) cephalometric tracing software like Dolphin Imaging, VistaDent (Dentsply Sirona), or Planmeca Romexis. Presently, delving deeper and committing to a greater use of digital technologies remains cost-prohibitive. Hence, the tools employed today are useful in their own right but are not integrable, making their contribution to orthodontics limited. The needed tools will allow combining of data from multiple diagnostic sources in order to compile a virtual patient complete with dynamic/functional reproduction.

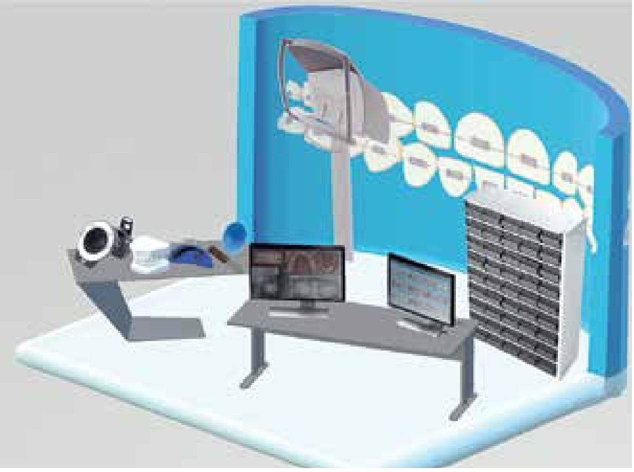


Fig 5-3 The semi-digital orthodontic office.

Fig 5-4 The digital orthodontic office.

The Digital Orthodontic Office

CBCT or volume scanning

Continuing digital innovation has driven the development of additional technologies relevant to orthodontics, which have been quickly introduced into daily practice and refined with greater usage for the benefit of the patient and the clinician[6,20–23] (Fig 5-4). Texts within medical literature credit dentistry for this pioneering development of digital technology.[24]

Computed tomography was first invented by engineer Sir Godfrey N. Hounsfield in 1967,[25] and CBCT was initially developed and used for angiography in 1982 before being adapted to dentistry in 1996, when the first CBCT machine (NewTom DVT 9000) was introduced. This new and experimental x-ray machine enabled the orthodontist to achieve 3D radiographs. This CBCT technology continued to develop, and additional companies ventured into its production and development.

From a purely experimental standpoint, CBCT provides the clinician with cumulatively more information than the previous imaging methods available, and its use negates the need to make separate periapical, panoramic, and lateral/anteroposterior cephalometric radiographs. Furthermore, it has become the standard of care under various clinical scenarios (ie, dental impactions, localizing nerve canals, etc).[26–29] However, the radiation exposure required by this method needs to be weighed against its value as a diagnostic tool.[30–32] Orthodontists must adhere to the ALARA ("as low as reasonably achievable") concept in order to minimize the risks of radiation exposure of the patient while achieving an acceptable CBCT image.[33]

The significant increase in the diagnostic value provided by this technology served as the impetus for developing more economical, simplified units that also enabled less radiation exposure. This was mirrored by the shift in priorities of companies that previously produced 2D radiographic imaging tools to those providing 3D craniofacial volume scanning acquisition and improved CBCT capabilities. These are now provided with less radiation exposure, better digital sensors for higher outcome quality, faster acquisition, ability to export DICOM or even STL files, and 3D facial color photographs (eg, Carestream CS9600, Planmeca 3D Max).

A cephalometric radiograph can be constructed when performing a high-FOV (field of view) CBCT. A panoramic radiograph can also be constructed when a medium-FOV CBCT is used. In the case where 3D photography is not an option when a CBCT scan is performed, special 3D face scanners can be used (ie, Bellus3D ARC). Both DICOM files (CBCT) and STL (3D facial photography) can be fused using special software, and both scans can be fused with an intraoral scan as well using software (eg, Viewbox dHAL, Dolphin Imaging). When the additional radiation is not justifiable, a digital cephalometric radiograph should be mounted onto the existing CBCT machine. Chapter 2 discusses the many advantages of CBCT in orthodontics as well as its indications. Nevertheless, there are some disadvantages compared to the 2D classic panoramic radiograph, such as higher radiation exposure and higher cost.

Currently, 3D cephalometric analysis is not easy to perform, nor has it been standardized; therefore, it is rarely done. Rather, it is used mainly in research and much less in clinical settings.[34–36] Software exists that provides a 3D cephalometric analysis such as Dolphin 3D, MIMICS (Materialize), and InVivo Dental (Anatomage).

Paperless examination, analysis, and treatment simulation software

An example of such multifunctional orthodontic software is Dolphin Imaging (Fig 5-5). The digitization of patient data has rendered analysis of the dental arches (ie, arch length, Bolton ratio, occlusogram, dental setup, etc) a relatively quick and simple procedure. Also, the superimposition of serial CBCTs is becoming more commonly available with relevant diagnostic software, permitting relatively simplistic assessment of treatment effects. In addition, this has been supplemented with a full digital appliance presentation in 2D photographs and 3D videos. This alignment of digital tools allows the centralization of all gathered patient data. This can then be used for diagnosis, treatment planning, and patient education purposes. Newer software such as Digital Smile Design or Hack Dental (Figs 5-6 and 5-7) or even freeware allow for digital photographs to be integrated despite the fact that they are a 2D rendering of the patient.[37–39] Other features have also been included that simulate treatment options.

Surface scanning

Intraoral scanning has undergone rapid development since Dr François Duret invented the first intraoral digitizer to acquire an optical impression.[40] Consequently, CEREC was introduced by Mörmann et al for use in restorative dentistry.[41] The demand for digitization of the dentition with an easy, precise, and accurate tool catalyzed the development of this technology. In recent studies, intraoral scanners have shown to be highly precise and accurate with reference to orthodontic requirements.[42,43] Surface scanning includes scanning of the teeth, soft tissues, centric relation, as well as other occlusion registrations needing recording. Desktop versions of surface scanners were initially available but were mainly employed in dental labo-

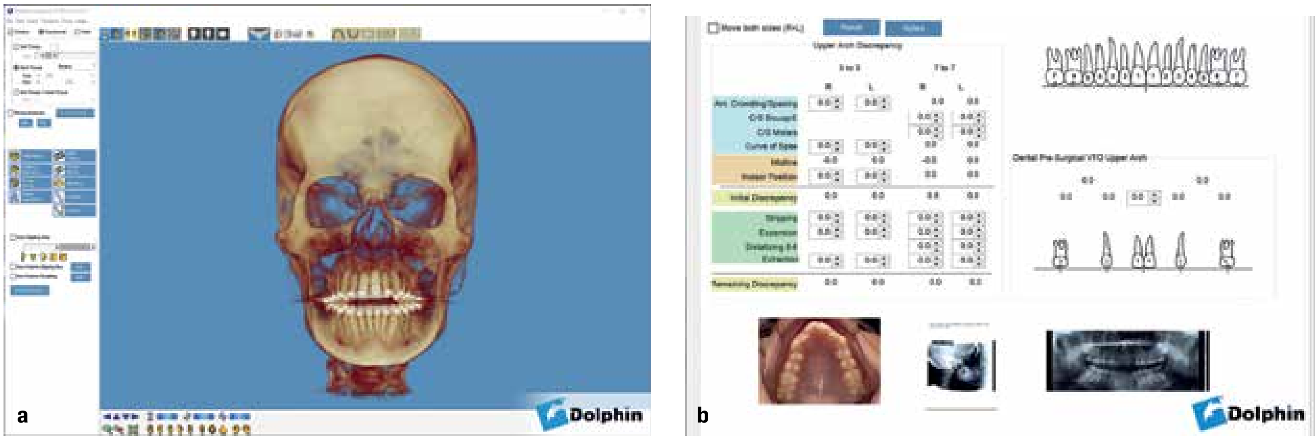


Fig 5-5 *(a and b)* Dolphin Imaging software, the digital data central station.

Fig 5-6 Digital smile design using Hack Dental software.

ratories (Fig 5-8). These were used to scan dental impressions or casts directly. Software like Dolphin Imaging has been expanded to include the importing of surface and volume scanning. These scans can be fused to reproduce the patient's craniofacial morphology with an associated 3D orientation of the dentition.[44] Digital facial scanning in 3D has also been introduced to clinical orthodontics. This additional dimension can be fused with CBCTs and dental arch scanning. Other CBCT units also offer the capability of simultaneously performing volume scanning and 3D face scanning (Fig 5-9).

Fig 5-7 Digital smile design using Hack Dental software combined with ClinCheck (Align Technology).

Fig 5-8 Maestro desktop surface scanner.

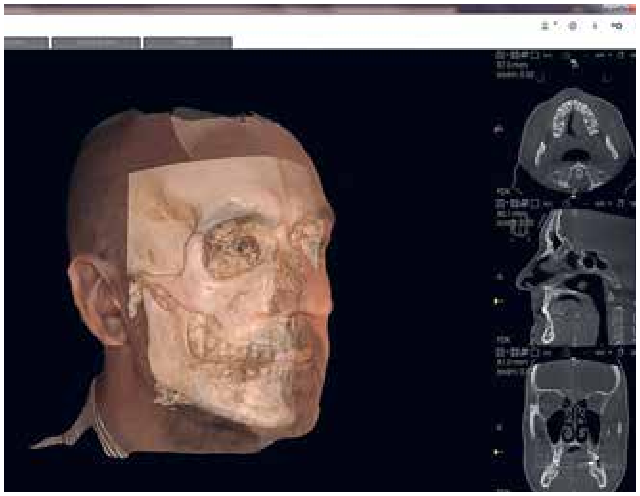


Fig 5-9 Volume scanning and 3D facial photography in CS9600.

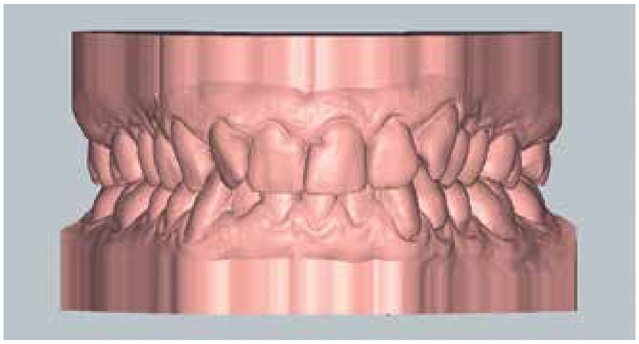


Fig 5-10 Aligner design with DeltaFace orthodontic CAD software.

Fig 5-11 Lingual arch design using OrthoSystem by 3Shape.

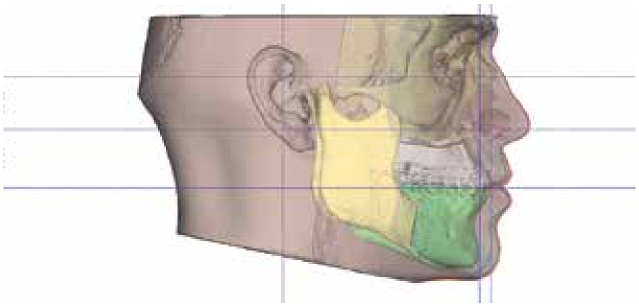


Fig 5-12 Orthognathic surgical splint design in Dolphin Imaging software.

CAD software

Advances have also occurred toward providing the clinician/technician with the digital capacity to design customized orthodontic appliances. These tailor-made appliances are becoming more commonplace in both the clinic as well as laboratory settings. The popularity of preplanned clear aligners encouraged the development of CAD software (DeltaFace, Maestro Dental Studio) as well as accompanying hardware to facilitate clinician-derived in-house production of such appliances (Fig 5-10). Presently, there are software packages that offer the features of orthodontic analysis and custom appliance design, such as clear aligners and virtual orthodontic bracket bonding with indirect bonding transfer design (DeltaFace, Onyx Ceph, 3Shape Orthoanalyzer, Maestro Dental Studio). Some orthodontic dedicated CAD software like Orthoanalyzer offer the orthodontist the ability to design customized appliances like lingual arches and rapid palatal expanders[9,45] (Fig 5-11). Other general-purpose engineer CAD software can be used to design customized orthodontic appliances and/or orthognathic surgical splints. Later chapters describe such capabilities. Orthognathic surgical planning with the Dolphin Imaging software is depicted in Fig 5-12.

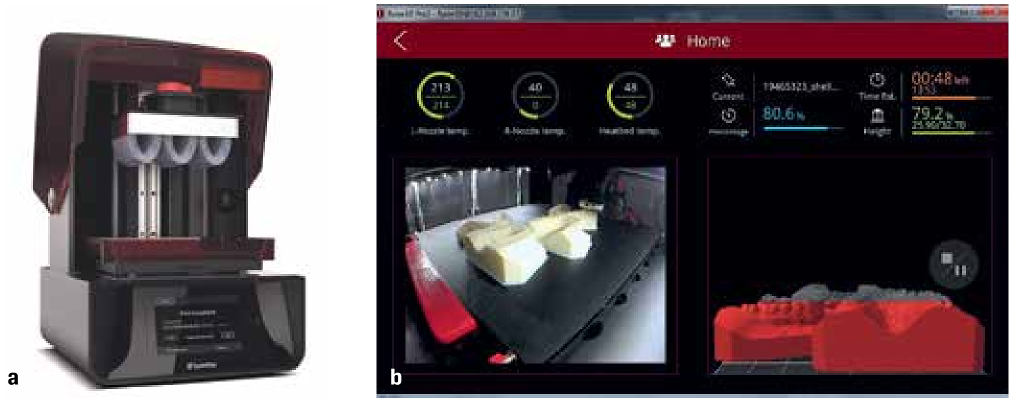
Subtractive and additive manufacturing

Subtractive manufacturing, known as *milling*, has been used in engineering and in 3D object manufacturing for many years. Subtractive manufacturing is a process by which an object is produced by removing material from a

Fig 5-13 Five-axis dental milling machine.

Fig 5-14 The dimension of the milling disk is not suitable for creating most orthodontic appliances.

Fig 5-15 *(a)* A digital light processing 3D printer: SprintRay Pro Desktop 3D Printer. *(b)* Printing of study casts on a fused deposition modeling 3D printer: Raise3D Pro2. (Courtesy of Dr Burkhart van Soest.)



stock to create the desired geometry. Subtractive manufacturing (CAD/CAM) has been used in general dentistry since the mid 1970s by Dr Duret, who, with the help of an optical impression, designed and milled a crown using a numerically controlled milling machine.[40] He later developed the Sopha system, which had an impact on the development of other dental CAD/CAM systems,[46] for example the CEREC and Procera systems.[47,48] Milling machines are used even in-house to manufacture dental prostheses such as crowns or bridges (Fig 5-13). Prior to milling, an operator, dental technician, or a trained dentist would need to design the given restoration using dedicated CAD software. This has evolved into the present five-axis milling machines, which greatly simplified this procedure while increasing the accuracy of the final product.

Subtractive manufacturing has proved to be a constructive development in restorative dentistry; however, it is less pragmatic in the field of orthodontics. The materials available are well suited for high-volume milling of prosthetic restorations. Currently, these are not well correlated with the volume of an orthodontic appliance, although some small-volume orthodontic appliances (ie, fixed orthodontic retainers) are feasible (Fig 5-14). Furthermore, these materials are limited mainly to dental crown manufacturing (although stainless steel could be used) like zirconia, polyether ether ketone (PEEK), etc. In addition, the process of subtractive manufacturing results in significant amounts of material waste. This can be a disadvantage concerning time and cost. Nevertheless, chapter 6 presents some orthodontic appliances manufactured using subtractive technology. Several reports of orthodontic appliances fabricated by PEEK in milling machines have been published.[49–51]

Additive manufacturing, also referred to as *3D printing*, is a technology that has been in use for several decades. Initially, this method was utilized by industry and then penetrated the dental and medical professions.[52,53] 3D printers are now used in dental laboratories as well as in clinical settings (in-house printing). The latter usage is limited to printing dental casts, occlusal splints, indirect bonding trays, and patterns for (laboratory) casting procedures (Fig 5-15). Direct printing of clear aligners is currently being attempted and is discussed in chapter 10.

Fig 5-16 *(a)* Meccatronicore washing machine for printed objects. *(b)* Meccatronicore postcuring UV machine.

Printing is achieved using DLP, SLA, and MSLA printers. For printing only dental models, some FDM printers can be used. However, if aligners are to be printed directly, this currently requires that the material to be used (filament) has specific characteristics in order to withstand the high temperature of the thermoforming machine (see Fig 5-15b). SLS, SLM, and polyjet printers are currently utilized only by dental laboratories. The high cost, the significant printer volume, the stringent safety precautions, and the need for postprocessing using debinding and sintering machines make these machines impractical for use within a clinical setting. They are used for crowns, bridges, frameworks of partial dentures, and, lately, metallic orthodontic appliances printed using cobalt-chrome, stainless steel, and titanium alloys. Printers that are used for in-house orthodontic purposes utilize special resins and do not carry the safety concerns mentioned above, although a slight odor may be emitted due to the resin and isopropyl alcohol used.

Following printing with a DLP, SLA, or MSLA printer (see chapter 4), a postprinting procedure must be performed. This requires the use of two other machines. First, the printed object must be immersed in a special type of either washing machine or an ultrasonic cleaner containing 91% isopropyl alcohol according to the resin manufacturer's guidelines; this eliminates uncured resin from the printed object's surface. This is followed by postcuring using a special UV postcuring machine (Fig 5-16). The duration of this step depends on the intensity of the UV light source, the curing temperature, as well as manufacturer guidelines.

FDM printers use special filamentous printing materials (PLA, ABS, etc) that do not require any postprinting procedures. Unfortunately, these materials are currently not biocompatible. The one exception is the filament-form PEEK, which is formulated in a biocompatible composition by EVONIK. This material currently has medical applications (dental implants, covering of bone defects, osteosynthesis applications) and has the potential to be used intraorally for manufacturing various appliances (lingual arches, etc). However, use with an FDM printer cancels its biocompatibility certification because each component of the printer must be approved for medical usage. This prerequisite has only been achieved with APIUM M220 medically oriented printers. At this time, FDM biocompatible PEEK printing is expensive and difficult to achieve. More detailed information about 3D printing is presented in chapter 4.

A complete digital orthodontic office

A digital orthodontic office can have all of the devices or software described previously or only a few of them, including the following:

- CBCT machine for volume scanning and a cephalometric x-ray machine
- Intraoral scanner for surface scanning
- A desktop scanner (where an intraoral scanner is not part of the armamentarium)
- A 3D face scanner (could be included in a newer-generation CBCT)
- CAD software for patient analysis, treatment presentation, treatment simulation, and treatment planning
- CAD software (if not included in above) for dental arch setup, aligner fabrication, aligner design (for direct aligner printing), virtual bracket bonding, indirect bonding transfer tray design, study model design, custom metal appliance design (lingual arch, rapid palatal expander)
- Free CAD engineering software for in-house appliance design (described in chapter 6)
- 3D printer (DLP, SLA, MSLA, or FDM; see chapter 4)
- An in-house wire-bending robot[54] (see chapter 13)
- Isopropyl alcohol washing machine
- UV postcuring machine
- Positive pressure thermoforming machine

The needs of a given office will dictate the minimal necessary digital tool requirements. For instance, where in-house aligners are to be fabricated, we believe that at least the following devices should be present:

- Intraoral or desktop scanner
- CAD software for setup and aligner design
- CAD software for patient analysis, etc
- 3D printer
- Isopropyl alcohol washing machine
- UV postcuring machine
- Positive pressure thermoforming machine.

A CBCT unit may not be mandatory if there is an option of referring patients to an imaging center that offers this service. CBCT machines and intraoral scanners can be intergraded even if from differing manufacturers because the working files to be exported are universal in a format that permits all devices to access their data. Nevertheless, CBCT machines and intraoral scanners made by the same company can integrate more easily because they share the same software platform. In the authors' opinion, the most useful digital tools to have are *(1)* the intraoral scanner that will digitize the dental arches and *(2)* the CAD software that will help the clinician analyze the data, set up the dental arches, and design aligners, trays, etc. Printing can be outsourced to a dedicated dental laboratory, although high-quality printers are now much more affordable.

The application of digital workflows has allowed dental clinical practice to become less reliant on dental laboratories and technicians. Although there are still types of appliances that can only be manufactured in a dental laboratory setting (metallic appliances, lingual appliances, rapid palatal expanders, etc), many of the appliances classically fabricated by laboratory technicians can now be designed and printed digitally in-house. As the cost and size of these devices continue to decrease, their incorporation into clinical practice will become more practical and feasible.

Advances in this field require that the unit/machine size be reduced, for instance with reference to the laser unit. Furthermore, postprinting machines like the sintering furnace pose insurmountable challenges to their inclusion into a clinical environment, making them not feasible at this time. However, recently a company in Russia (3DSLA.RU) developed a non–laser sintering printer based on an experiment done at the Technological University of Tel Aviv using microwave technology to build by sequential layers metallic objects using stainless steel, cobalt-chrome, and titanium.[55,56] While currently the layer resolution of such a printer is too low for dental applications, plans are underway to decrease the size of the printer to create a desktop version and to increase its resolution.

The current trend of advances in digital technologies applicable to the orthodontic clinical setting suggests that the future of designing and printing individualized appliances will initiate a "migration" of external laboratories into the orthodontic office itself. There will be no reason for the fully digital clinic to collaborate with an external partner when everything that is needed presents itself in the clinic. Therefore, it is logical that a dental technician can be the person in charge of the in-house designing and printing of orthodontic appliances, especially in multi-practitioner orthodontic centers where several clinicians might be utilizing this kind of workflow.

The Virtual Patient and the Future of the Digital Orthodontic Office

Digitization, as previously explained, converts all real-world information into digital data that can be displayed on a computer screen.[3] The combined data from volume scanning, surface scanning of the dental arches and face, and the fillable form are transferred to a CAD software to build the "virtual patient" for orthodontic diagnosis (ie, Bolton analysis, occlusion evaluation, dentoalveolar assessment, other 3D measurements) and for simulations of tooth movement. Treatment goals are then defined together with the treatment options. Finally, a treatment plan can be made that will define the custom appliances to be designed. Appliance design can be carried out using dedicated CAD orthodontic software or other CAD freeware.

The orthodontist can design clear aligners, metallic appliances (rapid palatal expanders, lingual arches, sagittal correctors, etc), orthognathic surgical splints in the presurgical orthodontic stage, or even custom orthodontic brackets. In addition, with the use of a wire-bending robot, the archwires needed for the orthodontic treatment can be designed and developed (using Prof Alfredo Gilbert's invention, Lamdabot 2). Aligners and surgical splints can be printed in-house while metallic appliances and custom orthodontic brackets are printed in a laboratory environment. In the near future, in-house printers could perform this task in the orthodontic office.

In essence, this in-house data workflow can only be achieved in a fully digitized orthodontic office. As clinical practices and academic institutions are changing their workflows to incorporate more and more digital technology, clinicians are changing their own thought processes. The availability and access to the completed digital data of the virtual patient allows the clinician to conceptualize this data in a spherical manner rather than the linear pathway prescribed by the analog office. This in turn catalyzes treatment planning that can be multiplanar and customized for each individual patient. Furthermore, AI is already on the horizon, and amassed data will serve to assist the clinician in diagnosis, treatment planning, and problem-solving (see "Artificial Intelligence and Blockchain in Digital Orthodontics" in chapter 6 as well as chapter 14 for more information on AI). Finally, with data storage practically unlimited with cloud-based systems in the digital orthodontic office, dental specialists can easily access and assess the patient's data if the need arises for interdisciplinary treatment.[57]

The ability to compose the virtual patient and to digitally design and print tailor-made appliances is the most revolutionary change in orthodontics since the concept of the preadjusted fixed appliance, and it is still in its early stages.[58] Nonetheless, it is important to state that digital technology can make a good orthodontist better, but it will never make a bad orthodontist good.

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6

In-House Custom Appliance Design

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The Traditional Orthodontic Laboratory

While much of modern orthodontic treatment can be administered with mass-produced “stock” items such as brackets and archwires, traditionally all orthodontic clinics also require an association with a technical laboratory in order to fabricate accessory appliances for specific patient needs based on individualized diagnosis and treatment planning.[1]

These appliances are commonly generated from dental impressions made in the orthodontic clinic and forwarded, together with a prescription for appliance fabrication, to the associated laboratory. These appliances include those requiring metal frameworks and soldering (eg, rapid palatal expanders [RPEs], lingual arches, space maintainers, tongue guards, Herbst appliances, etc) as well as acrylic-based appliances (eg, Hawley retainers, functional appliances, etc), and all of them require that the laboratory technician pour a dental cast and make use of a multitude of materials and tools to fabricate the prescribed appliance. As such, the laboratory technician has become an essential partner of the orthodontic clinic.

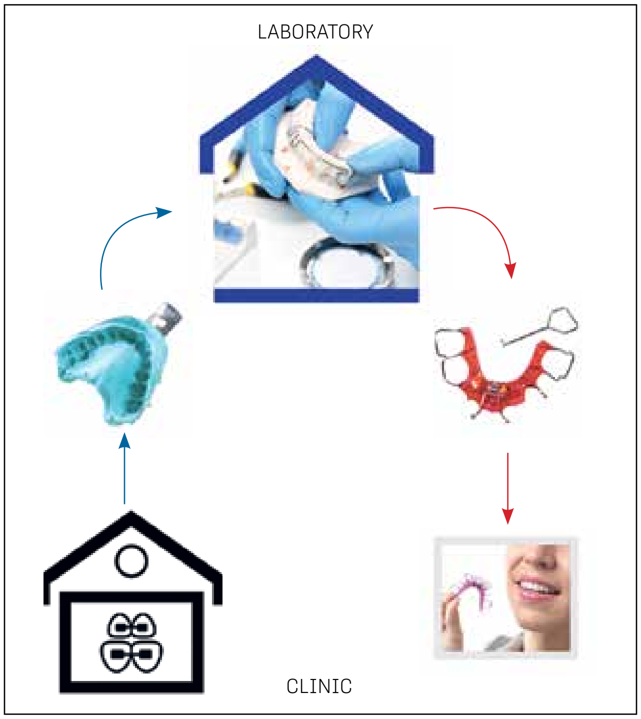


Fig 6-1 The workflow of an appliance from the orthodontic clinic to the laboratory and back.

Orthodontic laboratory technicians typically *only* produce orthodontic appliances, making them specialists in orthodontic appliance design and manufacturing. Although this is done according to a transcribed prescription from the orthodontist, the technician must possess great skill to achieve the desired result. For example, a simple removable retainer includes metal clasps and anterior bows requiring detailing and incorporation into fitted acrylic frameworks. These entail proper manipulation and understanding of their properties. Furthermore, the laboratory technician is responsible for appliance cleaning and polishing before it is transported back to the referring orthodontist for patient delivery. Therefore, the workflow of an appliance starts in the orthodontic clinic, passes to the laboratory, and then returns (Fig 6-1).

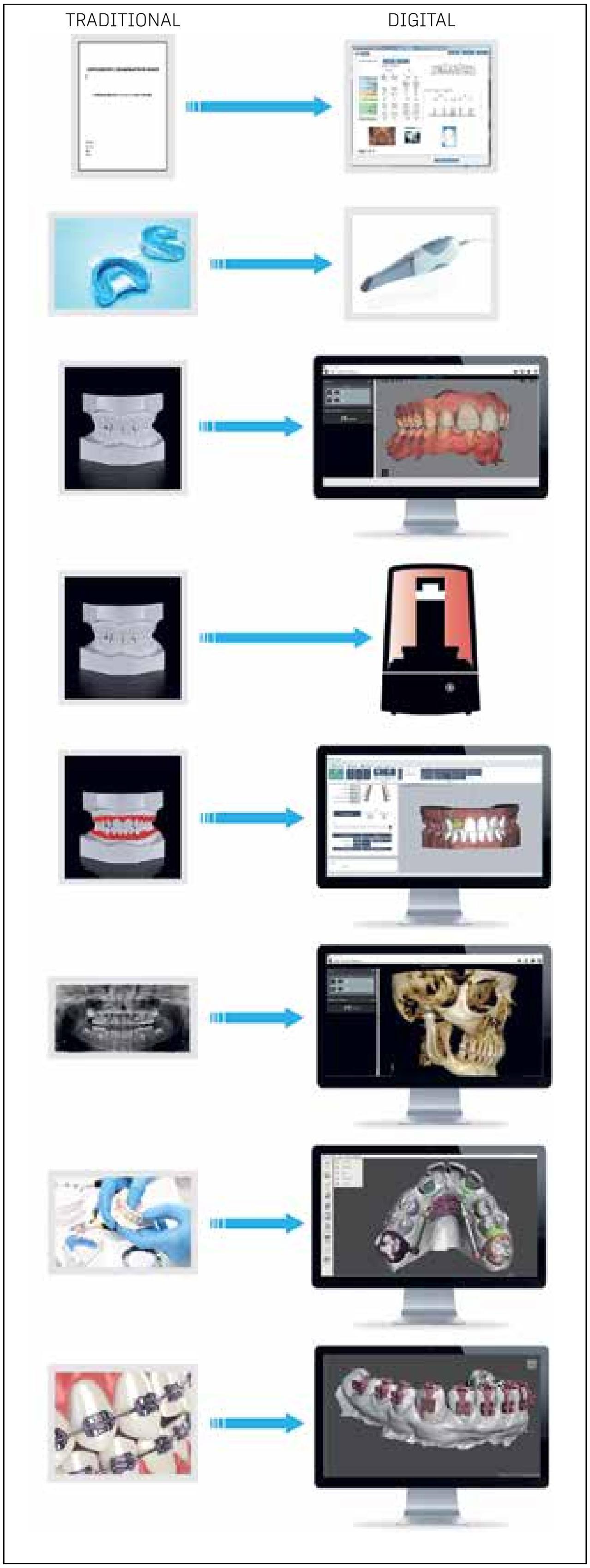


Fig 6-2 Shift from a traditional to a digital office.

Digital Evolution in Orthodontics

The progressing digital revolution has ushered the advent of new tools that have shifted this "traditional" relationship between orthodontist and laboratory.[2–4] The availability of intraoral scanning has eliminated the need for any kind of dental impression, and the digital data captured during scanning can be used to design custom appliances with computer-aided design (CAD) software in the orthodontic clinic before that information is sent to the laboratory for fabrication (Fig 6-2). A primary example of this is the paperless clinic. Previously, patients, doctors, and staff were required to manually complete physical paper forms for diagnostic and office use. These have been replaced with software versions that, with network access, have eliminated the need for the former.

Robotic tools have also become available to fabricate orthodontic archwires, and 3D printers can now "print" appliances or even customized orthodontic brackets direct from scanned data[5–7] (see chapters 4 and 5). For appliance design, dedicated orthodontic CAD software (eg, 3Shape Orthoanalyzer) has provided operator-driven design of bands, metal arms, and wires as well.

This chapter explains the design of metallic and nonmetallic appliances using free CAD software called Meshmixer (developed by Autodesk), which is described as "state-of-the-art software for working with triangle meshes."[8] A manual can be easily downloaded from the Autodesk site, and YouTube videos are available that demonstrate all of its tools. The capabilities of this software are enormous, being that it is designed for general usage and not strictly for dental or orthodontic purposes. Despite this, it has found use by dentists and oral surgeons but not frequently by orthodontists.[9,10]

It is important to note that many other general-purpose CAD programs can also be used for dental purposes, including Blender, Rhinoceros, and Apple Shapr3D. The unique feature of the latter application is the wireless pencil for on-screen drawing, making this an easy way to design parts of orthodontic appliances.

In order to use the Meshmixer software successfully, the orthodontist must spend a few hours self-educating by watching videos, reading the manual, and experimenting with the tools and functions. Understanding of the software is derived primarily from the video tutorials and is the primary method employed by the author to gain understanding (Fig 6-3). Moreover, as operator skill and

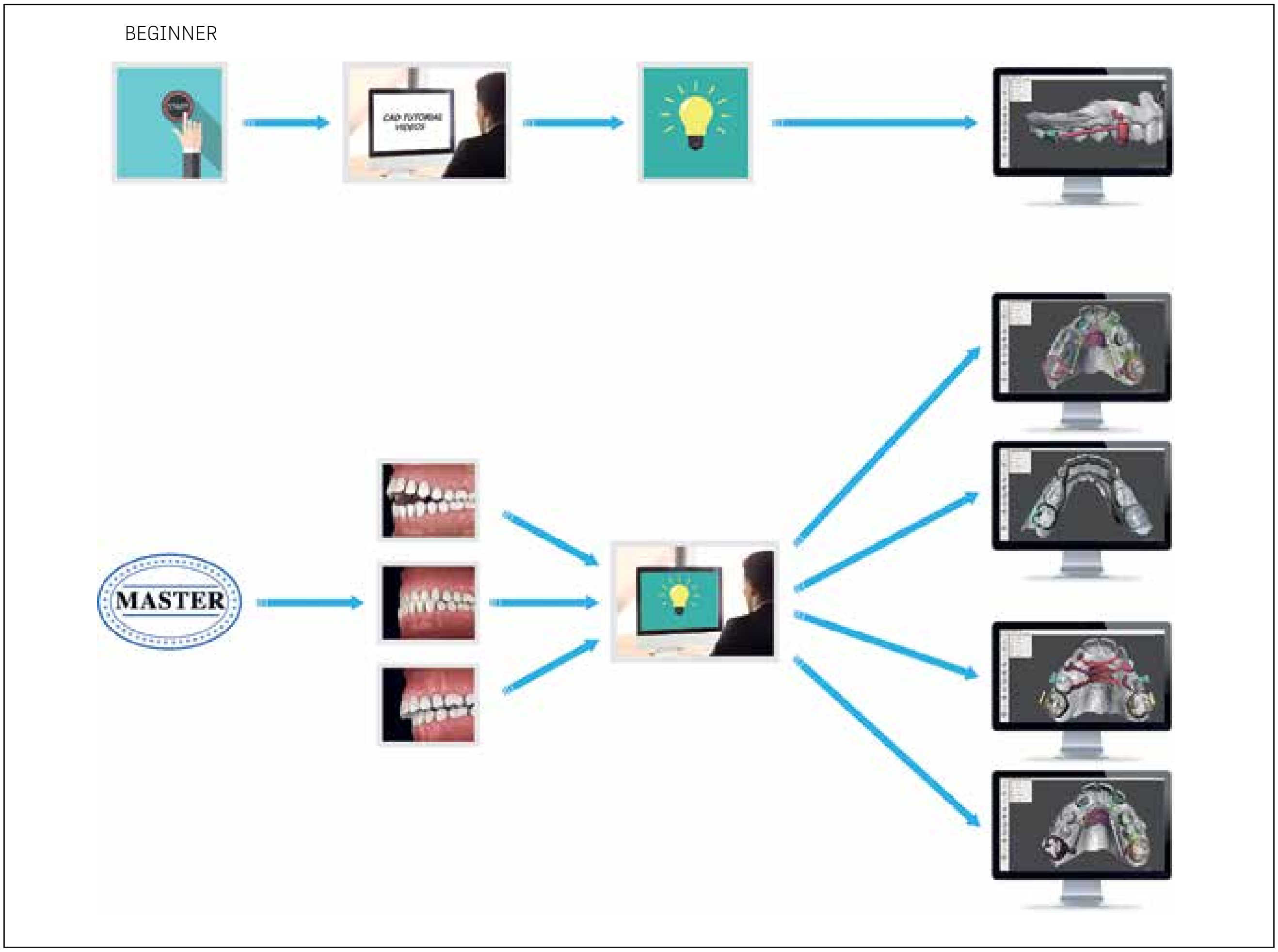


Fig 6-3 Difference in workflow between a beginner and a master in appliance design.

competence with the software increases, operator creativity blossoms, stimulating more imaginative and freethinking possibilities in individual patient appliance design such that patient treatment demands trigger the imagination to build the appliance needed. The limitless possibilities available through the use of this tool mirror those of the human mind, so that imagination catalyzes the use of the software to create combinations to arrive at the imagined appliance.

These possibilities are not generated by some innate mechanism and instead require learning of both the digital tools available and the basic manual laboratory procedures required for appliance fabrication. An understanding of how to use the software must be accompanied by the manual dexterity and material understanding of a laboratory technician. The latter is normally part of specialty training in orthodontics, and the former requires applying one's imagination. It is not the intention of this book to present a complete how-to manual for orthodontists but rather to trigger this imagination in order to facilitate the design of customized in-house appliances that will help the individual orthodontist achieve specific treatment goals for the benefit of the patient as well as elevate the profession to a higher level.

Digital vs Traditional Laboratory Design and Manufacturing

In order to better understand the benefits of in-house custom orthodontic appliance design, a comparative description of the currently prevailing traditional laboratory manufacturing and 3D printing is essential.

A general comparison between traditional laboratory and 3D custom appliance design and manufacture is presented in Table 6-1. Customization is the biggest advantage of

Table 6-1 **Laboratory vs digital design and manufacturing**

	Traditional orthodontic laboratory	3D custom appliance design and manufacturing
Appliance customization	+	++++
Time required from impression to appliance delivery	+++	+
Number of materials used from impression to manufacture	++++	+
Required personnel from impression to office delivery	++++	+
Learning curve for designing	+	+++
In-house designing cost	++	$0
Cost from impression to office delivery	++	+++
Ability to combine different appliance materials	++++	++
Required workflow equipment	+	++++
Orthodontist's control over appliance design	+	++++
Ability to correct appliance defect after manufacture	+++	+
Software-sensitive procedure in design and manufacturing	NA	+++
Ability to fabricate flexible appliances	++++	+
Ability to fabricate single-material metallic appliance	+	++++
Biocompatibility of materials	++++	++++
Manufacturing system cost	+	++
Health hazard materials in manufacturing (eg, Co-Cr)	++	++
Flexibility in designing	++	++++
Options for manufacture location	+	++++
Internet integration with other orthodontists or laboratories	Not possible	++++
Molar band flexibility	+++	Zero flexibility
Titanium option	No	++++
Biocompatible PEEK option	No	++++
Possibility for in-house 3D printing	NA	++++
Direct aligner in-house printing	NA	+++
Integration of CBCT, face scan, intraoral scan in appliance design	NA	++++
Esthetic appliance design	+	+++
Possibility for in-house orthodontic laboratory	+	+++
Use of novel materials	+	+++
Blockchain implementation	NA	++++
AI implementation	NA	++++
Research in design and manufacturing	+	++++

digital design over traditional analog methods. Another significant advantage of 3D custom appliance design is the reduced time from impression taking to appliance delivery. Furthermore, with traditional "stock" bands, decalcifications and/or caries may result from cement wear or microleakage due to gaps between the band and tooth surface.[11] A customized band that is manufactured for a specific tooth on which it is to be placed can be conjectured to reduce this risk.

The armamentarium required for traditional design and manufacture techniques is also greater (eg, alginate, impression trays, disinfection liquid, water, stone); in digital design, besides a preexisting computer supplemented by an appropriate 3D printer, a UV curing unit and an isopropyl alcohol washing machine are needed. In the case of metal printing, there is also a need for a heat-treatment unit, polishing devices, etc. In some other instances, wires or acrylic may also be needed. Because the computer takes on more work in the digital method, this approach also requires fewer staff to design and print a customized appliance, albeit with a steeper learning curve. Whereas traditional laboratory manufacturing procedures permit combining different materials, this is not possible with current 3D printing capabilities (single-metal material printing). This combination of materials can be accomplished during postprinting procedures; ie, components can be added (hyrax screws, etc) after the basic appliance has been printed.

The designing cost using Meshmixer, given an appropriate level of competence, is nearly zero, while an external laboratory will apply a fee for this service. Currently, the cost of a printed appliance is generally higher than that of an appliance manufactured manually, but the trend is moving toward decreased costs. For example, the use of a selective laser melting (SLM) printer for orthodontic appliance printing bears an expensive upfront and materials cost, and this process also requires a postprinting procedure (debinding and sintering equipment); furthermore, the sheer size of the needed equipment makes it impractical for inclusion as part of clinic armamentarium. However, these costs are continuously dropping, and desktop versions that eliminate the laser component are under development, which would make this technology realistic and practical in a clinic.[12,13]

Although specialized software and equipment (ie, scanner) are needed to design orthodontic appliances, this affords the clinician a significant advantage in controlling appliance design when using CAD software such as Meshmixer. This does not happen with the use of traditional laboratory procedures; granted, the latter has a certain latitude in resolving manufacturing errors. The trade-off with customized printed appliances is high accuracy but less material flexibility. Therefore, any error in digital manufacturing cannot be corrected. For example, a printed cobalt-chrome (Co-Cr) band does not have any flexibility, as opposed to existing metal alloys used to manually fabricate orthodontic devices.[14] Printed appliances must result in perfect fitting, which cannot be adjusted for, whereas analog appliances afford a degree of formability chairside after completion of the laboratory procedures. Printed metallic appliances have low ductility, which can easily result in fracture; for this reason, they cannot be used to exert force or as springs. This is why metal printed appliances are often combined with conventional laboratory metals.

Another major advantage of 3D printing is that multiple biocompatible materials such as Co-Cr, stainless steel, titanium, and polyether ether ketone (PEEK) can be used. PEEK is a polymer that has excellent properties for medical or dental use and comes in different colors, mostly white shades, that are more esthetic than metal.[15] It is also possible to print some small orthodontic appliances in-house using stereolithography (SLA) 3D printers using Class II materials, and resins will soon become available to print in-house appliances more predictably and efficiently. An example is the recent release of denture base resins by NextDent, Formlabs, and other companies that gives the clinician the ability to print the denture base in the office. A major recent advancement is also the release of a hybrid ceramic resin by Formlabs and Bego for permanent crown printing. This resin is described in chapter 8 for customized bracket printing. Nevertheless, the health hazards associated with some of these materials must be considered. Co-Cr powder can cause allergic reactions and skin eczema, and a study confirmed possible pneumoconiosis in personnel inhaling Co-Cr powder.[16,17] For this reason, there is a tendency to use stainless steel or titanium as printing material.

In addition, the flexibility of digital design through the use of CAD software means that the appliance can be printed in various locations based on wherever the data is sent. Aligner design is also possible with the CAD software, which eliminates the need for the technician to perform several wax setups on dental casts to develop sequential aligners.[1,18] Direct aligner printing using a special resin is presented in chapter 10.

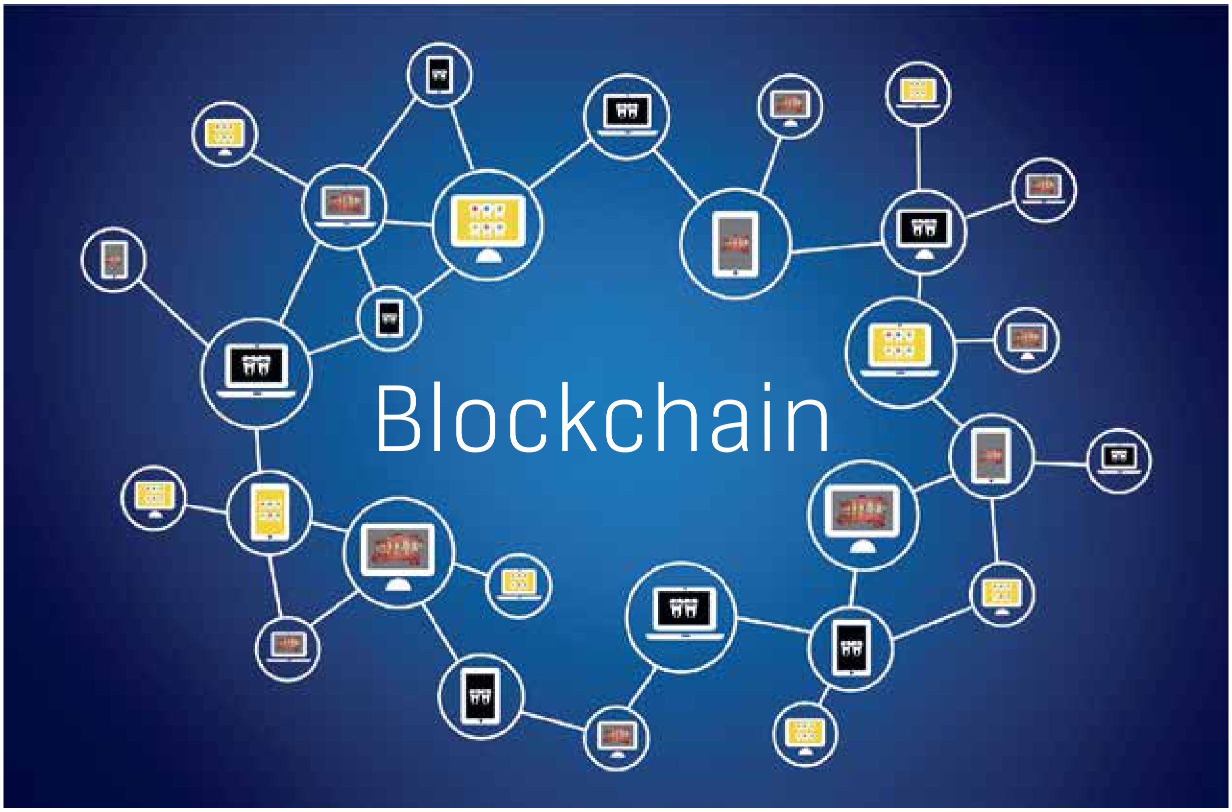


Fig 6-4 A future orthodontic blockchain network.

The cost of the materials and equipment used in digital design and 3D printing is decreasing, making the technology more attractive to increasingly more orthodontists. New materials are also being released that are opening new horizons in 3D printing (direct aligner printing resin, PEEK, etc).[19–21] The combined speed of the technologic advances in materials and equipment, decrease in costs, and reduced size of machines are paving the way for 3D metal printers to become part of the orthodontic office in the foreseeable future.

Artificial Intelligence and Blockchain in Digital Orthodontics

Orthodontics is a profession combining science and art that requires information synthesis and manual dexterity. Attention needs to be paid to practical matters like wire bending, analyzing force systems, choosing different kinds of brackets/prescriptions, etc. Presently, these are influenced by clinical experience and educational background. However, increasingly, human endeavors are cataloged digitally with pooled information being analyzed by deep learning software (artificial intelligence [AI]). Analogous environments could be made to serve as an assistant to every orthodontist in the world. Case data may be transferred to a central AI server, which will gather information from multiple orthodontists worldwide, helping in diagnosis and treatment planning and proposing appliance design options.[22–25]

Another possible technologic advancement that could be used is blockchain. Initially developed for use with cryptocurrency (Bitcoin), it has also found other applications in medicine and real estate. To explain blockchain, Dr Cécile Monteil proposed to use a simple metaphor called the “magic notebook.” She suggests imagining a notebook with numerous copies simultaneously held by different people in various locations. Each copy would be the mirror image of each other so that if something is written in one copy, it will instantly appear in every other copy, meaning that the magic notebook is always in sync (Fig 6-4). Blockchain has no central authority or leader like a president or a CEO; rather, it is controlled by the people using it. Decisions are made by consensus from the community, so the more people that are involved, the more trustworthy the network becomes. Dr Monteil states that the main idea of blockchain is to create a new form of trust when there is a need to trace and share data across multiple parties with a high standard of security, with a possibility to be able to verify the integrity of all the data.[26] For the purposes of orthodontic treatment, this implies that data from many digital orthodontic practices concerning digital appliance design treatment choices could be easily shared over a blockchain, helping orthodontists to design their appliances, visualize examples of treatments or other designed appliances, as well as benefit from the experience and errors of colleagues. Therefore, blockchain is suitable for applications where independently managed biomedical/health care stakeholders (ie, hospitals, providers, patients, dentists, orthodontists) wish to collaborate with one another without ceding control to a central management intermediary.[27] Furthermore, this community-driven access to data could be useful in administering clinical trials and research, which could be conducted from multiple institutions/clinics in a simplified manner.[28–30]

Both AI and blockchain are emerging tools that could be adopted by health care companies or orthodontic societies that contain many orthodontists whose participation would be mutually beneficial. In any event, the data from CAD appliance design can be used to contribute to this essential database.

The CAD Software: Meshmixer

As previously stated, it is not the intention of this chapter to present a manual for using Meshmixer. Rather, its main tools will be presented together with practical examples of design to demonstrate the capabilities of the software as well as to guide the orthodontist in creating the appliance needed for a specific patient in a fully in-house customized manner. Understanding these main tools and the way they work will free the mind of each orthodontist to design new orthodontic appliances.

General tools for simple appliance design

Any specialist in orthodontics realizes that a cookbook approach to treatment cannot be adopted to guide its performance. Similarly, there is no such mechanism in Meshmixer that will serve to exclude analytical thought from the process of designing patient-specific appliances. Reading the manual and understanding the tools while "playing" with the software is the proper method and essential to start designing.[8] Watching tutorial videos on YouTube as well as those of experienced operators will supplement and enhance the learning process. Learning from our mistakes and trying to find ways to correct them is the best way to become an expert in designing.

Dedicated orthodontic CAD software for appliance design, such as Orthoanalyzer, differs from a more general CAD software such as Meshmixer in that it offers several tools that can help the operator to design virtual appliances.[6] This difference is ultimately advantageous for the more general CAD types of software because they are unencumbered by the preset/provided appliance design possibilities accompanying the former. As a corollary, this requires a more prolonged learning phase. This in turn enhances the ability of the operator to make use of its spectrum of utilities, allowing for a much larger range of design options and complexity. In order to facilitate the learning process and to improve the user interface, Meshmixer has been coupled with the Shapr3D iPad app. This makes it possible for the user to design forms in an intuitive fashion directly onto the device screen with the use of a wireless pencil. These renderings are then imported into Meshmixer for further editing.

CAD software such as Meshmixer also provides an incorporated library containing a large number of 3D geometric shapes such as cylinders, cubes, triangles, cones, boxes, planes, rhomboids, spheres, etc, not all of which are directly applicable for use in orthodontic appliance design. In addition, there are also available files of preformed numbers, letters, animals, and symbols, which are useful in creating labels on items such as study models or designed appliances (Fig 6-5). Shapes/forms such as these can be cut, decreased in any dimension (x, y, z planes) uniformly or not, and combined or altered to form other objects by using Boolean operations. Boolean operations are a subset of algebra and are frequently used in CAD software.[31] Meshmixer provides three such tools: union, difference, and intersection. To demonstrate these applications, a description of the recommended method for designing customized appliances is presented here.

This approach entails importing the 3D virtual dental casts of the patient into the software and then using several

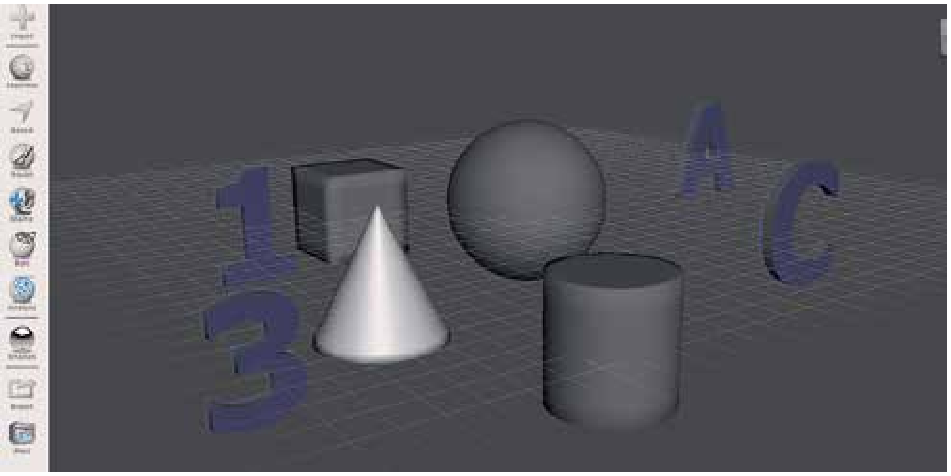


Fig 6-5 Different shapes, letters, and numbers to be used in the Meshmixer software.

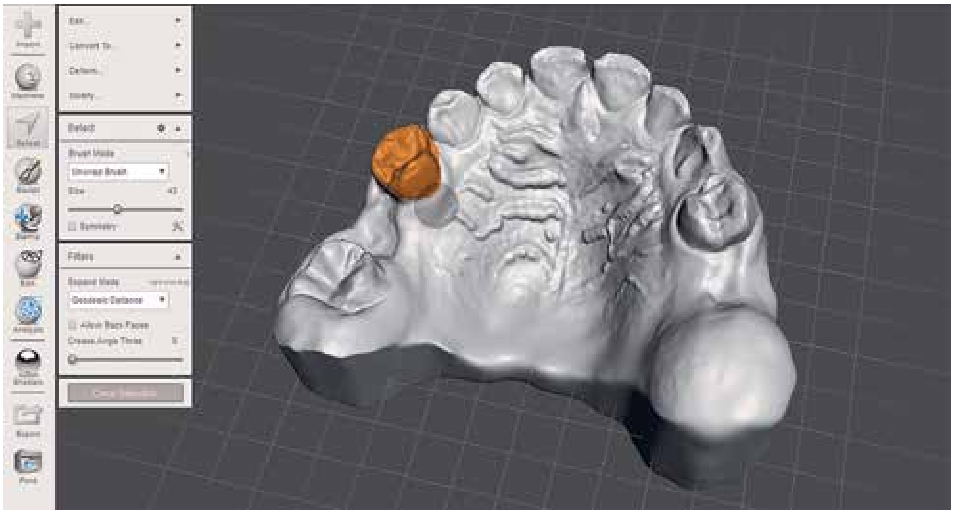


Fig 6-6 Selection tool in the Meshmixer software.

tools to virtually construct the appliances directly onto them. Once it has been imported, the **SELECTION** tool can be used to perform several tasks such as erase, reduce, remesh, offset, extrude, and/or extract the selected parts (Fig 6-6). A **STAMP** tool can also be used, which provides the operator a shortcut to "stamping" or placing a preset form where it is perceived to be needed and then transforming it into the desired final object by selecting it and performing the required manipulations. Additionally, the **EDIT** tool can be employed to perform various changes to the 3D object such as mirroring, duplication, transformation, plane cut, solidifying, hollowing, etc. Another tool called **SCULPT** can be used to change the shape of the area that is selected.

Meshmixer provides an **ANALYSIS** tool that inspects possible errors and corrects them and supplies technical data such as dimensional measurements. It is also possible to add colors to parts of an object by using the **SHADERS** tool, but colors cannot be printed in an SLA or powder bed fusion (ie, SLM) printer. The **PRINT** tool allows printing of the designed object provided that there is a link between the Meshmixer and the printer before using the command. **EXPORT** of the designed appliance can be done in several 3D file formats (STL, PLY, OBJ, etc). Familiarity with all the tools and commands is essential for software learning. For each tool, it is suggested to refer to the help menu, the manual, or tutorial videos.

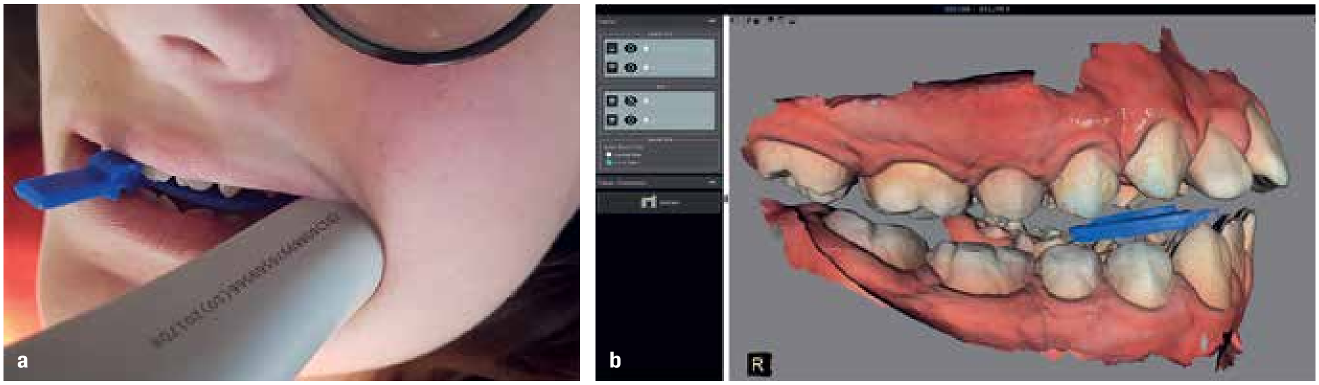


Fig 6-7 *(a)* Surface scanning of the dental arches in the working registration bite position. *(b)* Surface scan achieved.

In-House Custom Design of Specific Appliances

Modified Twin Block: The DIGI-TWIN appliance

The DIGI-TWIN appliance can be manufactured in two different ways. First, it can be designed in Meshmixer before models are printed and the appliance is created using thermoforming plastic foil. Second, the appliance can be designed in Meshmixer and then the data can be imported into DeltaFace software for virtual design of the appliance prior to being printed directly via 3D printer.

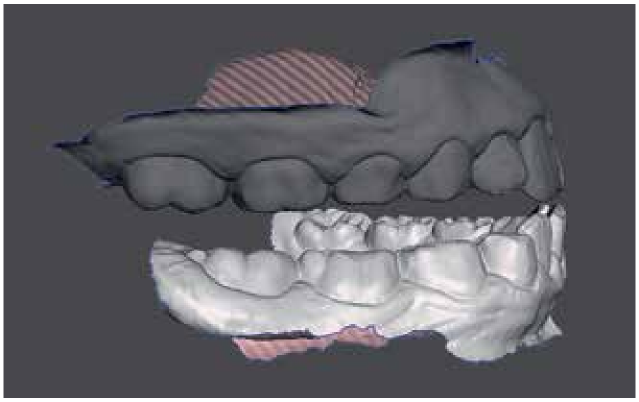


Fig 6-8 The dental arches automatically positioned in Meshmixer.

Appliance manufacture using thermoplastic foils

Dr William Clark's Twin Block appliance was proposed as an alternative to the family of monoblock functional orthodontic appliances to permit more comfortable full-time use and harness occlusal forces as a mechanism in mandibular advancement.[32] For the laboratory manufacture of this appliance, specific guidelines have been established (inclination of the blocks, etc). Designing this appliance in the virtual environment of the Meshmixer permits further refinements with the goal of fabricating a clear as well as a comfortable appliance within a clinical setting.

First, the maxillary and mandibular units are digitally designed according to the standard guidelines of Dr Clark. Following this, all necessary patient diagnostic records, including an intraoral scan in maximum intercuspation/centric occlusion (in this case using the CS3600) are gathered. A digital construction bite is attained using a special intraoral gauge, as shown in Fig 6-7a, moving the mandible forward to the desired corrected position, where this relationship is also scanned (Fig 6-7b). It should be noted that multiple jaw positions can be scanned and kept as separate files.

The next step is to import the construction bite and digital dental casts into the Meshmixer, which positions these automatically as they were scanned and oriented (Fig 6-8). At this time, the preformed bite blocks created initially are positioned onto the appropriate area of the scanned dentition, taking care that the opposing surfaces of the upper and lower blocks are parallel. To improve retention of the appliance in this case, several teeth were augmented with temporary "male" projections corresponding to "female" profiles on the DIGI-TWIN appliance. If leveling of the mandibular arch is needed, virtual elongation of the premolars is performed to create space for premolar eruption (Fig 6-9). If expansion of the maxillary arch is needed, the maxillary dental cast can be digitally duplicated so that each reconstruction will include a 0.2- to 0.4-mm sequential transverse increase. In this way, every 4 to 5 weeks, a new maxillary DIGI-TWIN unit will be delivered to achieve this requirement.

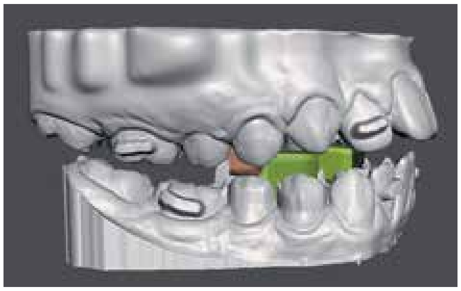


Fig 6-9 The two maxillary and two mandibular blocks that were designed are positioned on the teeth.

Fig 6-10 The dental models printed on the 3D printer's platform.

Fig 6-11 The DIGI-TWIN block appliance in the mouth.

The final steps are to export the files and print them in the office 3D printer using a dental model resin (Fig 6-10) and proceed to postprinting procedures for residual resin removal and UV curing. In this case, using a positive pressure thermoforming machine, two clear DIGI-TWIN appliances were created for each dental arch, one from 0.5-mm and the other from 1.5-mm Duran foil (Scheu). The former was used as a mold for the male projections attached to the teeth, and the latter was worn as the actual DIGI-TWIN functional appliance. An example of the appliance is shown in Fig 6-11. In treatments that required a stepwise mandibular advancement, cold cure acrylic resin was applied onto the lower block inclined plane, or it was reprinted in a more forward anteroposterior relationship. Golfeshan et al reported on the use of an analogous appliance where less mandibular incisor proclination was found than reported with the classic Twin Block appliance.[33]

The same procedures can be slightly modified and applied to manufacture a hybrid functional appliance that can correct a transversely inclined occlusal plane on a Class II, division 1 malocclusion. The areas requiring leveling of the occlusal plane to allow for posterior tooth eruption are planned into the appliance so that the prescribed tooth eruption will transpire with the anteroposterior correction (Fig 6-12).

Appliance design and direct 3D printing

Alternatively, the DIGI-TWIN can be designed in Meshmixer and then imported into DeltaFace, where the two upper and lower splints are designed (Fig 6-13). In this specific case, buttons were previously designed in order to be placed on the anterior labial part of the appliance. These could serve to attach elastics in case the patient failed to keep the upper and lower blocks in contact, especially during nighttime. Following the design, the files are sent to the 3D printer to be printed using a special resin (Fig 6-14). The resin used in this case was OrthoClear by NextDent, which is a clear hard resin for splint printing.

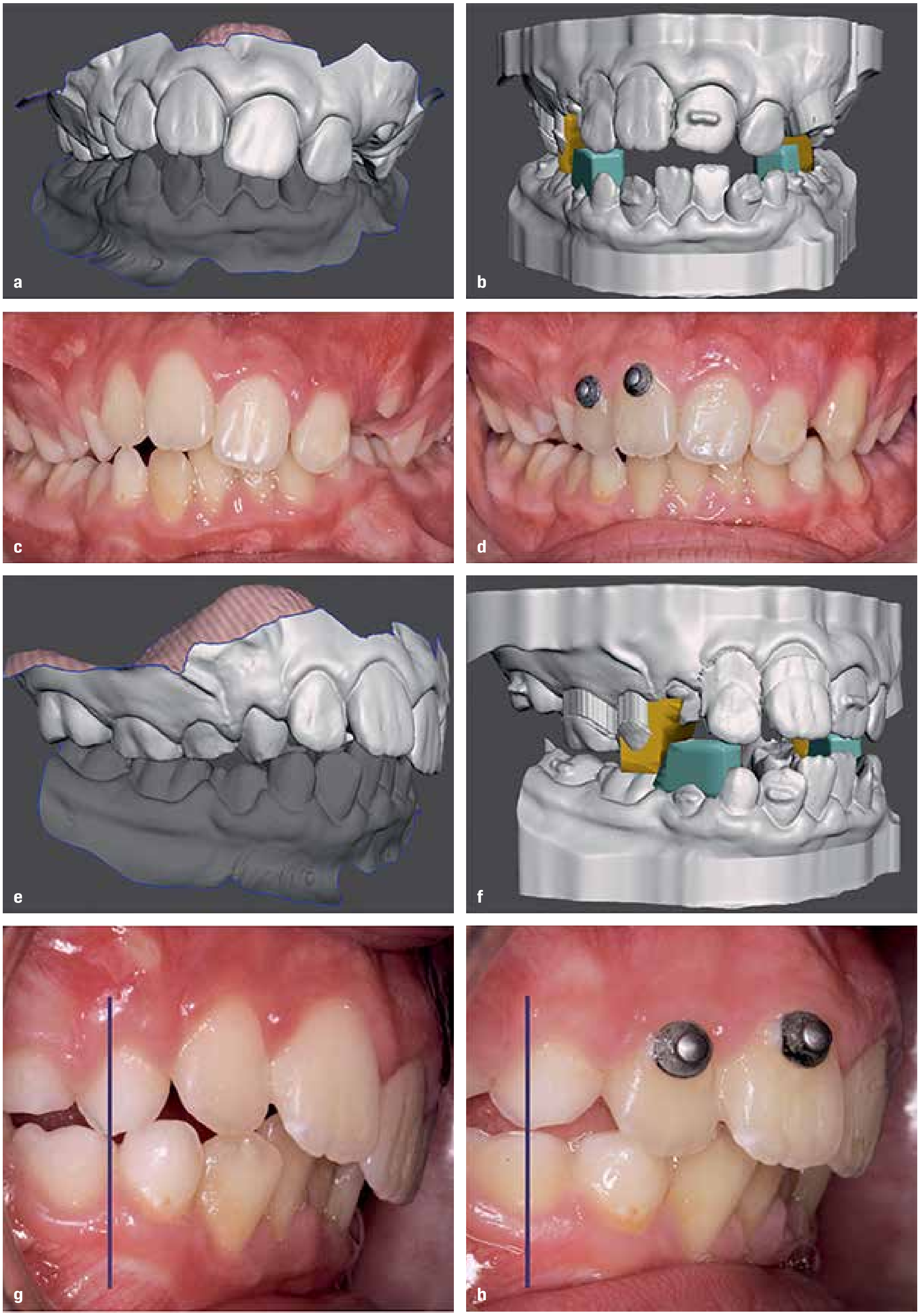


Fig 6-12 *(a to h)* Digital workflow of a hybrid functional appliance.

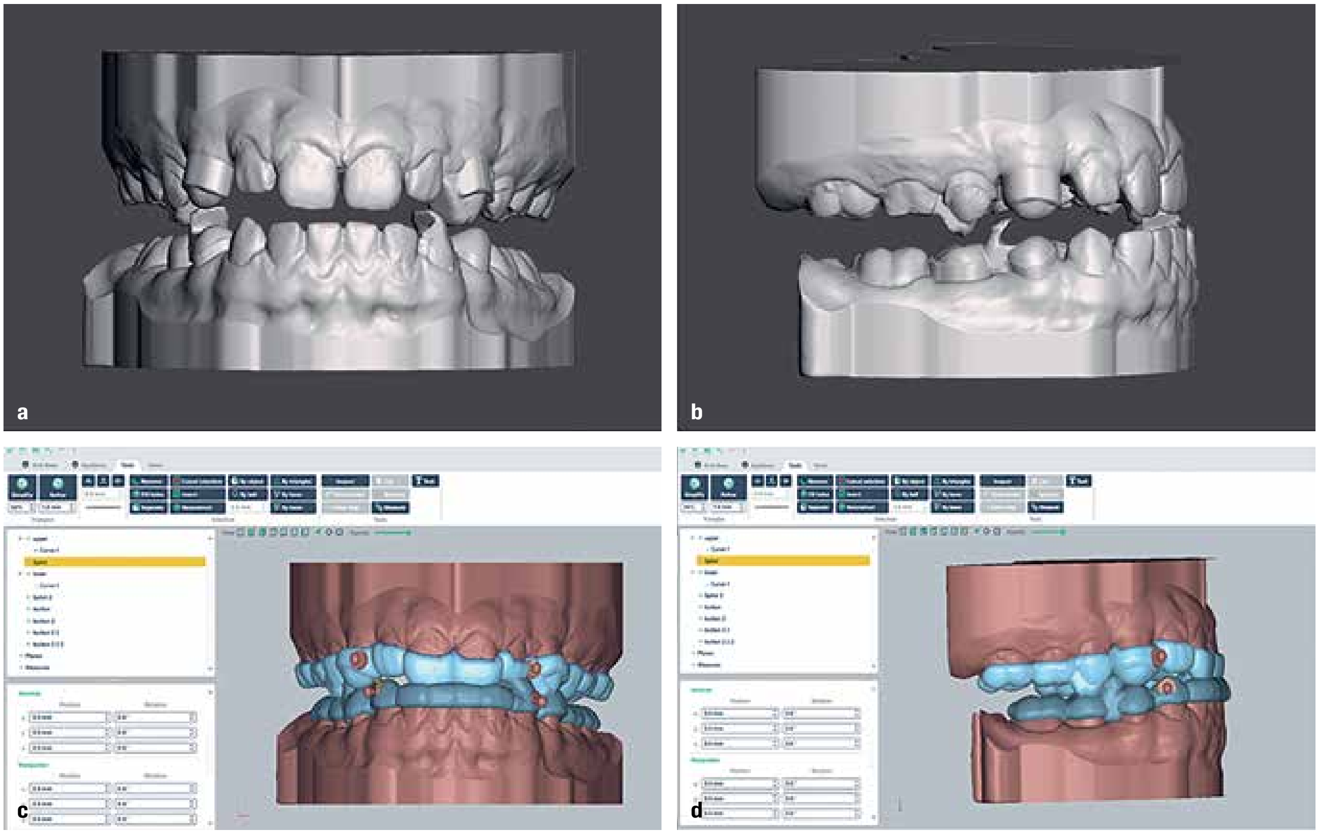


Fig 6-13 *(a to d)* Design in Meshmixer and DeltaFace.

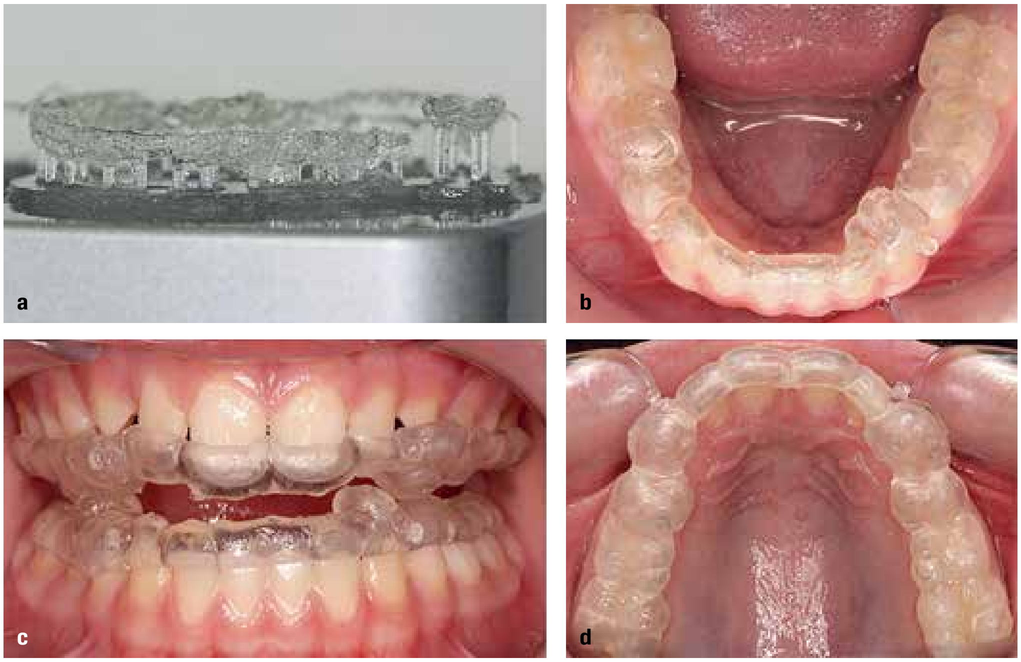


Fig 6-14 *(a to d)* DIGI-TWIN appliance printed via 3D printer.

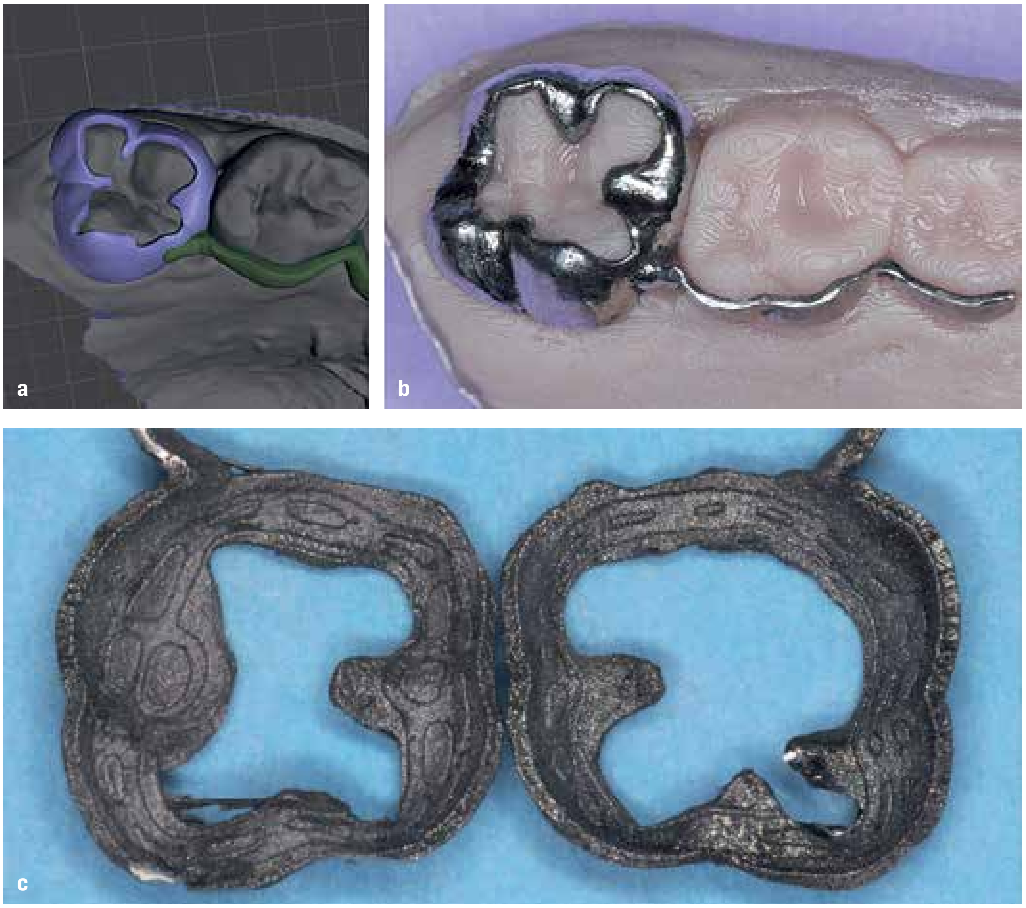


Fig 6-15 *(a)* Band design in Meshmixer. *(b)* Customized band. *(c)* Band retention mesh.

Band design using Meshmixer

In order to design any appliance, a 3D dental cast must be imported into Meshmixer. The area where the band is to be located must be selected using the "select" tool. In situations requiring intimate band seating (ie, banded RPE with extensions), it is better to extend the selection further on the buccal and lingual grooves of the molar to act as a key (Figs 6-15a and 6-15b). To improve retention after band cementation in this case, a customized mesh base was designed (Fig 6-15c). This, together with the aforementioned extensions of the band, were found to enhance device retention. The primary author noted that almost no failures were observed in the printed appliances.

After several trials, it was decided that the band thickness should be 0.6 to 0.7 mm. This applies when printing with Co-Cr but will require empirical reassessment if other materials such as stainless steel or titanium are to be used for the same purpose.

At this point, the band is ready for exporting and metal printing.

Lingual holding arch

The lingual holding arch (LHA) appliance is designed by first selecting the areas where the bilateral bands will be seated as described previously and then creating a customized wire connecting them using the same tool. Essentially, three separate forms are produced in this manner that are fitted together using the "combine" tool to form a single object (Fig 6-16a). The wire has a flat ribbon shape with a labiolingual thickness of 0.6 to 0.7 mm.

The use of a digitally designed flat-faced LHA permits exact adaptation to the lingual morphology of the teeth and permits offsetting its location without enlarging the diameter of the wire, which could be uncomfortable for the patient (Fig 6-16b and 6-16c). These capabilities are superior to the currently produced laboratory devices, which

Fig 6-16 *(a)* LHA in Meshmixer. *(b)* Completed printed LHA seated on the dental cast. *(c)* LHA seated intraorally.

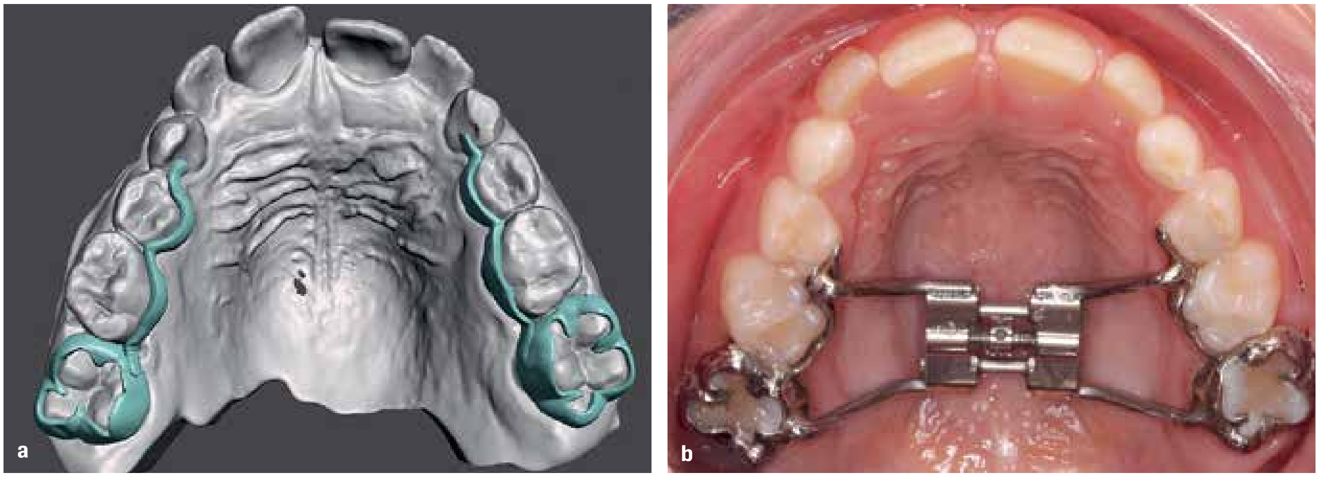


Fig 6-17 *(a)* Customized bands and palatal arms in Meshmixer for the manufacture of an RPE. *(b)* Printed RPE seated intraorally.

require several chairside appointments to fabricate using a laboratory-supplied thick round wire that at best provides single-point contact with the dentition.

The LHA shown here was printed using Co-Cr, currently the most commonly used material for such purposes; however, other materials can be considered for either 3D printing or milling of this appliance such as PEEK or polymethyl methacrylate (PMMA).

RPE

The RPE is also a multiband (typically two or four) supported orthodontic device. Its framework design is undertaken as described previously for the LHA (Fig 6-17). However, presently it is not possible to include the hyrax screw element directly into the digital form. In this instance, a dental model needs to be printed to enable its soldering to the bands.

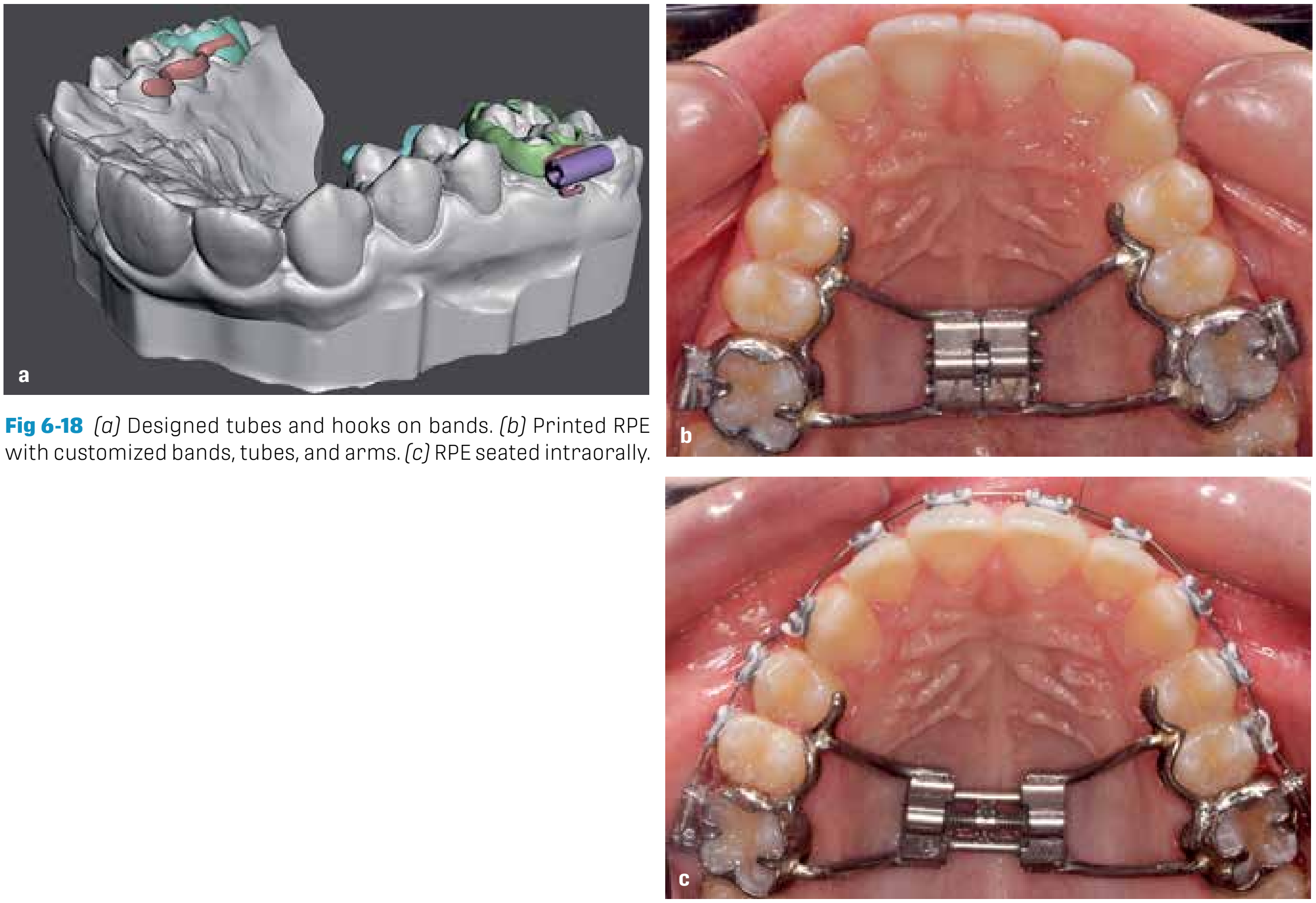


Fig 6-18 *(a)* Designed tubes and hooks on bands. *(b)* Printed RPE with customized bands, tubes, and arms. *(c)* RPE seated intraorally.

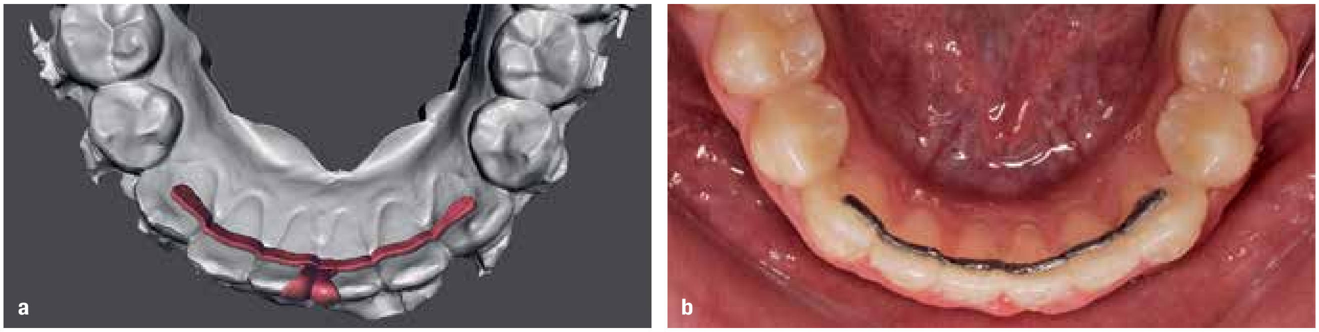


Fig 6-19 *(a)* A tailor-made 3-3 fixed lingual retainer. A placement guide is added for accurate bonding. *(b)* Co-Cr printed fixed lingual retainer.

The bands can also be supplemented with designed buccal surface tubes and hooks for attachment to the bands. In this way, the RPE bands can be utilized together with other fixed labial orthodontic appliances (Fig 6-18).

Customized fixed lingual retainer

The design of a fixed retainer is similar to that of the lingual archwire with the added recommendation that a placement guide at the central incisors is included as an aid for accurately orienting it during bonding (Fig 6-19a). As with the LHA, the shape of the fixed retainer is ribbonlike, whose dimensions are 1.0 × 0.5 mm (Fig 6-19b). Co-Cr is the most often used printing material for this purpose; however, its hardness precludes bonding it across an entire tooth segment, which is contraindicated where physiologic tooth movement is desired. Rather, it is advisable to do so only to the canines, as recommended by Zachrisson and Büyükyilmaz.[34] Other materials can also be used to print the retainer, such as stainless steel or titanium.

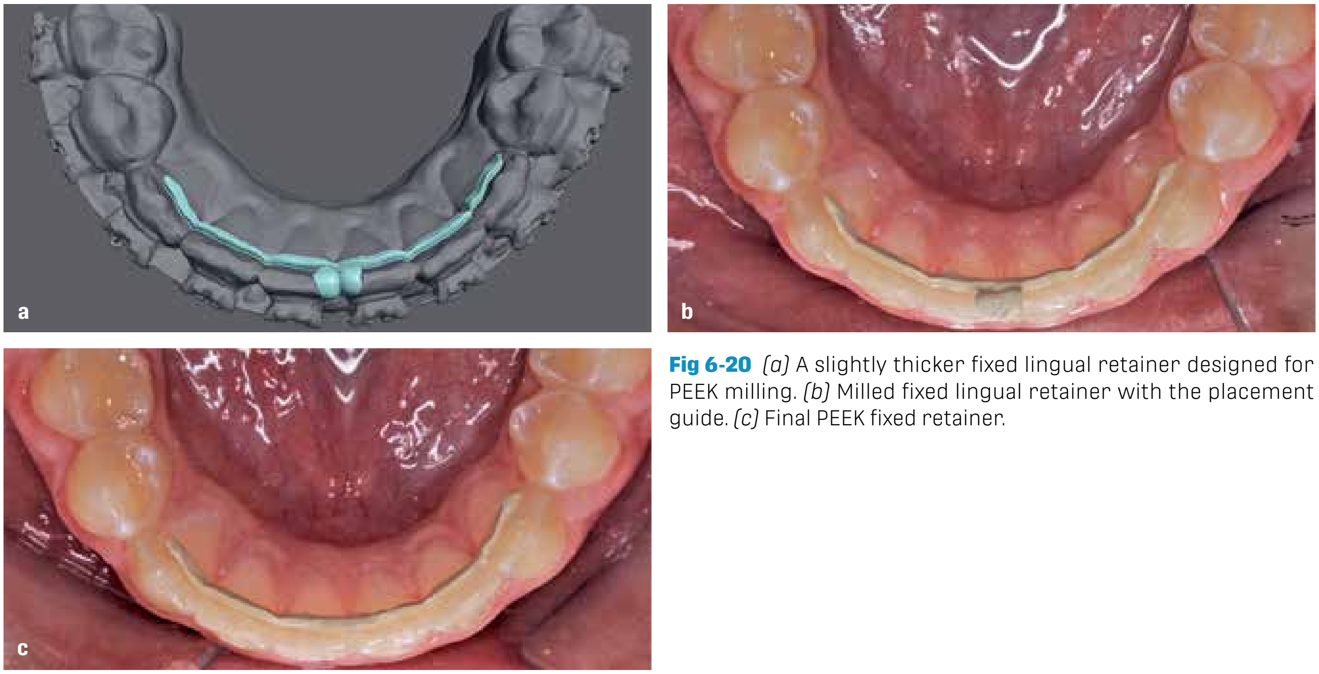


Fig 6-20 *(a)* A slightly thicker fixed lingual retainer designed for PEEK milling. *(b)* Milled fixed lingual retainer with the placement guide. *(c)* Final PEEK fixed retainer.

Fig 6-21 A custom-designed fixed lingual retainer printed in resin polymer.

Customized fixed lingual retainers can also be milled, as described in Fig 6-20. In this example, PEEK underwent subtractive manufacturing in a dental CNC milling machine. This material possesses greater flexibility than Co-Cr, which permits normal periodontal ligament behavior, allowing bonding to all teeth in the prescribed dental segment. Its dimensions should be slightly larger than those used in Co-Cr printing.

Presently, there is only one biocompatible PEEK material: EVONIK (RAG-Stiftung). It is provided in a filamentous form for use in an FDM (fused deposition modeling) 3D printer, which could in theory be used for in-house printing of custom appliances. The biocompatible filament material is relatively expensive and is currently utilized with specific medical FDM printers for fabricating prosthetic implants. (Most PEEK printers are not suitable for medical or dental biocompatible printing due to the materials used in their construction and lack of proper regulatory compliance.)

Fixed lingual retainers can also be printed from resin polymers rather than metal. For example, NextDent C&B Micro Filled Hybrid resin, a biocompatible material developed for crowns and bridges, was used in Fig 6-21. An advantage of using this material is that the retainer can be printed in-house in as little as 20 minutes. The retainer was made slightly thicker to give it more rigidity and hardness, and it was bonded using adhesive resin cement.

The traditional method of delivering a fixed orthodontic lingual retainer entails its fabrication from a multistranded stainless steel wire either directly on the patient or on a plaster dental cast. These are both labor-intensive and time-consuming. Alternatively, a dead-soft wire can be adapted directly; however, its ease of formulation detracts from its effectiveness as a retainer. Furthermore, although fixed retention has reduced the need for patient compliance and has overall improved clinical stability of certain treatment outcomes, it is sometimes associated with inadvertent complications. It has been proposed that the risk of these detrimental tooth movements can be reduced if the lingual retainer is constructed so as to be totally passive when

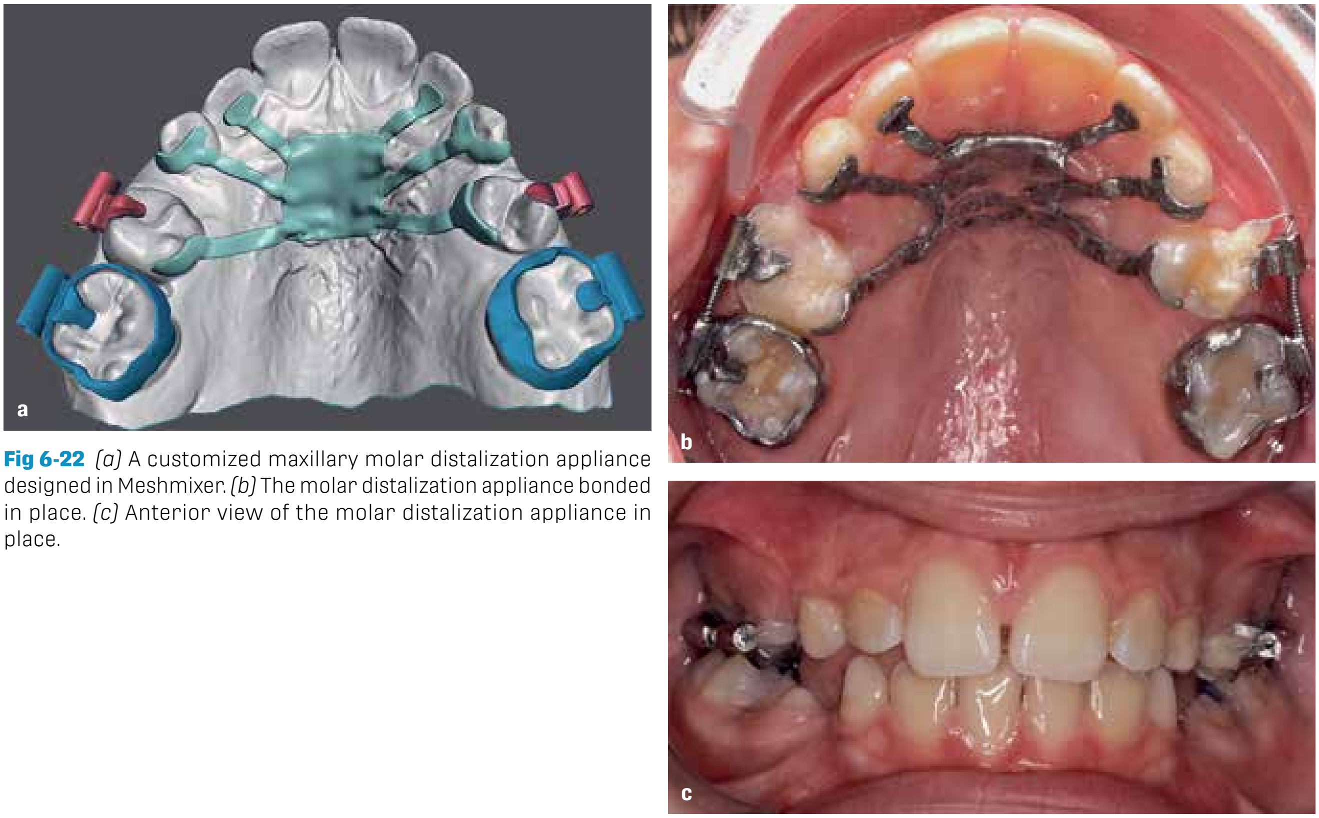


Fig 6-22 *(a)* A customized maxillary molar distalization appliance designed in Meshmixer. *(b)* The molar distalization appliance bonded in place. *(c)* Anterior view of the molar distalization appliance in place.

placed.[35] Given the differences in fabrication and materials used between manual and digital methods, it would seem logical that this could best be achieved with the latter.

Customized maxillary molar distalization appliance

The need to unilaterally distalize a maxillary molar that has drifted forward in order to regain space can be achieved using a customized appliance digitally designed for this purpose. Bands can be designed in Meshmixer and the required tubes added using Shapr3D. In Fig 6-22, the anterior part of the appliance that contacts the palate was designed using the same tools used in band and lingual arch design. Extension arms for stability of the appliance and enhanced anchorage can be designed according to patient-specific needs.

In the present example, stainless steel archwires (0.018") and open coil springs (0.010 × 0.030 inch) were used to distalize the maxillary right and left permanent first molars. The appliance abutments were designed with meshed bases and were bonded to the dentition using adhesive. Adequate space was gained after 3 months of wear, with no need for reactivation.

Modified customized maxillary molar distalization appliance

The appliance shown in Fig 6-23 is similar to and presents a modification of the previous example. Here, "power arm"–like extension arms were designed in Shapr3D and combined with tubes on the palatal surface of the maxillary first molars positioned at the level of the center of resistance to achieve bodily movement.

Starting from the molar tube, a round wire (1 mm in diameter) was extended through an open coil toward the anterior tubes. The wire was virtually joined in Meshmixer with the molar tubes so that as the molars moved distally, it would slide through the anterior tubes (Fig 6-23).

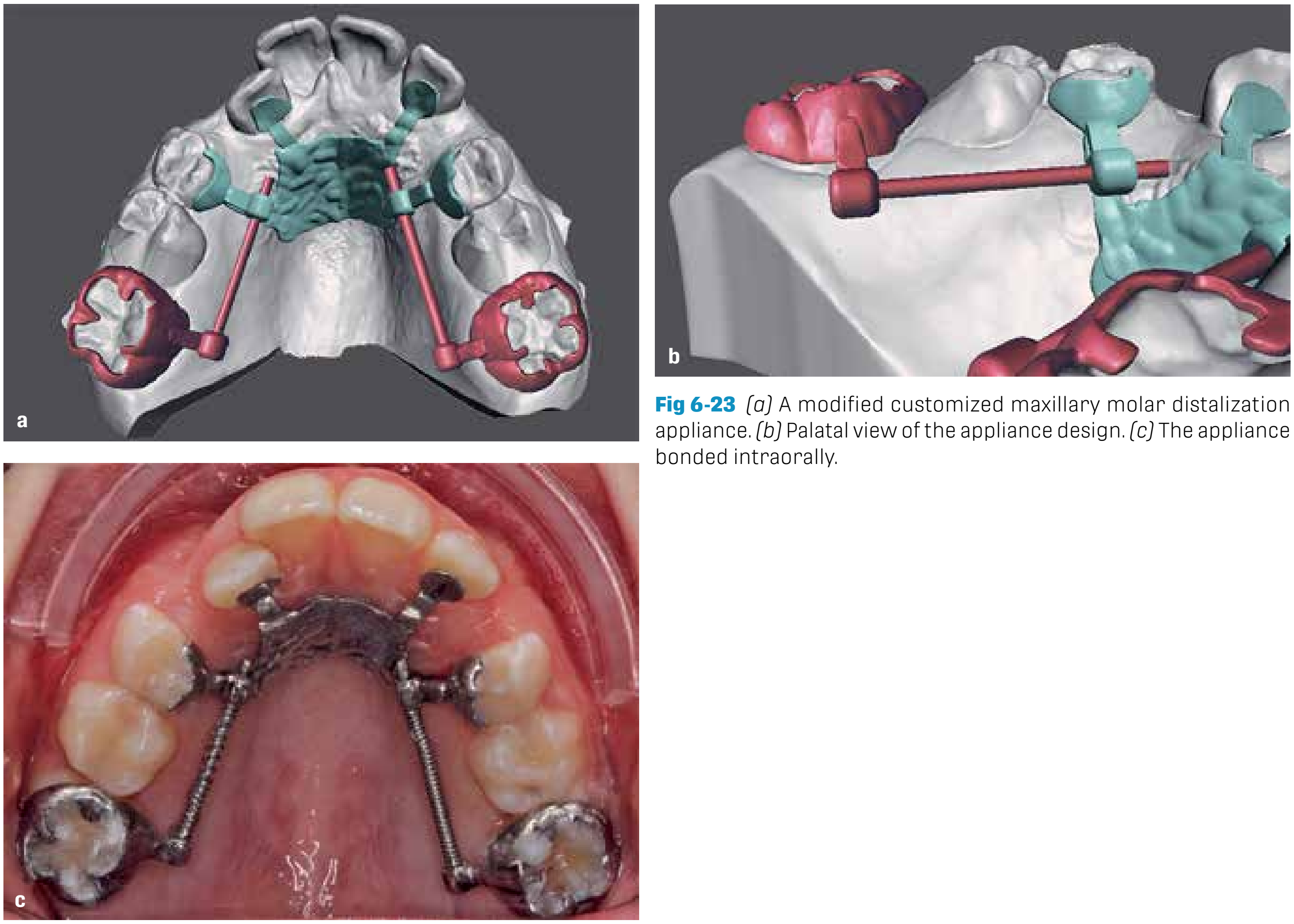


Fig 6-23 *(a)* A modified customized maxillary molar distalization appliance. *(b)* Palatal view of the appliance design. *(c)* The appliance bonded intraorally.

Customized Class II corrector

When presented with an Angle Class II molar relationship where it has been determined that correction requires nonextraction and maxillary molar distalization, several treatment modalities are available. One effective method is the use of a Class II corrector (Fig 6-24a), such as the Carrière Distalizer (ClassOne Orthodontics) introduced by Dr Luis Carrière in 2004 based on the modular sectional arch.[36–38] Its mechanism of action is driven by the use of Class II elastics to generate a distopalatal rotation of the maxillary first molars while moving the canine-to-molar segment distally en masse. Presently, this device is available in metallic and acrylic versions, and the clinical effects of this appliance have been previously reported.[39–42]

The flexibility of CAD design allows the orthodontist to develop Class II correctors tailor-made for a specific patient. For instance, the base of the corrector can be adjusted to allow for intimate fitting of the appliance onto the molars and canines to which it is meant to be bonded, and bonding guide extensions can be included to simplify even more its intraoral placement. The marketed appliance requires that a necessary "best fit" bonding approach be used. The posterior/molar component is provided as a ball-in-socket joint for molar rotation mentioned. Unfortunately, this arrangement also generates molar distal tipping and canine extrusion, side effects that may or may not be desirable (Fig 6-24b). This is where custom modification of the appliance can be especially helpful.

These Class II distalizers utilize the mandibular arch as the anchorage unit, as described by Carrière.[38] In order to achieve this without untoward effects on the mandibular molar where the elastic is attached, a removable vacuum-formed retainer/appliance covering the clinical crowns of the mandibular dentition is required. In the example shown in Fig 6-24, 1-mm Duran foil was used for the fabrication of the retainer. Class I canine and molar relationships were achieved in 5 months (Figs 6-24c to 6-24h).

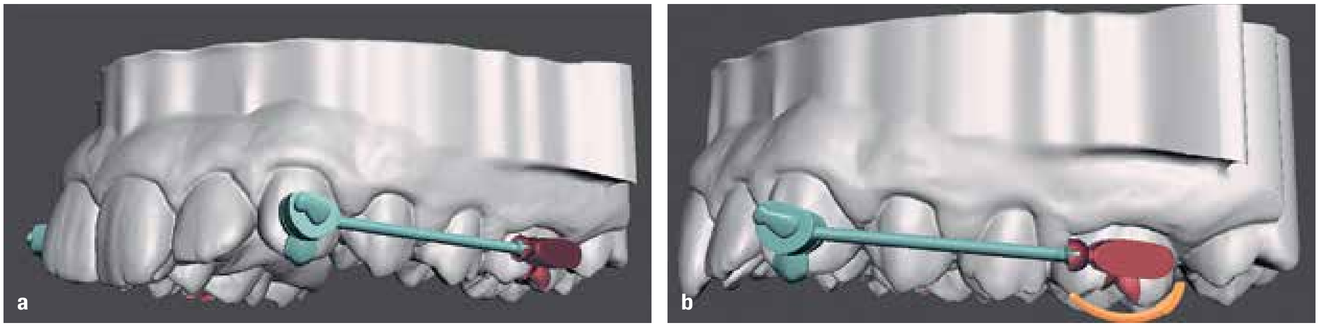


Fig 6-24 *(a)* Customized Class II corrector. *(b)* Distal tipping of the molar that can occur with en masse movement of teeth. *(c to f)* The Class II corrector bonded on the maxillary arch. *(g and h)* Class I canine and molar relationships achieved after 5 months.

Class II T-corrector

To avoid the distal tipping of the molar as described earlier, a T-shaped joint was designed that allows only a horizontal molar movement (Fig 6-25a). An elastic hook gingival to the front aspect of the appliance was also designed and included in order to create a line of force closer to the center of resistance of the tooth to prevent canine tipping (Figs 6-25b to 6-25d), with the caveat being that this should not be too high to avoid excessive vertical forces when Class II elastics are used. In the mandibular arch, first or second molar tubes need to be bonded, and a vacuum-formed removable retainer must be constructed as above.

Tubes can also be created on the canine component of the appliance for wire insertion. This modification allows the use of the appliance as an anchorage device for anterior tooth retraction after a Class I canine relationship is achieved. The T-corrector as shown in Fig 6-26 was used

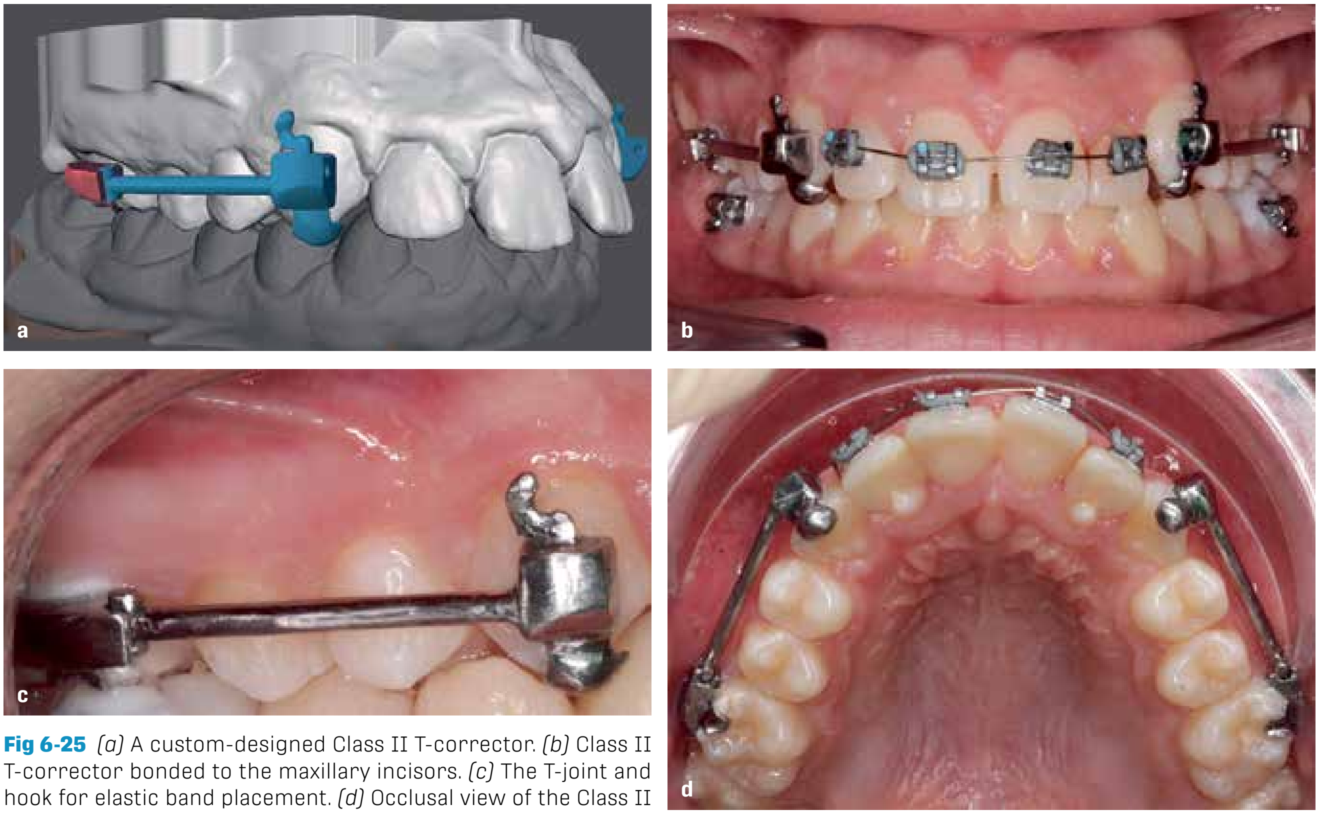


Fig 6-25 *(a)* A custom-designed Class II T-corrector. *(b)* Class II T-corrector bonded to the maxillary incisors. *(c)* The T-joint and hook for elastic band placement. *(d)* Occlusal view of the Class II T-corrector.

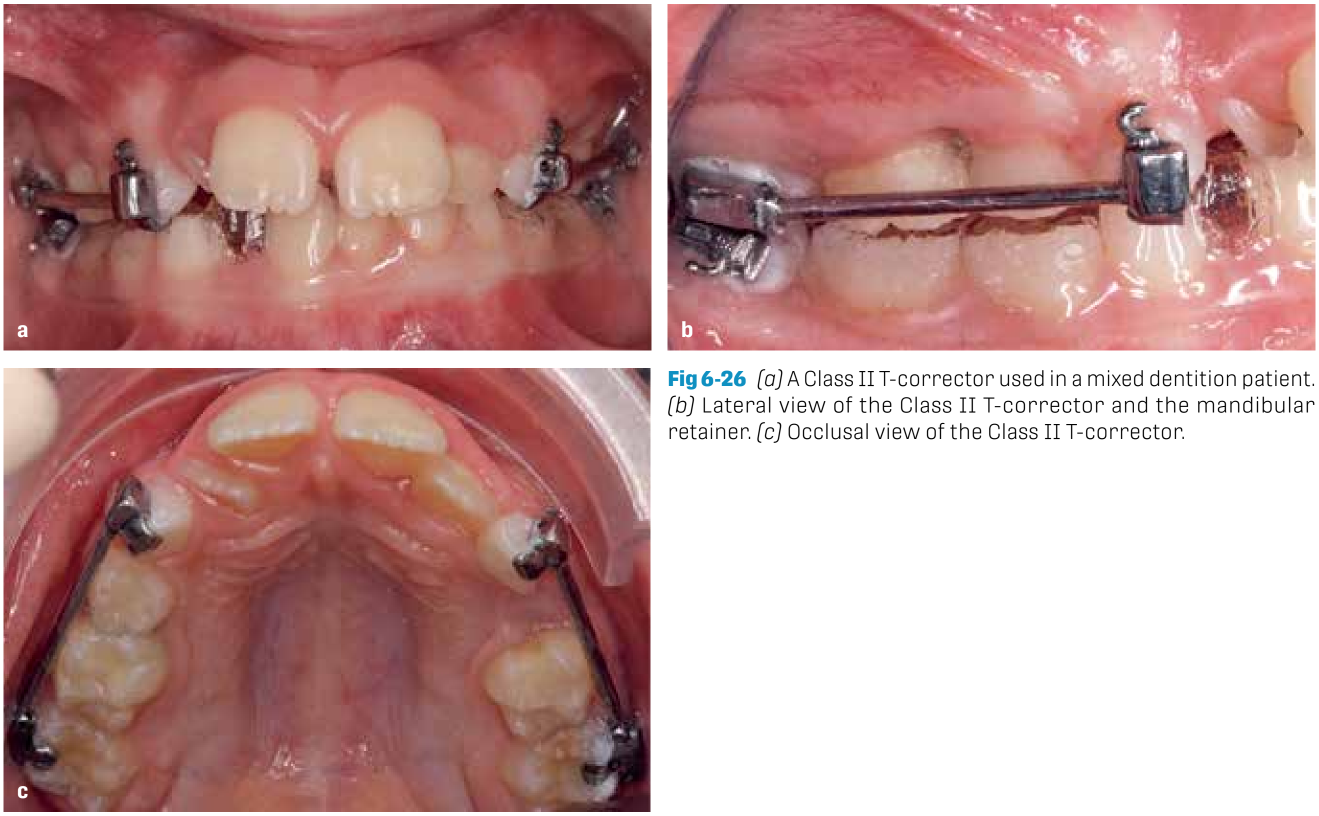


Fig 6-26 *(a)* A Class II T-corrector used in a mixed dentition patient. *(b)* Lateral view of the Class II T-corrector and the mandibular retainer. *(c)* Occlusal view of the Class II T-corrector.

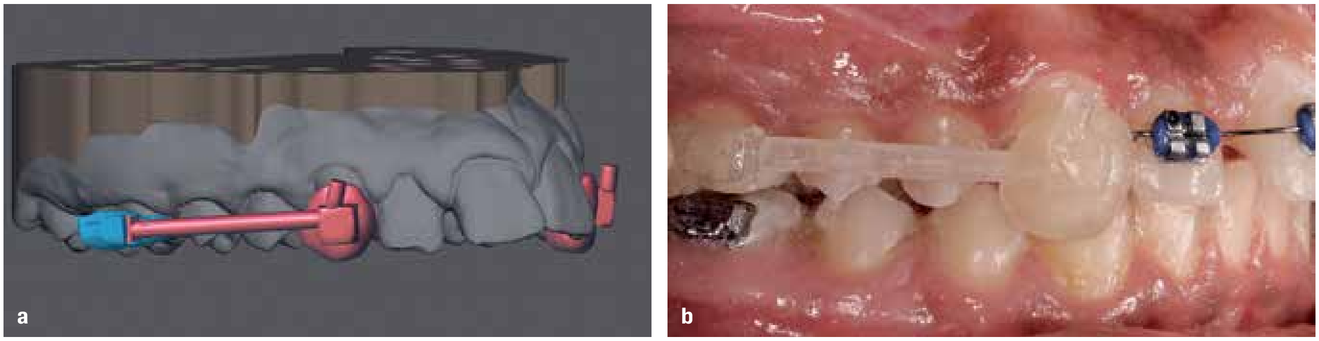


Fig 6-27 *(a)* Modified Class II T-corrector designed in Meshmixer for a Class III malocclusion. *(b)* Class II T-corrector printed in office with NextDent OrthoClear resin.

in the case of Class II malocclusion in the mixed dentition. Note the tubes on the canine part for wire insertion. After Class I achievement, the appliance will be used as an anchorage device to retract the maxillary incisors on a rectangular wire. The use of this appliance was without any bond failures, probably due to the customized bases and the occlusal keys of the corrector.

The Class II T-corrector can also be used in a Class III malocclusion as a one-piece appliance with no T joints. The author used NextDent OrthoClear resin to print a Class II T-corrector in-house for this purpose. The corrector was designed slightly differently; the molar and canine parts covered a more significant part of the teeth in order to give more stability and rigidity to the device, while the bar extending from the canine to the molar was thicker (Fig 6-27a). The total time for printing the appliance was 25 minutes in a 100-µm resolution using the Moonray S DLP printer (SprintRay) installed in the author's office. The clear Class II corrector was bonded on the teeth using adhesive resin cement (Fig 6-27b). No failures with this method have been observed, and the patients were satisfied due to appliance transparency.

Class II T-corrector combined with an RPE

In an attempt to expand and at the same time start correcting the Class II dental malocclusion, the hybrid appliance shown in Figs 6-28a and 6-28b was designed. The T-joint was designed to allow the movement of the bar as the dental arch was expanded; however, rotation of the molars was not possible due to the rigidity of the RPE (expansion screw was removed after 5 months). Progress intraoral photographs and scanning performed after 2.5 months of appliance use show expansion of the dental arch and distalization of the maxillary lateral segments (Figs 6-28c to 6-28f). The initial surface scan was superimposed with the progress scan using Meshlab software (the light blue color shows the initial scan; Fig 6-28g). The only undesired tooth movement was the mesiolingual rotation of the mandibular left first molar.

Thumbsucking habit appliance

There are several appliances to inhibit thumbsucking and whose use also improves the resultant anterior open bite.[43–47] This has been shown to be stable after appliance removal given habit elimination.[47,48] A version of this appliance is presented here, designed with two bands that will retain the appliance and a platform containing rounded vertical spikes that prevent thumb sucking as well as correct tongue position (Fig 6-29).

RPE combined with a thumbsucking habit appliance

Figure 6-30 shows a hybrid appliance combining an RPE and a thumbsucking habit appliance. The anterior thumbsucking plate was designed in two parts, allowing the opening of the RPE for crossbite correction. After the crossbite correction, the anterior plates were still overlapping, with no space between them (see Fig 6-30c).

Modified Nance appliance

Presented here is a modified Nance button/appliance used in the treatment of an 8-year-old patient with premature loss of the maxillary primary second molars (Fig 6-31a).

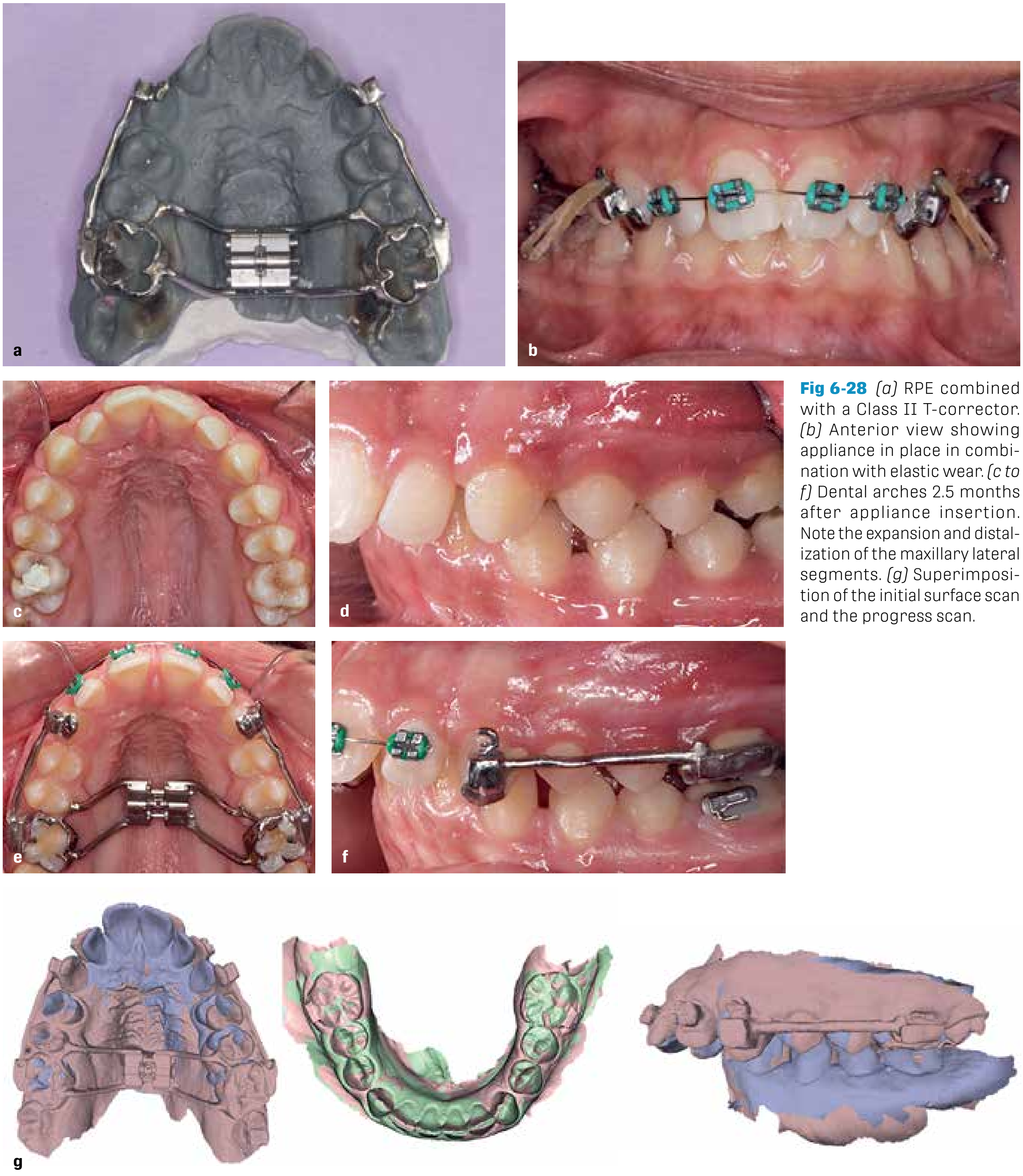


Fig 6-28 *(a)* RPE combined with a Class II T-corrector. *(b)* Anterior view showing appliance in place in combination with elastic wear. *(c to f)* Dental arches 2.5 months after appliance insertion. Note the expansion and distalization of the maxillary lateral segments. *(g)* Superimposition of the initial surface scan and the progress scan.

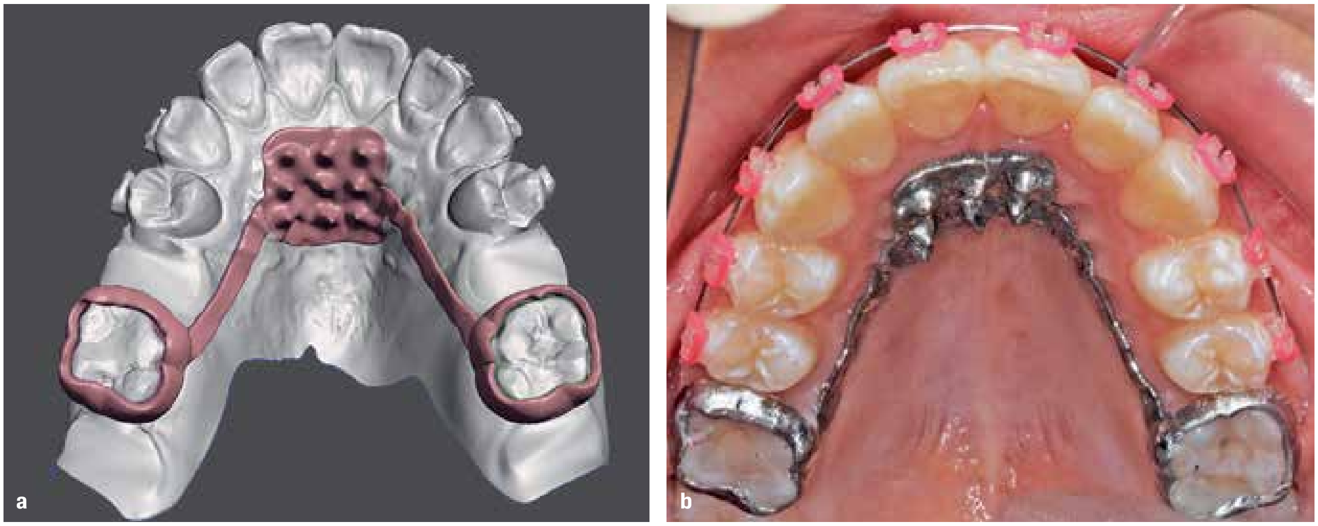


Fig 6-29 *(a)* Custom-designed thumbsucking habit appliance. *(b)* The appliance inserted in the mouth.

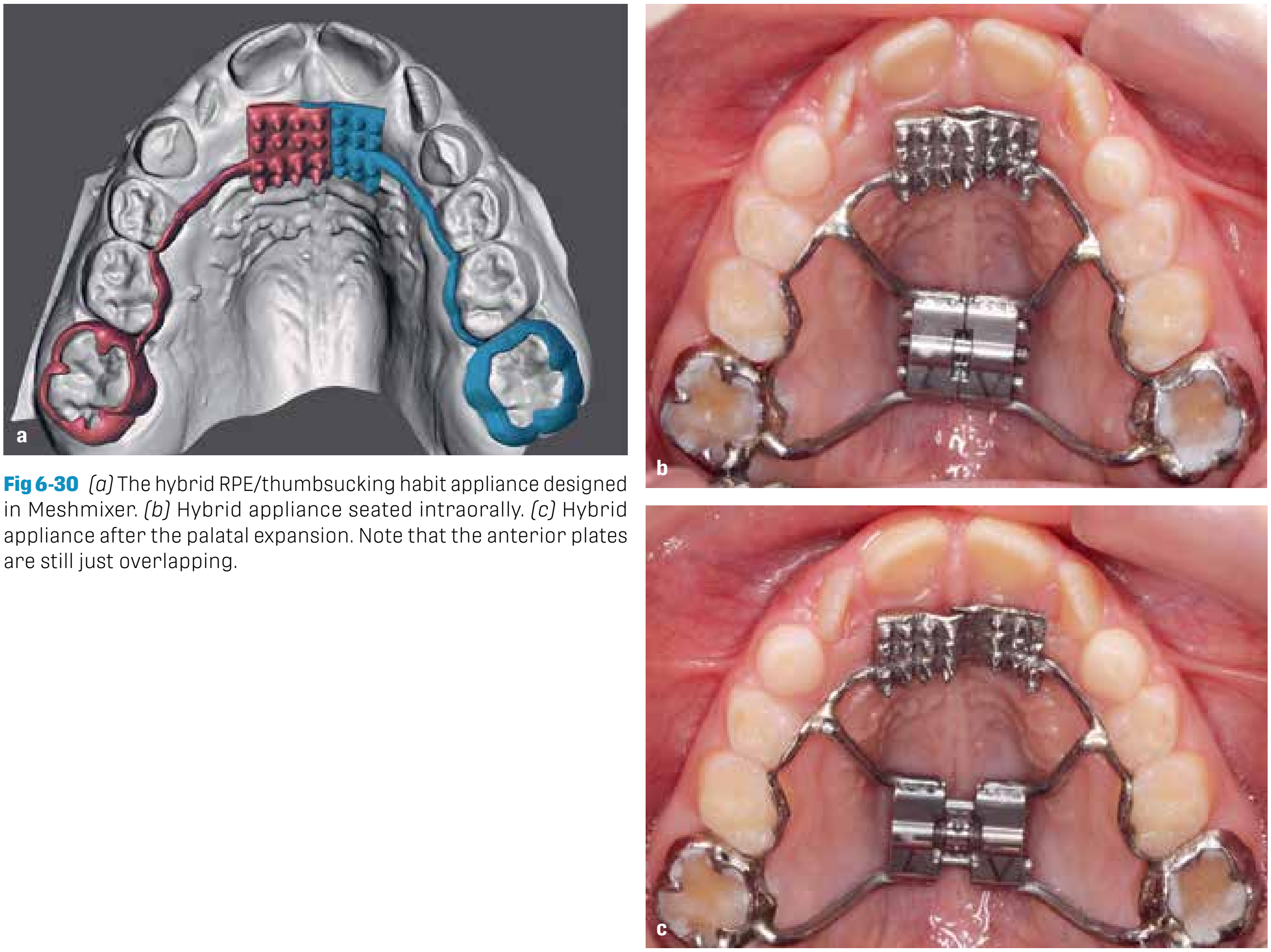


Fig 6-30 *(a)* The hybrid RPE/thumbsucking habit appliance designed in Meshmixer. *(b)* Hybrid appliance seated intraorally. *(c)* Hybrid appliance after the palatal expansion. Note that the anterior plates are still just overlapping.

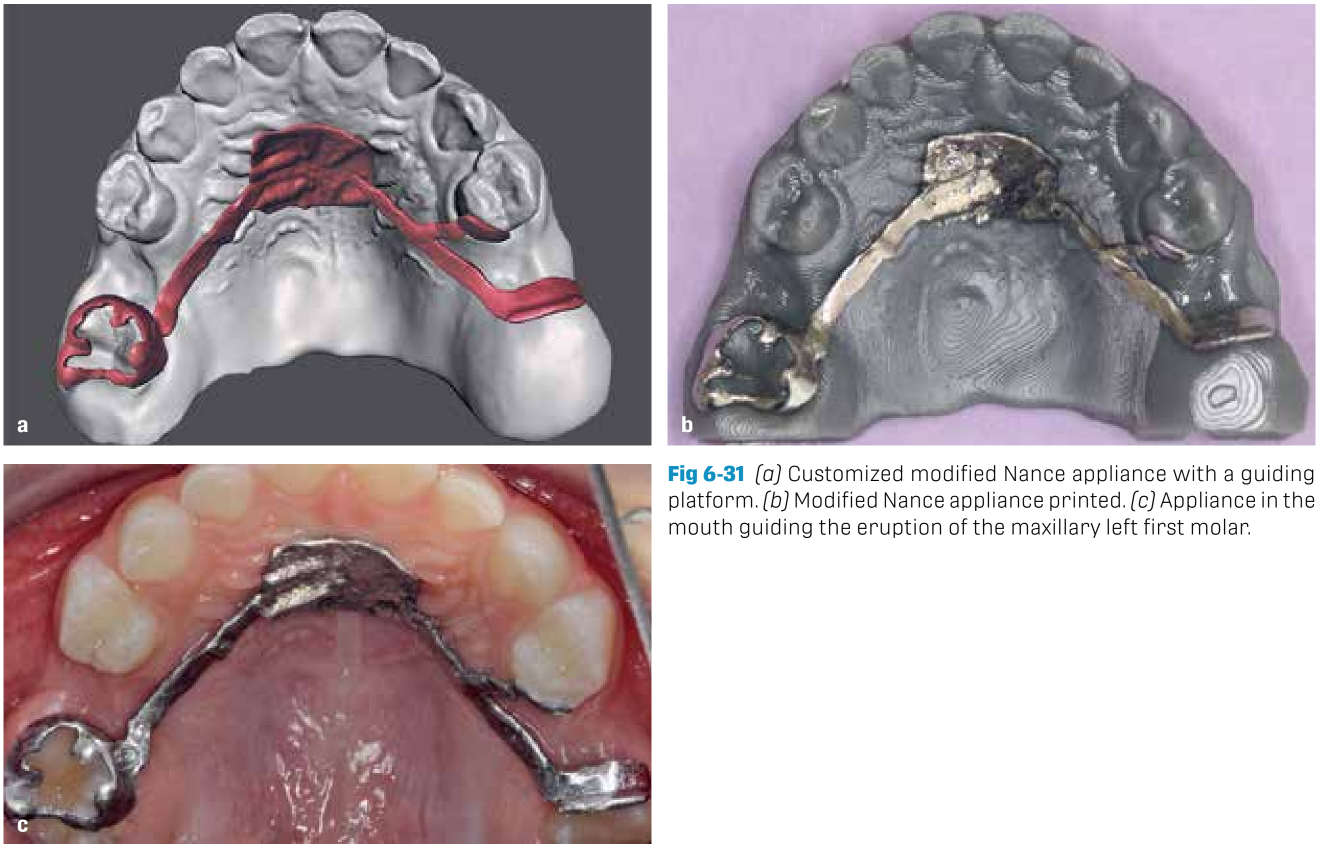


Fig 6-31 *(a)* Customized modified Nance appliance with a guiding platform. *(b)* Modified Nance appliance printed. *(c)* Appliance in the mouth guiding the eruption of the maxillary left first molar.

The appliance served as a space maintainer for the permanent second premolars as well as an eruption guide for the permanent left first molar, which prevented mesial drift during its eruption (Figs 6-31b and 6-31c).

RPE with face mask hooks

The need to perform both maxillary transverse expansion and protraction can be carried out with an appliance designed to enable these therapies. In this case, elastic hooks can be incorporated into the RPE design to provide a place to engage elastics from the appliance to a reverse-pull headgear (or face mask). In the example shown in Fig 6-32, the palatal arms were connected with the buccal arms for better stability of the appliance.

Surgical guiding stent for computer-assisted microimplant placement

Surgical guiding stents/splints were first used in computer-assisted implant placement by oral surgeons.[49–52] They are designed with the use of CBCT 3D diagnostic records, which enable dedicated software to virtually place a dental implant, from which a stent can be constructed to direct duplication of this maneuver clinically. A surface scan is performed and fused with the CBCT data in order to generate an even more detailed rendering of the alveolar bone and dentition. The designed 3D file of the stent/splint is exported to a 3D printer, which fabricates it using a biocompatible material.

In the case of Fig 6-33, the CBCT DICOM files were converted to an STL format, and the CBCT and intraoral scan were fused in Meshmixer (Fig 6-33a). A stent was designed with two guiding cylinders (Figs 6-33b and 6-33c), corresponding to the dimensions of the blade used to place the OrthoEasy Pal microimplants (Forestadent; Figs 6-33d and 6-33e). These serve not only to orient the path of microimplant insertion but also to determine the depth of microimplant penetration. The microimplants used here have a length and diameter of 8 × 1.7 mm and are intended to skeletally anchor palatal appliances. They are provided with an abutment and retaining screw to

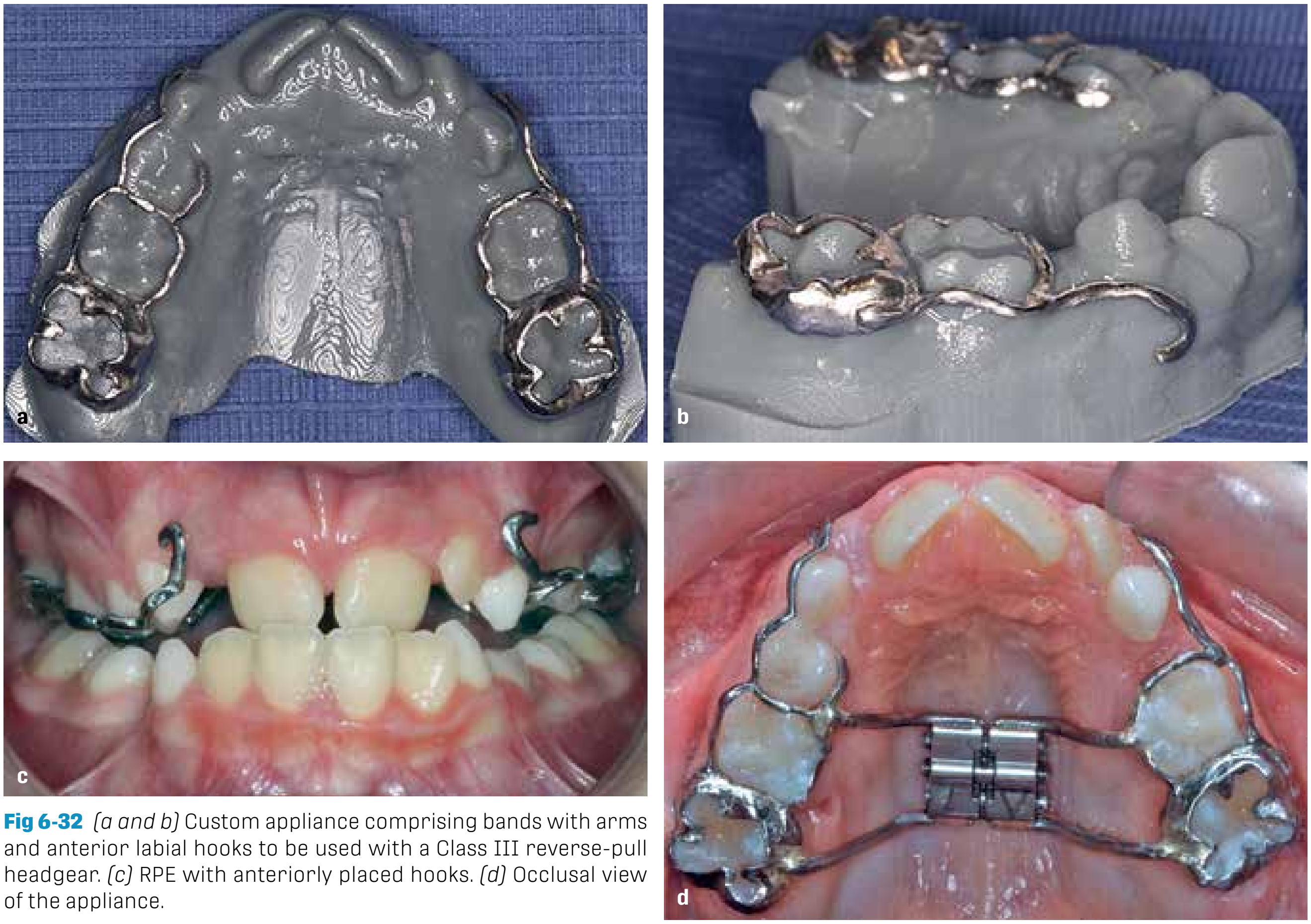
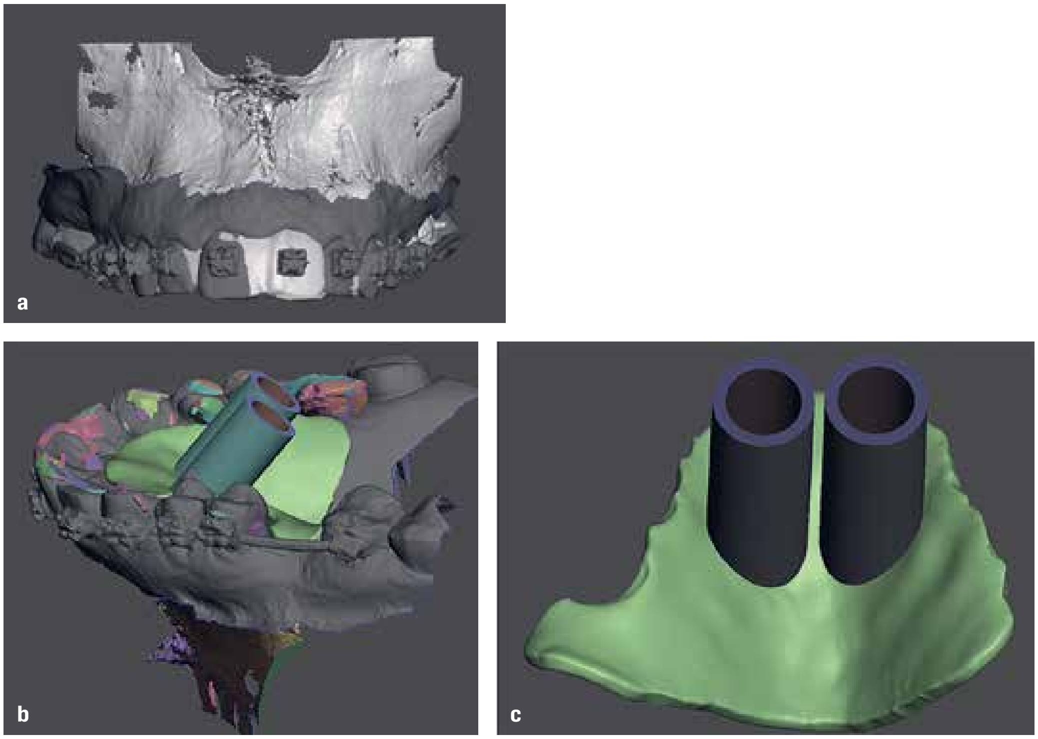


Fig 6-32 *(a and b)* Custom appliance comprising bands with arms and anterior labial hooks to be used with a Class III reverse-pull headgear. *(c)* RPE with anteriorly placed hooks. *(d)* Occlusal view of the appliance.

Fig 6-33 *(a)* Volume and surface scanning fusion in Meshmixer. *(b and c)* Surgical guide design.



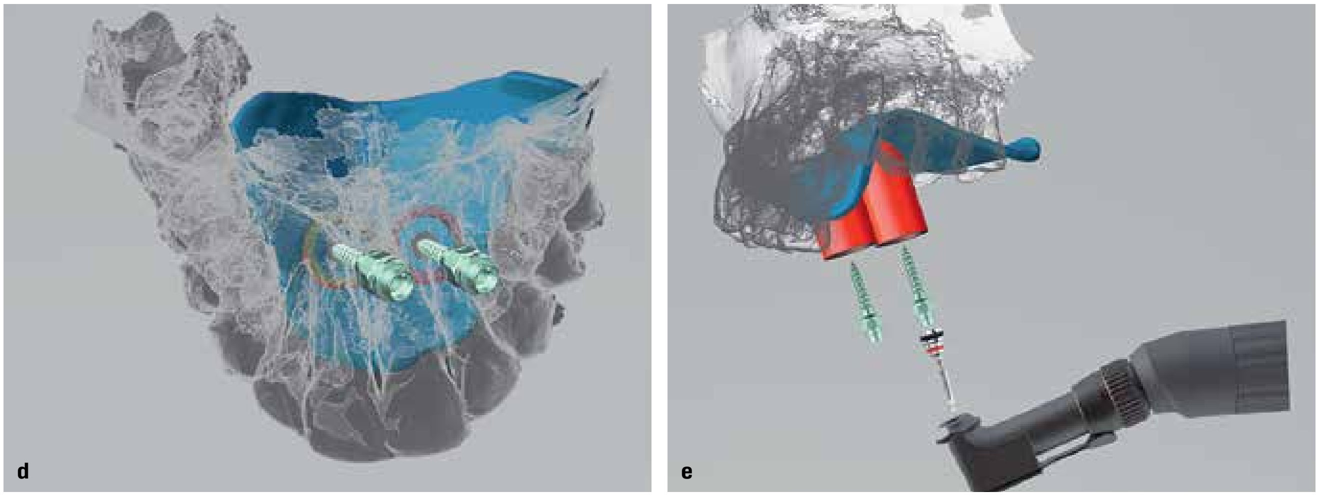


Fig 6-33 *(cont)* *(d and e)* Virtual placement of the OrthoEasy Pal microimplants with the help of a blade placed on a low-speed handpiece. *(f)* The surgical splint printed on the 3D printer's platform. *(g)* The surgical splint after alcohol rinsing and UV curing.

connect the microimplants with a variety of orthodontic appliances.

Once 3D printed, the guiding stent is required to undergo alcohol rinsing and UV curing procedures (Figs 6-33f and 6-33g).

Palatal microimplant-supported molar anchorage appliance

The digital designing and printing of the stent to place the palatal microimplants described in Fig 6-33 precedes the design and 3D printing of the customized appliance they will anchor.

An intraoral scan of the dentition and palate, including the inserted microimplants, is performed and imported into Meshmixer. This requires intraoral careful airborne-particle abrasion in order to enable scanning of the microimplants. In Fig 6-34, maximum molar anchorage and retraction of the anterior teeth was required, so a customized appliance comprising two hemimolar bands was designed with a lingual wire connecting them and extending to the microimplants, where two corresponding openings were precisely located so that fitted retaining screws could fix this appliance to the microimplants. As in the above examples, this appliance was 3D printed using Co-Cr.

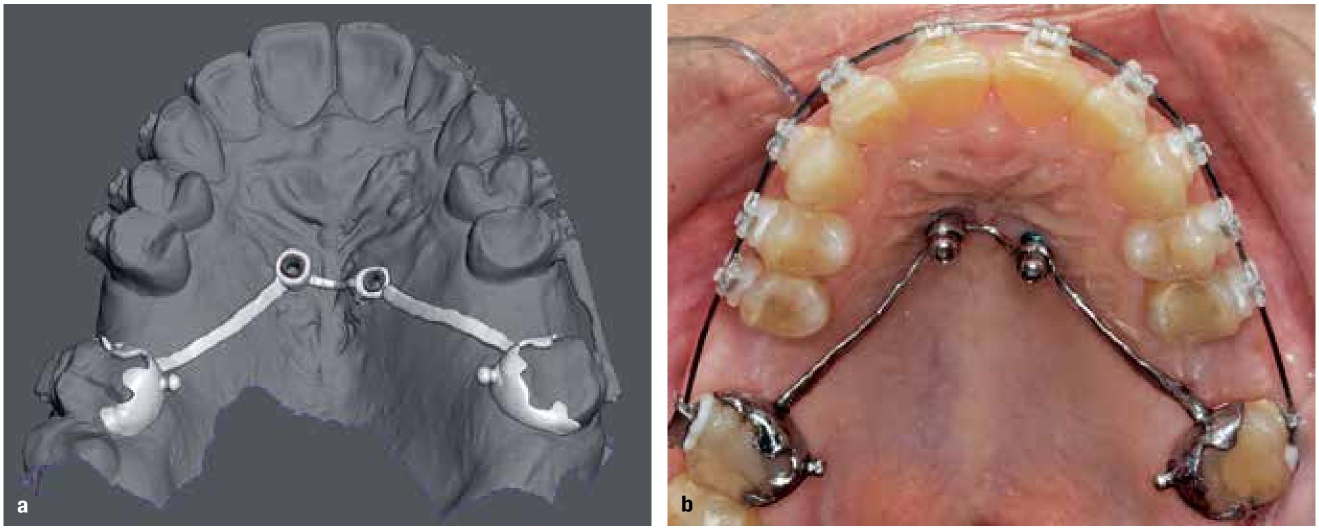


Fig 6-34 *(a)* Custom palatal microimplant-supported molar anchorage appliance in Meshmixer. *(b)* Printed appliance.

Palatal microimplant-supported molar distalization appliance

When distalization of the posterior segment is needed, power arms are designed to be extended occlusally to the premolars from the microimplants. Four hemibands are designed on the first premolars and first molars. The molar's bar extends to the premolar's power arm tube. An open Ni-Ti coil spring is placed around the bar in order to distalize the molars (Fig 6-35). Similar appliances using temporary anchorage devices can be easily designed using Meshmixer.

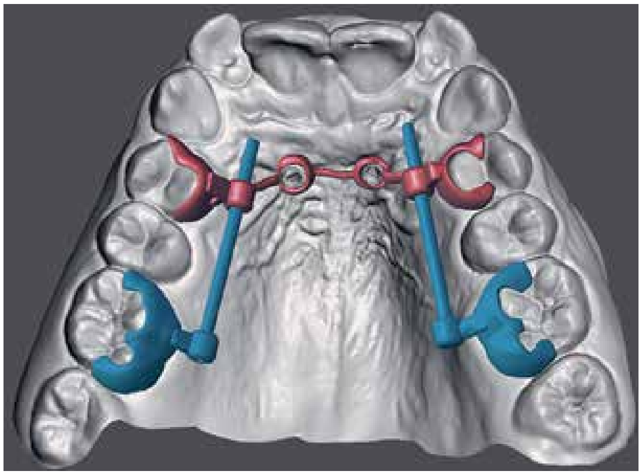


Fig 6-35 A custom palatal microimplant-supported molar distalization appliance designed in Meshmixer.

Conclusion

The variations of orthodontic appliance design are limited more by clinician imagination rather than technical boundaries. Currently, in-house customized appliance design is predominately being adopted by orthodontic laboratories, because the task allotment (time) and monetary cost of keeping pace with these technologic advances have not justified their inclusion in every orthodontic clinic. However, intraoral scanners are becoming standard armamentarium, and 3D diagnostic records are becoming increasingly more available. Furthermore, CAD software is becoming more intuitive, and a wider range of biocompatible materials are under development. It is only a matter of time before the cost and efficiency of 3D printing will intersect with justification for their inclusion within every clinical setting, enabling clinicians to design and fabricate (print) their own custom appliances.

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7

Custom Appliance Design Using Dedicated Orthodontic Software

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Stefano Negrini

An alternative to in-house custom appliance design using general-purpose CAD software is custom appliance design using dedicated orthodontic software. This model allows the orthodontist or the orthodontic technician to design patient-specific appliances, while the external laboratory can house and utilize the expensive and often environmentally sensitive equipment.

Digital Workflow from Scanning to Laboratory Fabrication (Printing or Milling)

The digital workflow from the orthodontic office to the laboratory depends on the data transmission systems used and the type of appliances requested by the clinician. Some companies producing intraoral scanners have a data storage cloud available to their users for the reception and validation of the data received, while others allow their users to export simple STL files to third parties (ie, laboratories).

The basic digital workflow between the orthodontic office and the orthodontic laboratory is as follows:

1. Data received from intraoral scanner via exchange data cloud
2. Staging design in the laboratory
3. Clinical validation (via the same receiving cloud or by the clinician)
4. Export of digital models and forwarding to the milling/printing center
5. Milling/printing
6. Finalization
7. Shipping

Digital Design and Manufacturing of an Orthodontic Appliance

CAD software

Various software products are available to custom-design appliances digitally. Each orthodontist and/or laboratory should choose a dental analysis and appliance design software according to their preferences in terms of user-friendliness of the design procedures, time involved in the preparation of the digital design, and pricing (annual fee vs one-off option). However, the most popular CAD software for orthodontics is the 3Shape Ortho System (Fig 7-1). All of the appliances presented in this chapter were designed with this software and exported to a laboratory for fabrication.

Access to various CAD software programs often dictates their appeal, and access is offered in one of several marketing options:

- Free software
- Paid software with an annual fee
- Paid software without an annual fee
- Software with file export payment

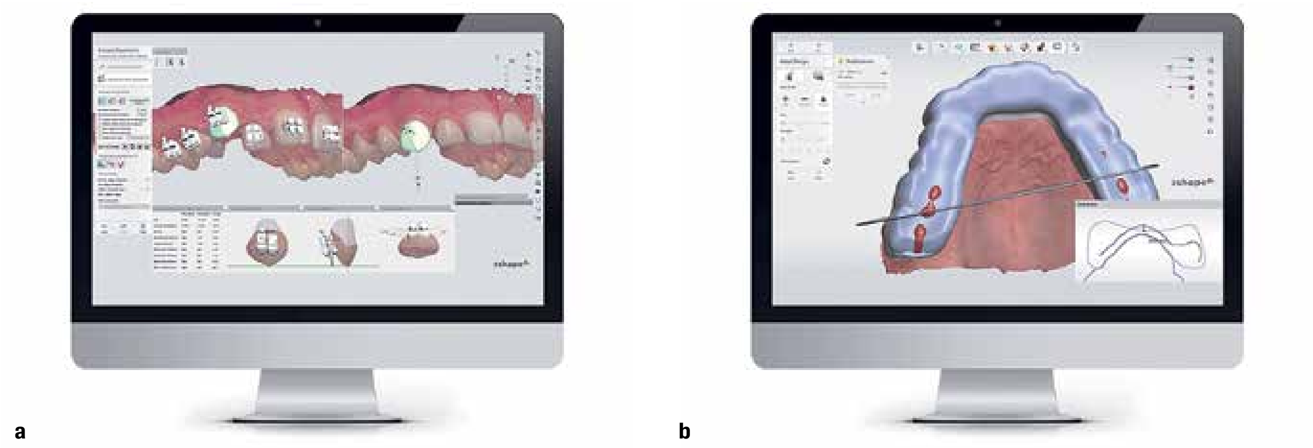

Fig 7-1 *(a and b)* 3Shape CAD software.

Free software

One of the best-known software programs in the orthodontic field for completely free use is Autodesk Meshmixer. Autodesk is one of the largest 3D companies in the world, and Meshmixer is a completely free program that allows the user to upload STL files of different kinds (attachment, teeth, geometric figures). Meshmixer is state-of-the-art software for working with triangle meshes. Think of it as a sort of "Swiss army knife" for 3D meshes. Meshmixer works on both Windows and iOS systems. Some examples of the capabilities of Meshmixer are drag-and-drop mesh mixing, 3D sculpting and surface stamping, branching support structures for 3D printing, automatic print bed orientation optimization, layout and packing, and many advanced selection tools.

Other freeware packages include Rhino3D (Robert McNeel & Associates) and Blender.

Paid software with an annual fee

There are several CAD software packages offered that grant access with the payment of an annual fee. These are usually packaged in different formulas or modules. The most common are Onyx Ceph and 3Shape Ortho System. These two software programs offer the user the flexibility to customize their purchase by supplementing the basic program with different modules that can be added to their user license according to specific needs. For example, 3Shape functions by the use of a dongle on which the user codes of the additional programs are encrypted, while Onyx Ceph provides customers with a personal activation code. Some examples of supplemental programs and functions include creating digital study models from either conventional impressions, plaster casts, or intraoral scans; the capability of merging CT/CBCT data, scans, panoramic radiographs, cephalometric tracings, and photos with digital study models for the analysis of arc shapes, overjet/overbite, Bolton ratios, occlusion, and spaces; and the capability of creating clear aligners, indirect bonding (IDB) trays, splints, nightguards, removable retainers, customized metal bands, lingual bars, palatal expanders, and devices for mandibular protrusion such as Twin Blocks, Herbst appliances, and more.

A big advantage of these digital products offered by such software is the added value in treatment planning that it offers the clinician and seamless connectivity for treatment communications.

Paid software without an annual fee

Paid software programs without annual fees are those that the user can purchase with a one-time payment without subsequent resubscription fees. Should a customer decide to upgrade the version in use, this would require a repurchase, which would have to include any version(s) developed prior to the latest purchase since the original purchase.

One of the best-known software products offered in this manner is Maestro Dental Studio (AGE Solutions). Another similar software is DeltaFace (Coruo). Both software packages offer more or less the same functions. Briefly, the module allows managing clinics, doctors, patients, and cases through a database. They create virtual study model bases (ABO, ABO-2013, Ricketts, Parallel, Tweed) and add them to the scanned stone casts. It is also possible to perform occlusal inspection analysis, 2D/3D sections, measurements of the teeth, and full arches. These also offer a virtual setup module that allows moving the teeth within each arch and evaluating distance contacts and intersections. It also enables the orthodontist to add and customize attachments/labels (both positive or negative) and to perform virtual dental extractions and interproximal reduction (IPR). These can be used in aligner manufacturing and IDB tray fabrication. In addition, the model builder function is available in Maestro Dental Studio, allowing the creation of transition models that are created and exported in STL/PLY/OBJ file formats and optimized for 3D printing. The user can decide the number of transition models by changing the parameters of tooth movement (ie, defining movement of each tooth in fractions of millimeters and degrees).

The bracket placement module for IDB allows the orthodontist to automatically place the virtual brackets on the digitized teeth. It offers various placement techniques (step, Roth, Alexander, MBT, Andrews, etc) and, in combination with the clear aligner module, enables the orthodontist to construct several types of trays for reproducing the transfer of the planned bracket positions to the patient.

The next anticipated step in clear aligner treatment is likely to be direct in-house aligner printing (see chapter 10). This option is already available in both these software options. The clear aligner module allows the operator to design and construct the aligners in a virtual environment. The aligner shape is demarcated, its thickness is chosen, and simulation of the thermoforming procedure is designed.

Software with file export payment

There are also software products that can be downloaded free from their respective reference sites with their use also free until the outcome process is validated and exported. In other words, the program is free to download and use, with a fee being paid only when the product is implemented. The two most popular software packages of this kind are ArchForm and BlueSkyPlan. BlueSkyPlan allows all users to design and fabricate surgical templates for all guided surgical kits and all implant systems. There is a surgical guide, orthodontic, cephalometric, and crown-and-bridge module. Unlike the BlueSkyPlan, ArchForm is designed exclusively for the creation of treatment plans for aligners.

Materials for additive (3D printing) and subtractive (milling) manufacturing

There are myriad materials being used today in 3D orthodontic device manufacturing, as demonstrated later in this chapter. Many established and new companies are producing these materials, so options in this field are only expected to expand. Currently, the most used materials are the following:

Cobalt-chrome (Co-Cr)

This material is used for all 3D-printed metal-based orthodontic appliances (eg, lingual arches, TPA/TPB, RPE/RME, Herbst, Forsus, etc). All of these devices are made with the laser melting sintering printer system. Implementation with CNC milling is not economically practical and not as efficient because this option would be lengthy as well as costly, given the existence of undercuts, offsets, etc, that are present in the CAD drawing of every orthodontic device.

Titanium

Titanium is a material that can be also used in the laser melting sintering system. An exception is the creation of canine-canine fixed retainers at the end of the orthodontic treatment, for which the systematic milling is used. This type of material is used in medical devices but mostly for specific types of patients such as those with nickel allergies.

PMMA

PMMA (polymethyl methacrylate) is a strong, transparent thermoplastic used as a substitute for glass. This material can be used for devices such as splints for temporomandibular disorders (TMDs), Twin Blocks, and plates or double plates. PMMA is an excellent material for these types of orthodontic medical devices.

PEEK

PEEK (polyether ether ketone) is a colorless organic thermoplastic polymer used in engineering applications but also for medical and dental appliances. The material is used in 3D orthodontics for the manufacture of TPA/TPB, expanding bars, retainers, and lingual arches. In general, it is a material that is used in CNC milling machines, although there are versions of medical PEEK that can be printed.

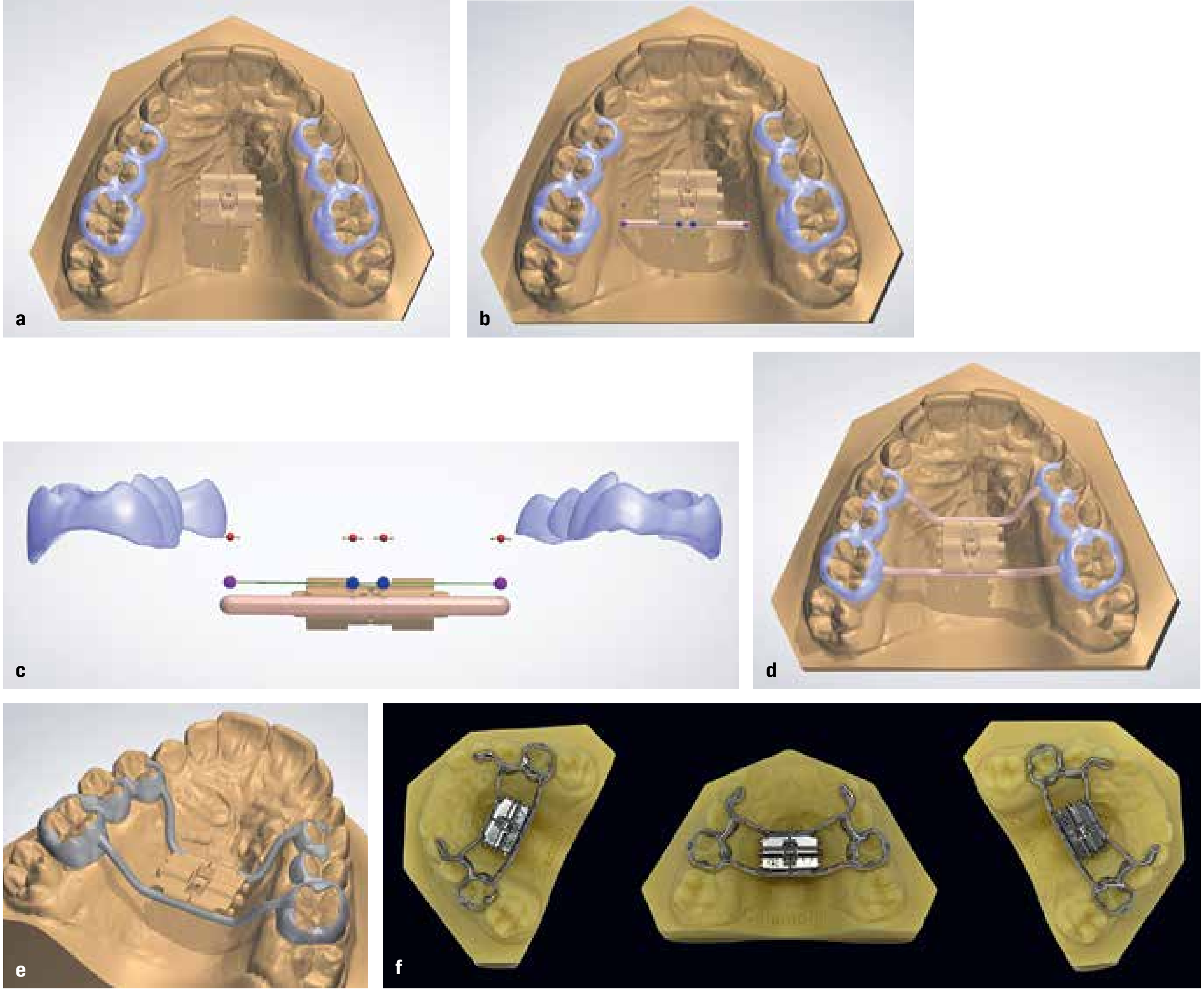

Fig 7-2 *(a to e)* RPE design using 3Shape. *(f)* Customized and printed RPE.

IDB tray material

This is a material that is used in 3D printers for the formation of IDB trays. Examples are the Ortho IBT (NextDent) and SprintRay IDB trays.

Hard material for splints

This is a material that can be printed to manufacture TMD splints, surgical guides, and retainers. Examples are the Ortho Clear (NextDent) and SprintRay splints.

Bioflex

Bioflex is a flexible and rubber-like polylactic acid used in FDM printers. The material is used for the manufacture of Twin Blocks (see Fig 7-11), mouthguards, and MPG3D.

Digital design and printing of a rapid palatal expander

The first step in the digital design of a rapid palatal expander (RPE) is to import into the CAD software (3Shape) the intraoral scan data collected in the orthodontic office. The next step is to create the bases of the virtual models and the positioning of the virtual expanding screw selected from the software's library. The screw is positioned in the determined position, which is followed by the design of the connecting arms (Fig 7-2a).

The digital band can be easily designed by contouring the edges of the tooth where the band is intended to be placed. It can be extended to neighboring teeth in the

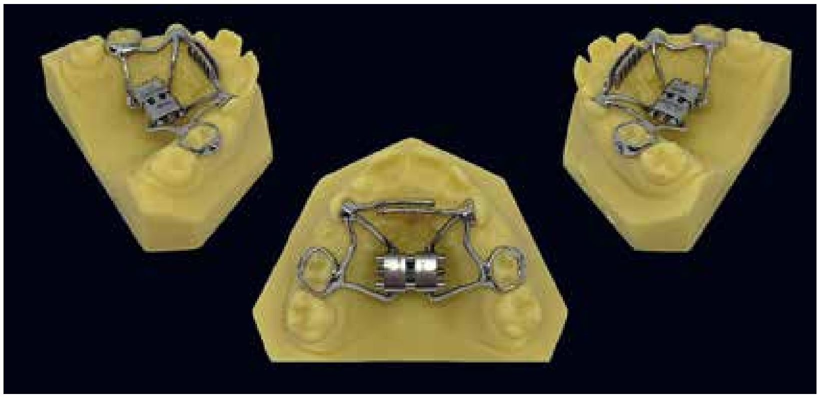

Fig 7-3 Customized RPE with a tongue shield.

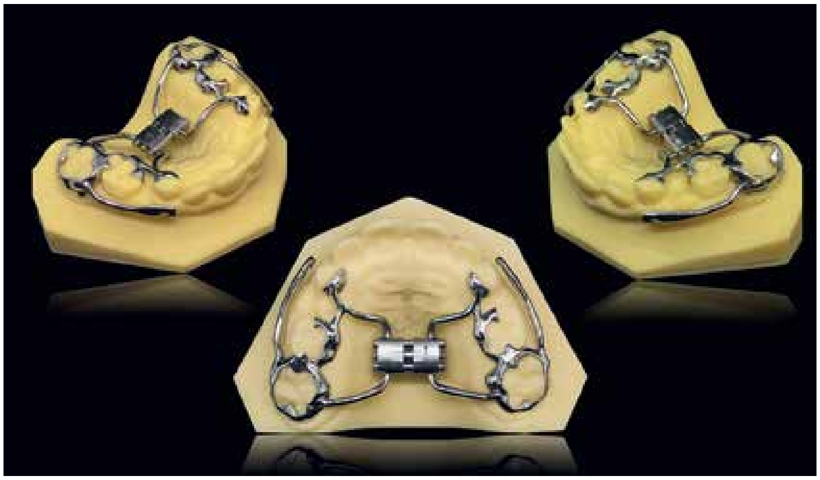

Fig 7-4 Customized RPE with buccal arms for a reverse-pull headgear.

form of a band, a pad, or a wire, according to the preferences of the orthodontist. The recommended thickness of a band is 0.6 to 0.7 mm. After being designed, the band is sent to a laser sintering or laser melting center (these two procedures alter the nature of the metal). The currently prohibitive cost of purchasing these machines for single clinic use dictates that this be outsourced. The band, or the "island" if it includes more than one tooth, is sent back with a rough surface to be polished on the side exposed to the mouth, while it has to be airborne-particle abraded on the inner surface to increase surface area for improved retention.

According to the type of appliance to be produced, it may also be necessary to fit it onto a printed resin model, but this should be minimized for ecological reasons. This procedure is justified when more traditional metal components (like active wires manually bent) are required to be laser welded to two different "islands." Hence, it becomes necessary to orient them on the model to facilitate this process. A clinical example of this would be the 3D sintering of an RPE where the unprintable (hyrax) screw mechanism will require welding to the printed connecting arms extending from the "islands" (Figs 7-2b to 7-2e).

After the bands or the "island" return from the manufacturing center, the metal is polished and the screw is positioned and attached using laser welding (Fig 7-2f). An appliance fabricated in this fashion is far more accurate than any produced using traditional methods.

Examples of customized 3D-printed orthodontic appliances

Other standard appliances that can be digitally designed and laboratory fabricated include the following:

- Standard RPE with screw and tongue shield (Fig 7-3)
- Standard RPE with extensions for reverse-pull headgear (Fig 7-4)
- Standard Herbst appliance (Fig 7-5)
- Standard Herbst Forsus (3M; Fig 7-6)
- Twin Block (Fig 7-7)

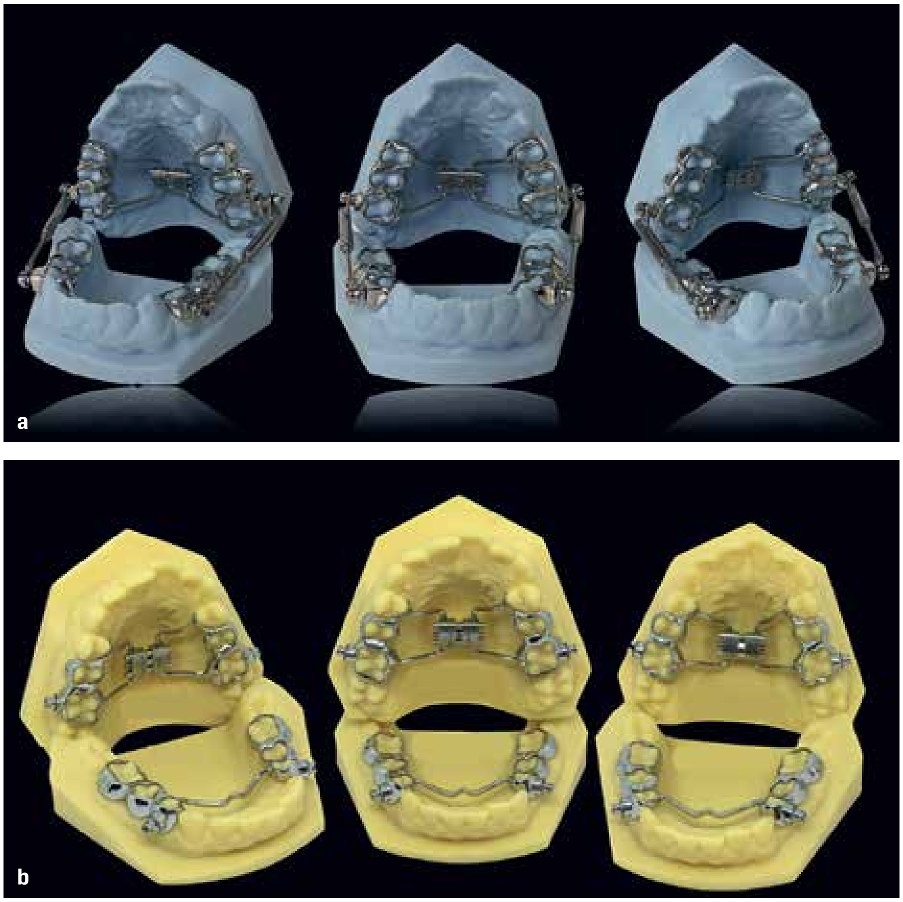

Fig 7-5 *(a and b)* Customized Herbst appliance.

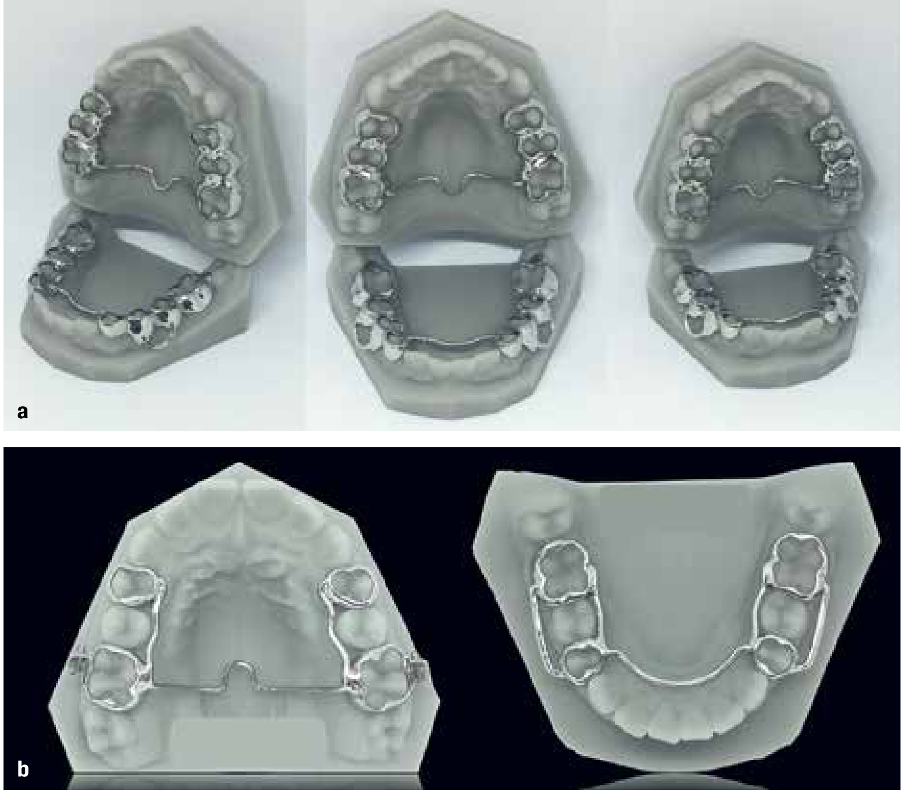

Fig 7-6 *(a and b)* Co-Cr frame for Forsus appliance.

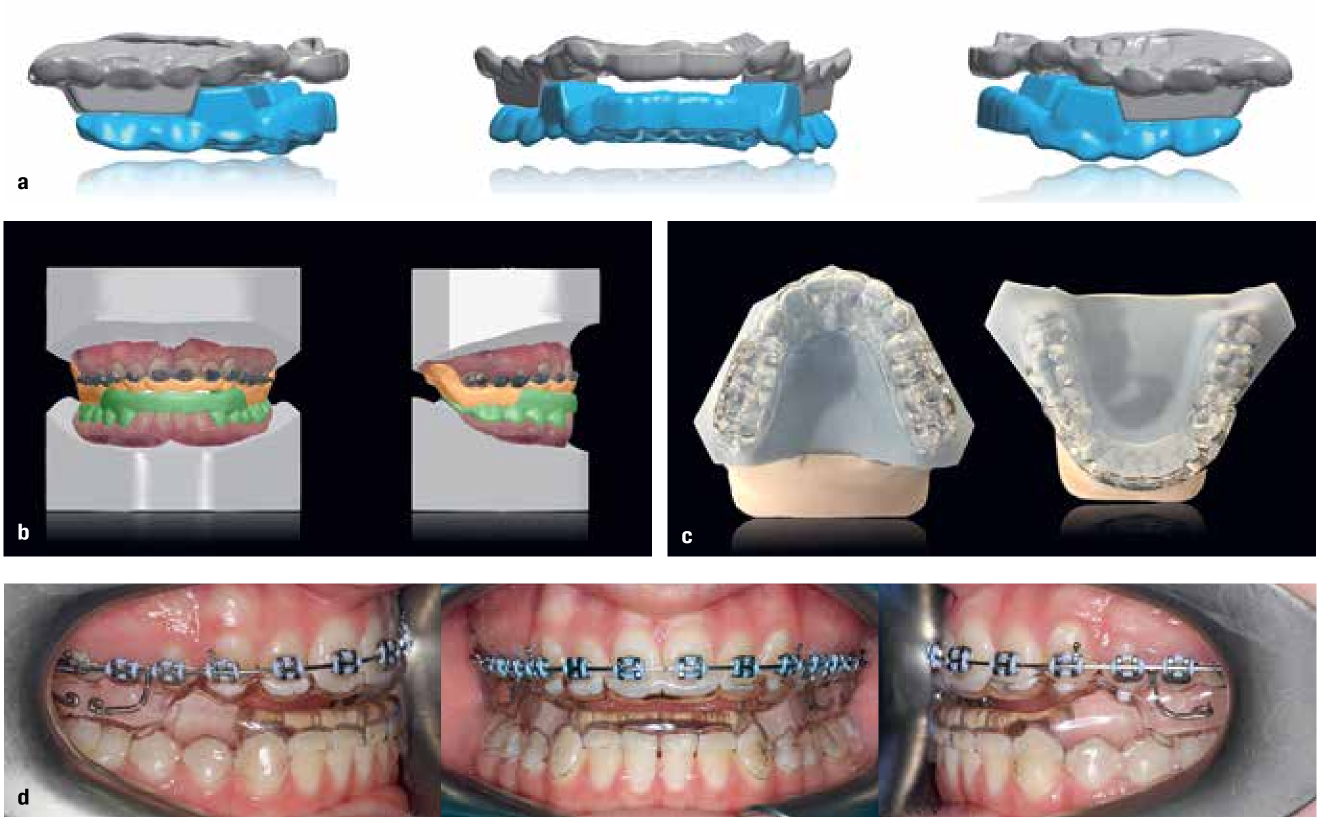

Fig 7-7 *(a to d)* Twin Block digital design and printing.

Author-Designed Prototype Customized Appliances

It must be stressed that the only limits to the design of new devices with 3D technology are operator imagination and patient comfort. After traversing the learning curve, each operator can develop new ideas and use the CAD software to design their own new orthodontic appliances. For example, the authors have designed two appliances based on the Beneslider appliance.[1]

Beneslider with TADs placed first

In this first case, the clinician places the temporary anchorage devices (TADs) prior to performing the intraoral scan (Fig 7-8a). Once the scan data is received by the laboratory, image checking is performed.

The first step is to match the scan with the real files of the TADs in order to have a more accurate (true) file to use for appliance design. The second step is to position the two TADs for distalization of the posterior teeth. In this case, the clinician's request was to use two 8-mm Tomas TADs (Dentaurum). Once these are positioned, the connecting arms are designed between the TADs and the screws, and the design is sent to the clinician for validation (Fig 7-8b). The last step is to manufacture the appliance using a laser melting printer, followed by finishing (polishing, etc) and delivery (Fig 7-8c).

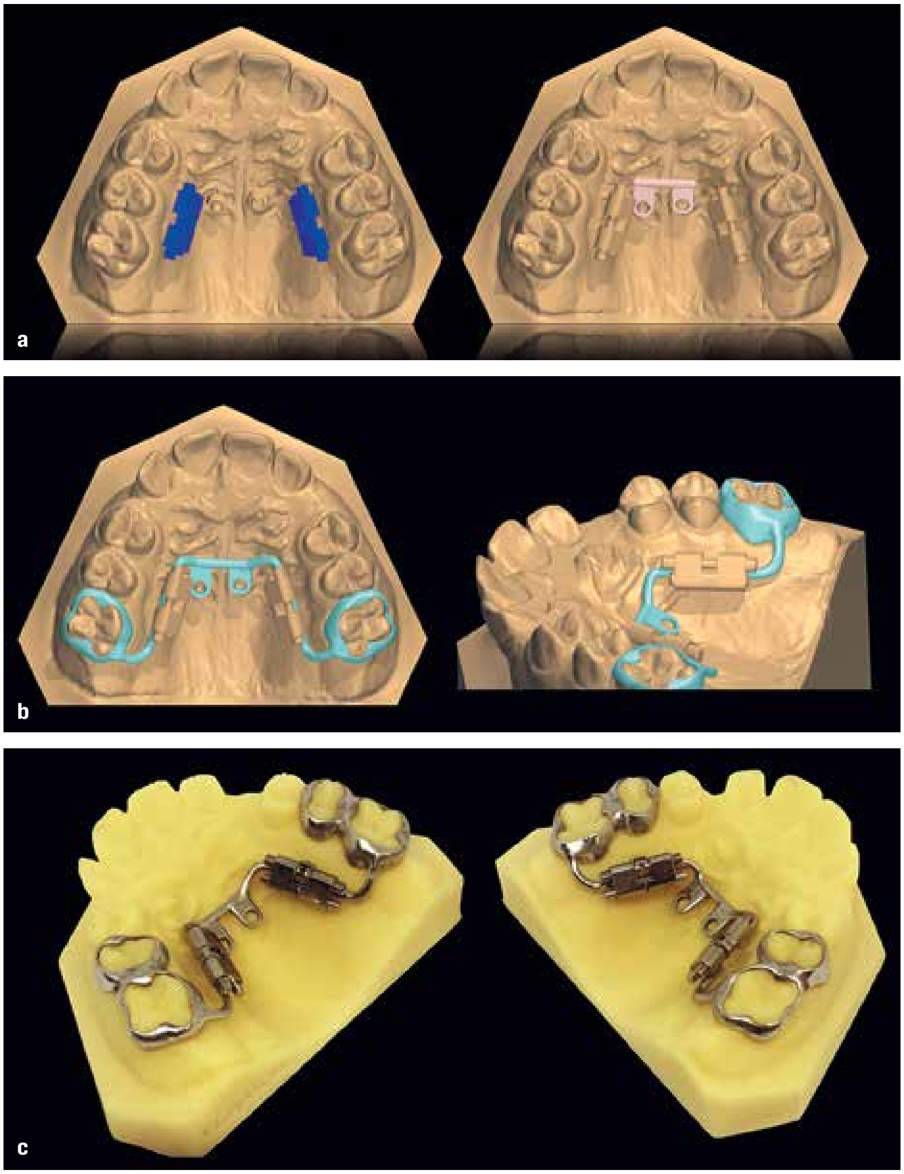

Fig 7-8 *(a to c)* Beneslider design and printing workflow.

Beneslider with TADs and scan body first

In this case, the clinician performs the intraoral scan after placing the scan body on the TADs (Figs 7-9a to 7-9c). This allows the dental technician to have the exact position of the TADs and to create a more accurate device.

After the scan data is received and the scanned bodies are aligned, the operator proceeds to design the bands and the arms of the Beneslider (Figs 7-9d to 7-9h). The virtual design is sent to the clinician for validation and subsequently to the manufacturing center. The last phase is the finishing and polishing, assembly of the pieces that make up the Beneslider, and shipping to the clinician (Fig 7-9i).

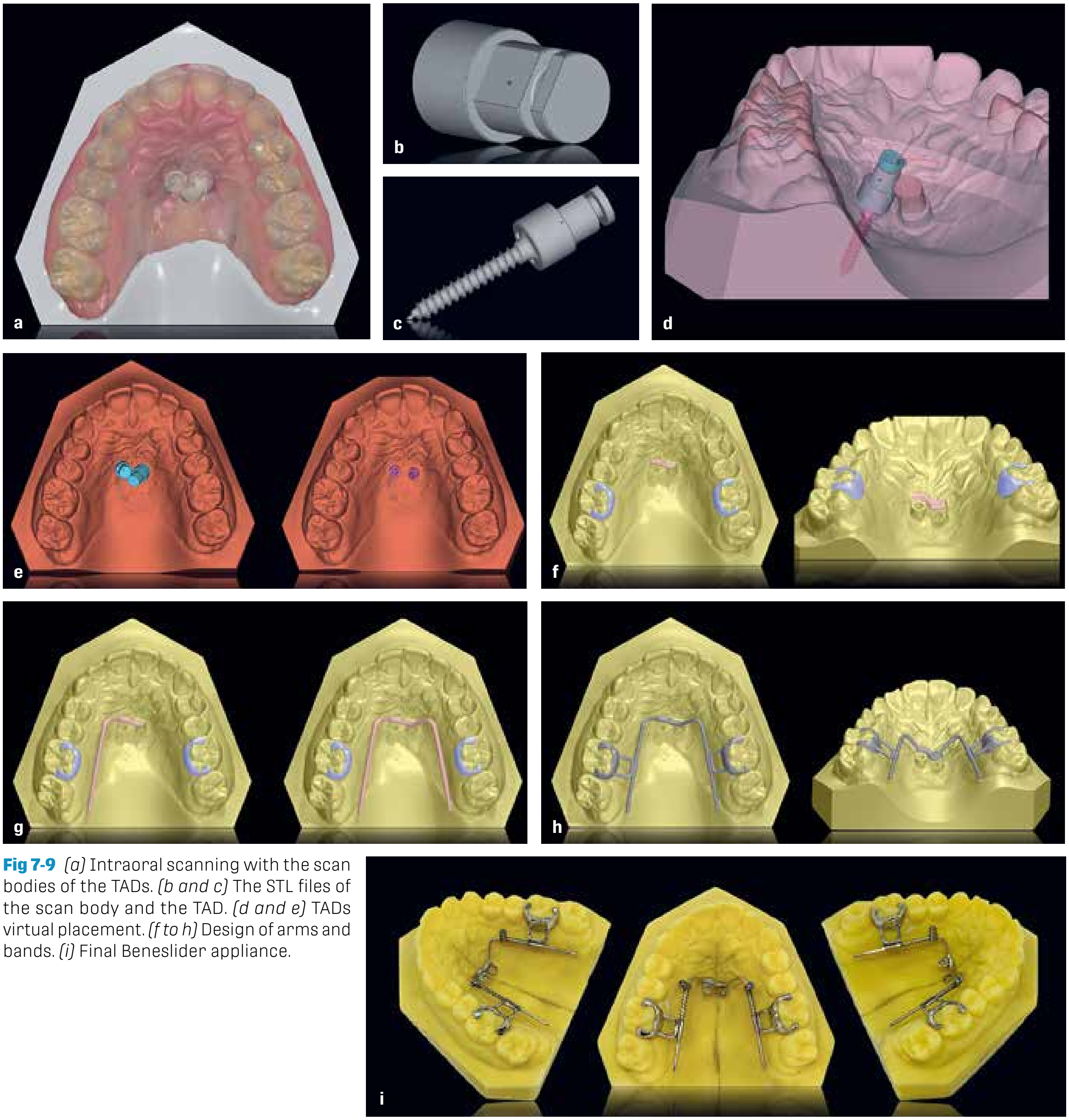

Fig 7-9 *(a)* Intraoral scanning with the scan bodies of the TADs. *(b and c)* The STL files of the scan body and the TAD. *(d and e)* TADs virtual placement. *(f to h)* Design of arms and bands. *(i)* Final Beneslider appliance.

Novel Designs and Materials

New innovative appliances are being offered thanks to the advent of new biocompatible materials that are constantly being developed. For example, a modification of a Frankel appliance has been developed using PEEK.[2] PEEK is white, radiolucent, and has great thermal stability; it is nonallergic and has low plaque affinity, and its mechanical properties do not change during the sterilization process. It is resistant to hydrolysis, showing nontoxic properties, and it is biocompatible. Dental devices made with PEEK can be both milled or 3D printed, showing high production versatility. In addition, PEEK has low solubility and water absorption values. All of these features make it a highly appropriate material for orthodontic device manufacturing.[3]

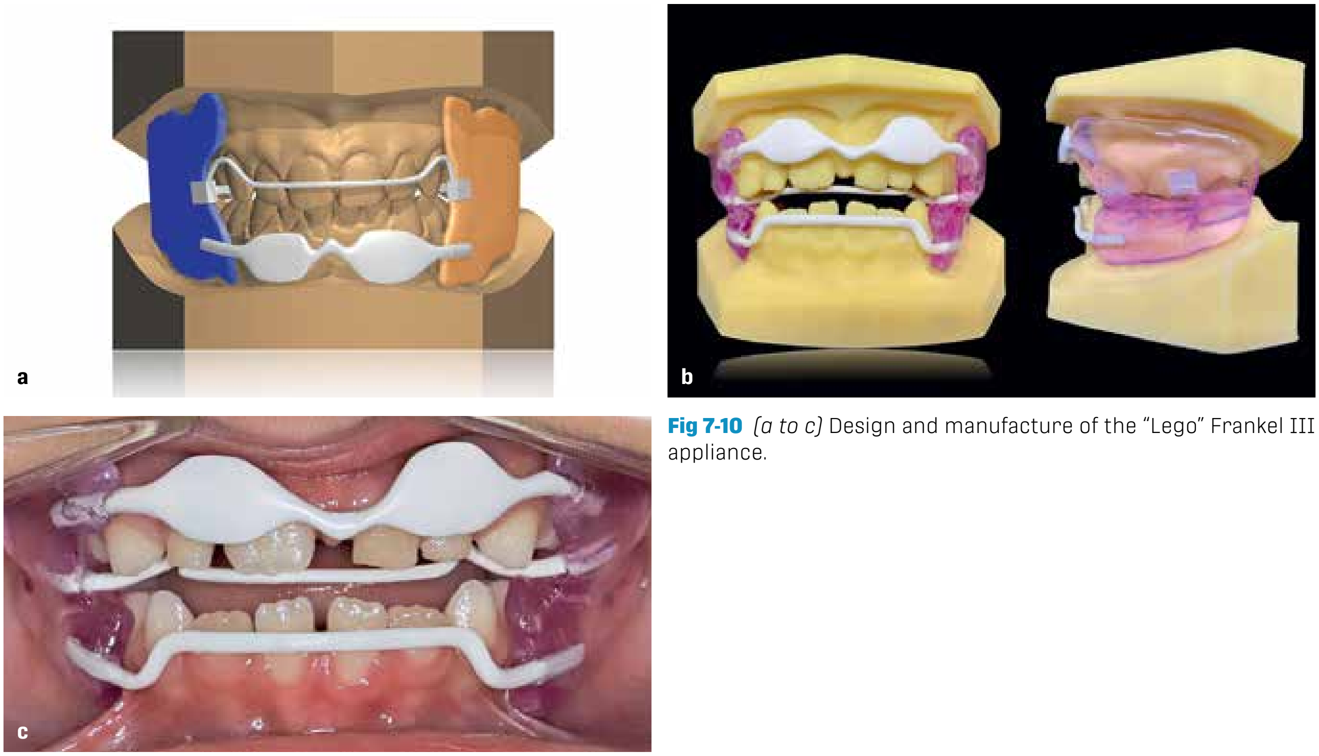

Fig 7-10 *(a to c)* Design and manufacture of the "Lego" Frankel III appliance.

Fig 7-11 Twin Block printed with Bioflex.

"Lego" Frankel appliance

This design concept consists of puzzle-style parts that are assembled step by step with resin (buccal and labial shields) and wire. The parts are connected through the use of specific biocompatible glues to manufacture the "Lego" Frankel appliance (Dextra Group I&D; Fig 7-10).

Bioflex Twin Block

Another interesting 3D application is the design and construction of the Twin Block functional appliance printed using Bioflex (Filoalfa; Fig 7-11). The design of the Twin Block does not change whether it is printed or milled.

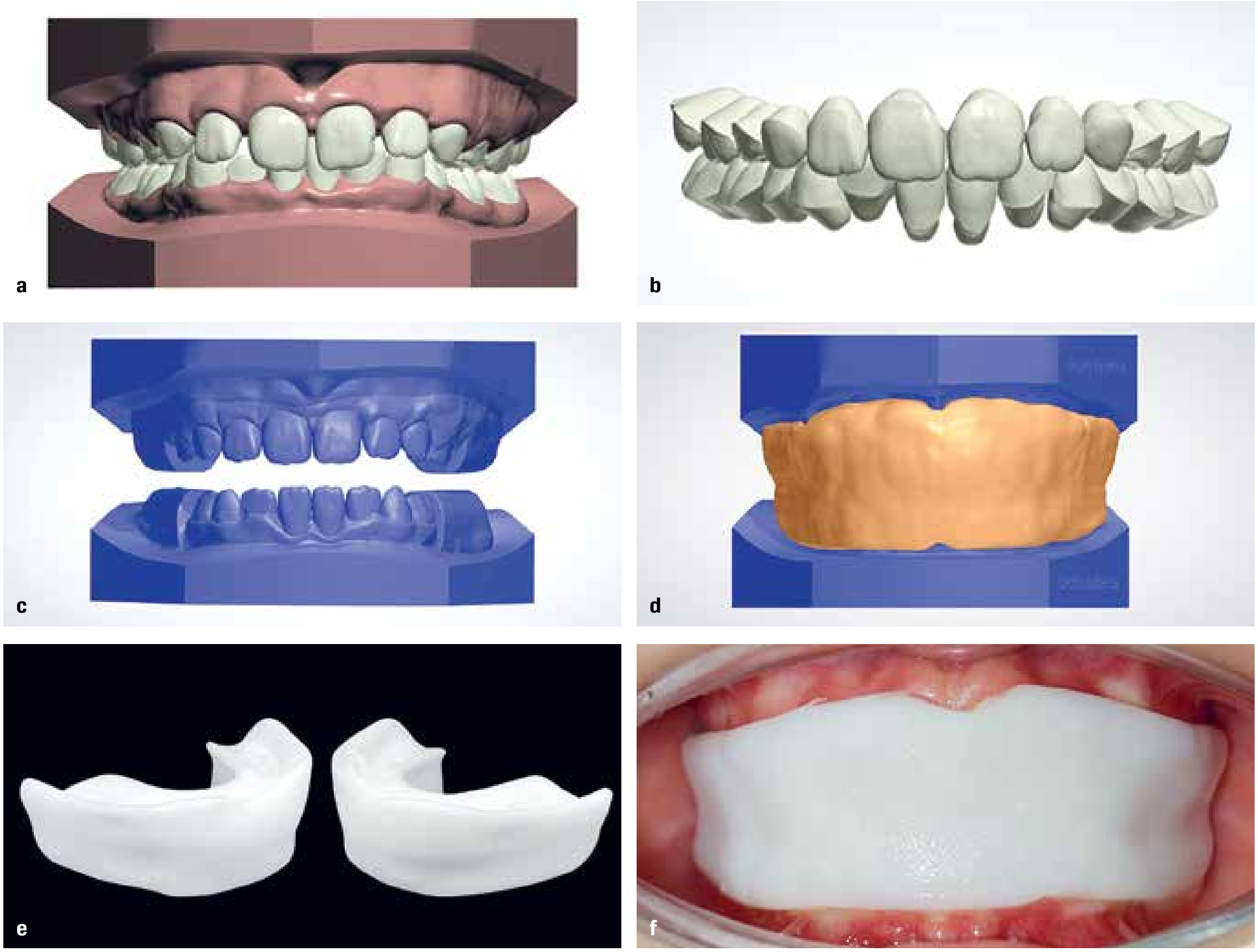

Fig 7-12 *(a and b)* Teeth setup for UNIKO design. *(c and d)* UNIKO design in 3Shape. *(e and f)* Finalized UNIKO appliance.

UNIKO appliance

Various types of preformed elastomeric devices have been proposed to be used together with myofunctional exercises to counteract detrimental habits and facilitate more harmonious growth of the stomatognathic system in cases of dental crowding and craniofacial growth abnormalities.[4,5] The decades of overall positive experience gained by the author in using this approach and the recent availability of digital tools has enabled the development of a new fully customized elastomeric device, the UNIKO appliance (Dextra Group I&D; Fig 7-12). This device is used in the mixed dentition or early permanent dentition for myofunctional intervention and as a guide for tooth eruption. The appliance can better align the teeth due to the higher degree of flexibility of the newer materials compared to the preformed stock versions previously available, and all aspects of its fit can be customized because it is designed digitally based on dental arch scan data. The individualized setup guarantees precise and reliable customization, maintaining the initial arch shape and increasing the chances that the desired Class I correction with associated improved function and greater stability can be achieved.

Cervera PEEK appliance

Traditionally, the Cervera appliance consists of a resin palatal button connected to an anterior metal bite plate and metallic wire–supported resin buccal shields. This design provides resolution for anteroposterior malocclusions as well as relief of deep bites. With the advancements in material science and technology, this device can now be digitally designed and manufactured entirely in PEEK, which is biocompatible, hydrophobic, and capable

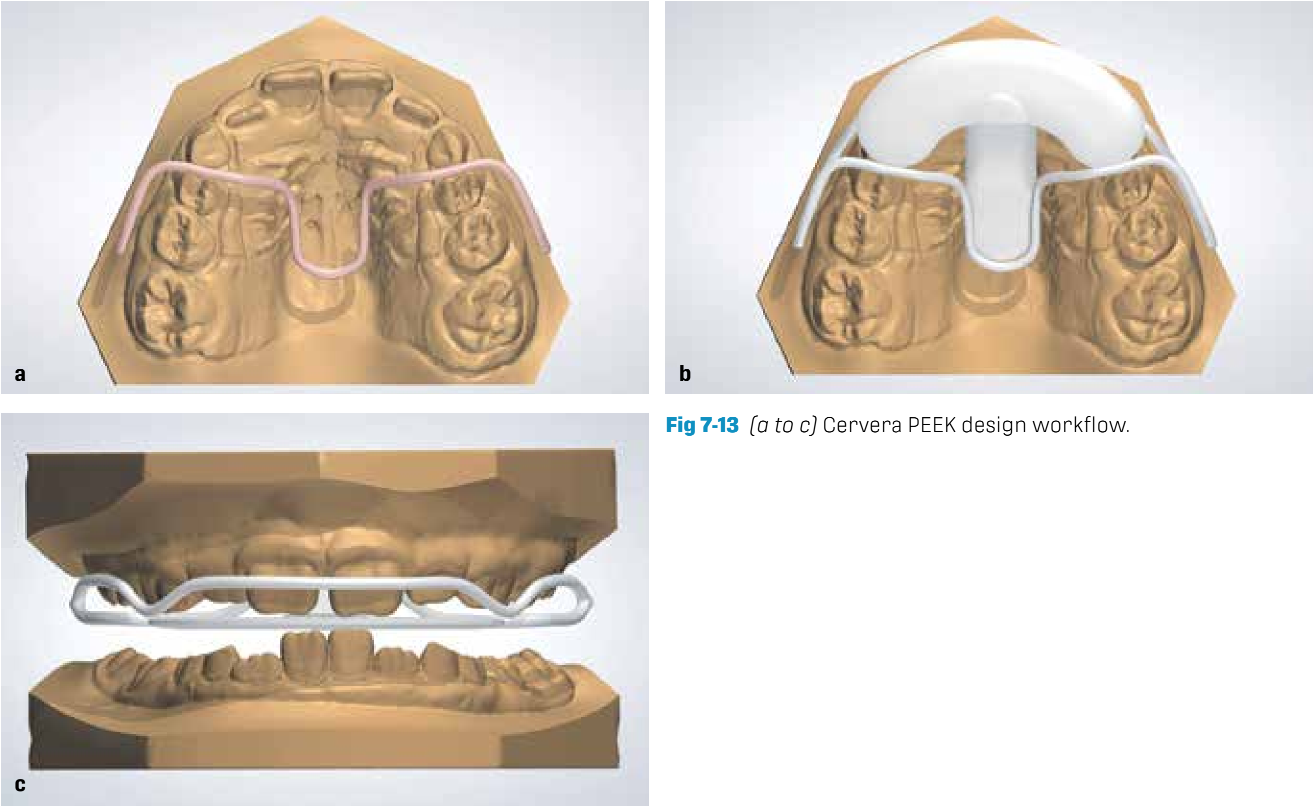

Fig 7-13 *(a to c)* Cervera PEEK design workflow.

of maintaining its physical properties in the oral cavity and under conditions of autoclave sterilization. The bite plate is designed and integrated with a palatine button and with the supports of the lateral shields (Fig 7-13).

Conclusion

The inherent nature of digital technology is to undergo continual development and improvement. This applies to all of its components, software, and hardware as well as the materials from which the appliances that have been individually designed are constructed. This continuous evolution undoubtedly "drags" all aspects of our life along with it. Change is the only constant that can be relied upon; therefore, it falls to the professional to constantly be aware of these changes in the same way that computer programs are constantly being upgraded. Failure to do so will leave the uninformed behind and impact the potential benefits to our patients. The utilization of these technologic tools will also benefit the specialty of orthodontics as well as the individual specialist. The future looks bright.

Acknowledgments

Special thanks go to Drs Jasmina Primozic, Alessandro Gianolio, and Matteo Beretta and Alessandro Mangano for their contributions on the "Lego" Frankel, UNIKO, and Cervera PEEK appliances, respectively.

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8

In-House Customized Orthodontic Brackets: UBrackets Software

Nearchos C. Panayi

A customized orthodontic appliance is one that is made specifically for an individual patient to effect a predetermined orthodontic result. Such custom orthodontic appliance systems are based on a "setup" of the dentition, which affords the clinician a direct method of visualizing multiple treatment outcomes, "keeping the end in mind." The orthodontist can predict the final occlusal result in the setup, which will also serve as the basis for the designing and printing of the conceptualized customized fixed appliances. This digital customization can be applied to even the most basic orthodontic appliance—the bracket itself.

Evolution of Orthodontic Brackets

Various kinds of orthodontic appliances were sporadically mentioned in articles and dental books prior to Angle's fixed orthodontic appliances.[1,2] But his edgewise appliance—the bracket—has been the treatment modality of choice since its inception in 1925. Angle arrived at this appliance through developmental stages resulting from his experiences with his earlier devices, including the E-arch, pin and tube, and ribbon-arch appliances.[3,4]

Although Angle's mechanism and essential design have endured, his edgewise appliance has been refined to reflect advances in material sciences and understanding of concepts of malocclusion. The most notable refinement of the edgewise appliance was Andrews's introduction of preadjusted brackets, which had built-in compensations for dental morphology and interdental relationships for each tooth, called the "straight-wire appliance." Unlike Angle's original appliance, which used the same universal/standard brackets for all teeth, Andrews's modification retained the edgewise approach but significantly reduced the amount of archwire bending required.[5]

Other appliances have also been introduced. For example, Begg, who was an accomplished student of Angle's from Australia, developed his appliance based on the precursor to edgewise, the ribbon-arch appliance. Kesling, a proponent of the Begg technique in the United States, developed a hybrid between the two designs called the Tip-Edge appliance (TP Orthodontics), referred to as the "modern Begg technique."[6,7]

For nearly five decades, the edgewise brackets used to treat patients were soldered to bands that were individually fitted for each tooth. This lengthy and painstaking procedure was eliminated with Newman's introduction of direct bonding using composite adhesives.[8] Indirect bracket bonding as described by Silverman et al became a viable tool soon thereafter.[9]

Lingual orthodontics as a technique to hide the edgewise appliance behind the teeth for esthetic purposes was introduced by Fujita in 1979.[10] This technique in particular has evolved significantly with the use of digital technology in recent years. Wiechmann introduced the first fully customized lingual orthodontic appliance, the Incognito appliance (3M).[11,12] This was a significant advancement for the development of customized orthodontic brackets with the use of CAD/CAM technology.

Since the introduction of the edgewise appliance, products have been developed to increase treatment efficacy, enhance esthetics, improve patient comfort, and facilitate more efficient and more accurate treatment. For example, self-ligating orthodontic brackets have been refined and reintroduced, as well as plastic brackets, ceramic brackets, gold (plated) brackets, superelastic wires, virtual indirect bonding (IDB) using CAD software, and more recently Creekmore's concept of customized orthodontic brackets.[13]

Driven by digital technology, medicine has taken strides to encompass all aspects of patient care in a holistic, individualistic manner. This is occurring in orthodontics as well. Diagnostic record taking, classically undertaken as separate measures, can now be coalesced into a single virtual patient, which can be visualized on a single computer screen. CAD software now permits diagnostic dental setups mainly for the fabrication of clear aligners and IDB trays. However, moving teeth virtually using software does not take into account the specific biologic envelope of the patient, consisting of the alveolar bone characteristics, root morphology, root position, occlusion, skeletal abnormalities, temporomandibular joints (TMJs), habits, or the force systems employed during the whole of the orthodontic treatment, which are themselves related to the setup. In essence, it is a mechanistic approach with biologic ramifications. Undoubtedly, maximization of the potential of such digital technologies will require a better understanding of the variety in nature.

Fixed Appliance Customization

The recent advances in digital technologies such as surface scanning, volume scanning, and additive manufacturing (3D printing) have allowed customized orthodontic brackets to become a possibility in clinical orthodontic practice. After all, companies now provide the service of manufacturing tailor-made fixed appliances (Incognito, Insignia, LightForce). Nevertheless, the usefulness and efficacy of customized fixed orthodontic appliances remains a point of controversy in the orthodontic literature. It has been reported that no difference in outcome assessment has been found between orthodontic treatment using conventional straight-wire fixed appliances and custom-made orthodontic appliances. Penning et al, when comparing noncustomized to customized brackets, found that the customized brackets group encountered more bracket bonding failures, required more time for planning and design, and led to more patient complaints. It was also reported that there was no significant difference in overall treatment duration between these groups.[14] However, Brown et al reported that orthodontic treatment using customized brackets required less time and fewer archwires to complete treatment.[15] Similarly, it has been reported that customized brackets were found to exhibit debonding rates superior to those of noncustomized fixed appliances.[16] In another comparison between Insignia customized brackets and preadjusted appliances, Weber et al found that "the ABO scores, which emphasize the details of tooth positioning, were superior in the Insignia group, especially alignment/rotations, overjet (arch coordination) and root angulations."[17]

Another concept that has been questioned by many authors is the straight-wire appliance. Many argue that an appliance fabricated in a disassociated factory with a "one size fits all" approach is not reflective of the range of malocclusions and tooth morphology that exist in patient populations. For this reason, Lim and Kim conclude that fully customized brackets should be used.[18] Miethke and Melsen also express that "it is unreasonable to anticipate that any straight-wire appliance without individual adjustments can be anticipated to lead to an optimal tooth alignment," further explaining that "if the straight-wire approach should be followed, the bracket would have to be custom made."[19] A true straight-wire appliance is almost impossible to achieve. Variations in tooth morphology, inaccurate bracket placement, skeletal discrepancies, and appliance mechanics deficiencies are some of the possible sources for this unlikelihood.[13,20–23]

On the other hand, filling the edgewise slot entirely with appropriately sized rectangular wires must occur in order to achieve any designed full tooth movement outcome from a customized appliance.[24] Nevertheless, the treatment result in terms of interocclusal fit of the arches does not necessarily coincide with the digital setup because factors such as the performance of leveling biomechanics, the severity of the original malocclusion, and the mandibular plane angle play a significant role.[17] According to Lim and Jeong, despite the possible limitations in fully achieving the preplanned results, customized brackets have their value in that they may reduce round-tripping tooth movements by reducing bracket repositioning or wire bending.[24] It was also concluded by Jheon et al that moving toward precision in orthodontics passes through appliance customization, which enables the orthodontist to deliver optimal, efficient, safe, and reproducible orthodontic treatment.[25]

Presently, two new companies involved with customized orthodontic brackets have emerged following the example of established orthodontic companies (eg, Ormco, 3M, etc), but they use a different way of bracket manufacturing. LightForce is a company that uses a ceramic bracket concept designed on a digital patient setup that is continuously 3D printed. Klowen, on the other hand, uses ready-made metallic brackets to which the base is customized by the orthodontist using existing composite resin adhesives as part of an IDB approach. Both of these companies work with received digital scans of a given patient's dentition, from which the customized brackets and accompanying IDB trays are designed and printed for delivery back to the orthodontist.

In-House Fixed Appliance Customization

At this time, customized orthodontic brackets are only manufactured by external companies offering this service to orthodontists. A few sporadic attempts have recently been made to accomplish this in-house; however, thus far, these attempts have only been academic in the form of research involving the applications of emerging technology.[26,27] Due to the complicated nature and multistage workflow procedure as well as the expense entailed in this procedure, it has only been undertaken by companies that have the technology and the know-how to manufacture customized orthodontic brackets and the foresight to invest in developing the in-house option.

Customized appliances are fabricated in a sequence of procedures that require special technologies and materials. In a scenario where an orthodontist would be able to design and manufacture customized orthodontic brackets, the following would be needed:

- Surface scans of the dental arches
- Digital panoramic and cephalometric radiographs or CBCT scans
- Digital photographs
- Orthodontic CAD software in order to perform the digital setup
- Predesigned virtual orthodontic brackets that would be customizable
- Dedicated orthodontic software that would virtually place and adapt customized orthodontic brackets onto the digitized teeth
- Special materials for 3D printing or milling
- 3D printer or milling machine for the manufacture of the customized brackets
- IDB tray for bracket bonding
- Wire-bending robot for the manufacture of wires or a prototype wire exported from the orthodontic CAD software that would be manually copied and used in all treatment stages

Patient records are routine to obtain, and a digital setup is also readily available as a module in all aligner orthodontic software (DeltaFace, Maestro Dental Studio, 3Shape Orthoanalyzer, Onyx Ceph, etc). However, the only currently available software for bracket customization is UBrackets, which, as of the time of this compilation, is in its beta version and is being tested in vitro and in vivo. The software is continuously expanded to include new tools and functions in order to help the orthodontist to design and manufacture in-house customized brackets. With the advances in digital technology and, more specifically, computer and software engineering, the composition of this software was reportedly not very difficult, given the early stage it is currently in. This software is discussed later in this chapter.

An important issue that has yet to be resolved is the inclusion of information regarding dental root length and shape, the characteristics of the periodontal tissues, the TMJs, and the patient's own characteristics and habits on the biologic process of the tooth movement. Unfortunately, these factors cannot yet be integrated into the digital setup.

Nevertheless, in the scenario described above, the most significant technical challenge is the "undigitization" of the customized brackets' 3D files—the manufacturing of the brackets. The whole procedure consists of many fragments that have to flow smoothly from one to the other in order to accurately manufacture the intended customized brackets. The printing material must have specifications that when used to print the appliance would behave similarly to existing metal or ceramic preadjusted fixed appliances. The 3D printer must also have the capability to print with high resolution. Failure to do so would result in an inaccurate bracket, base, and slot dimensions. In-house 3D printers that could fulfill these requirements have started to appear on the market. However, a high printing resolution at present is not necessary for any of the appliances that are

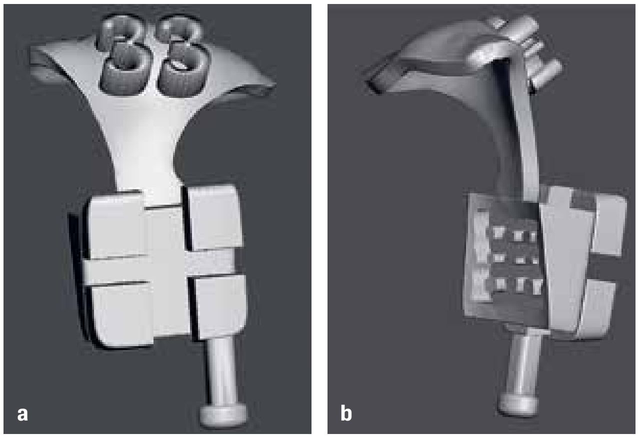

Fig 8-1 *(a)* Canine customized bracket. *(b)* Customized bracket base.

manufactured with 3D printers (dental models, IDB trays, etc). For this reason, 3D printer companies do not produce in-house high-resolution printers. The demand for accurate printing of small objects like brackets will force companies to develop high-resolution printers, while new materials for bracket printing will also be invented.

Postprinting resin curing is also a procedure that has to be accounted for, as it gives the object its final characteristics. Metal printing can be performed in laboratories where all the necessary machines for printing are present, but currently this is not possible in the office. Unfortunately, power bed fusion printers are generally not capable of accurately printing the slot of a bracket. CNC milling is an excellent tool that results in highly accurate 3D milled objects, but milling is not an easy procedure; it requires trained personnel and special milling material and as such carries a much higher cost.

The in-house bracket customization concept has an appeal to the modern clinician because it allows the result of the entire process of holistic diagnosis and treatment planning to culminate in the hands of the practitioner as the individualized tool to deliver the patient-specific treatment. UBrackets is proof that bracket customization could be the next significant step in orthodontics. An excellent parallel example of this concept is clear aligners, as popularized by Invisalign (Align Technologies). When the concept of applying CAD/CAM capabilities to produce serial removable appliances for the purposes of correcting malocclusions was first offered commercially, there was certainly skepticism in the field. However, the system has steadily evolved and established itself as a viable orthodontic tool. The UBrackets software presented in this chapter is a similar product in that it is establishing and catalyzing the customization of fixed appliances within a self-sufficient orthodontic office.

Using Meshmixer in Orthodontic Bracket Customization

An attempt at bracket customization was made by the author using general-purpose CAD software. At the time, software that could help in designing such brackets did not exist. Logically, orthodontic companies that manufacture custom orthodontic brackets do not have any incentive to provide open access to their proprietary software for such a procedure. For that reason, a general open-sourced CAD software was used in order to design customized brackets (Meshmixer). After many weeks of trials, designing and redesigning, and a few failures, the author managed to establish a protocol for the designing of metallic customized orthodontic brackets.

A patient was chosen to undergo treatment with customized orthodontic brackets following proper informed consent. Intraoral scanning was performed, and all the necessary records were taken (radiography, photographs, clinical examination). The first step was to import the dental scans into the DeltaFace software and then to perform a virtual setup while "keeping the end in mind." Then the setup digital records were imported into the Meshmixer software for design of the brackets.

Designing

Using CAD software that is not specifically intended for custom bracket design is not an easy task, and it required more than 20 trials in order to design the brackets correctly. Even still, these brackets were extremely basic four-wing brackets with no specific dimensions that were fitted to match each tooth separately (Fig 8-1). Hooks were designed in Shapr3D (Apple), while all other parts were designed in Meshmixer. The Hiro system laboratory procedure was the basis for the method followed by the author to design the orthodontic brackets.[28]

An ideal arch was designed as close as possible to the most prominent or best-matching part of the setup teeth with a thickness (buccolingual dimension) of 0.025 inch (slot of a 0.018 × 0.025–inch bracket; Fig 8-2). Then, using Meshmixer tools in a specific order, the height of the slot

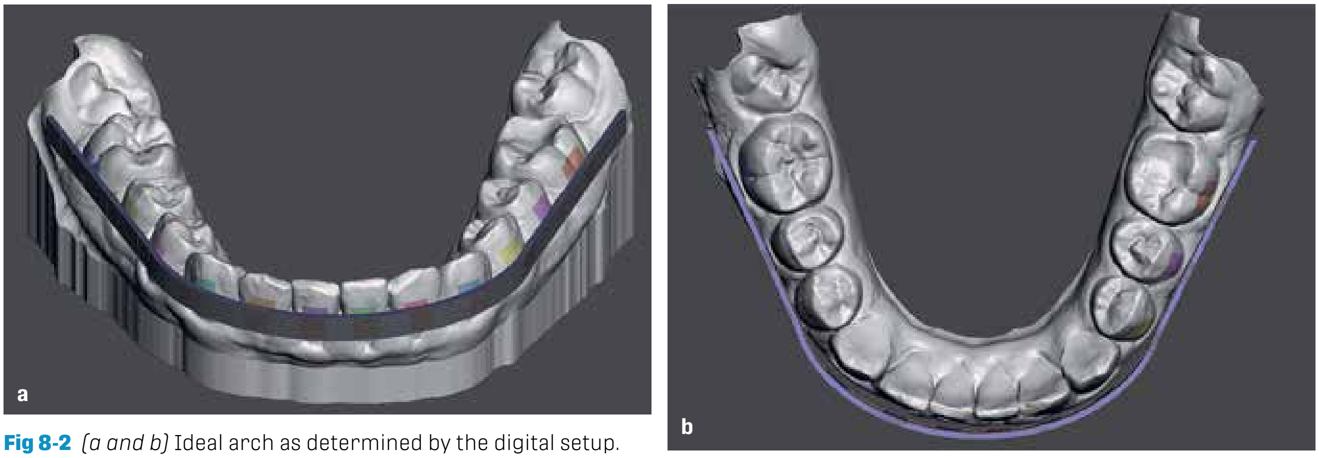

Fig 8-2 *(a and b)* Ideal arch as determined by the digital setup.

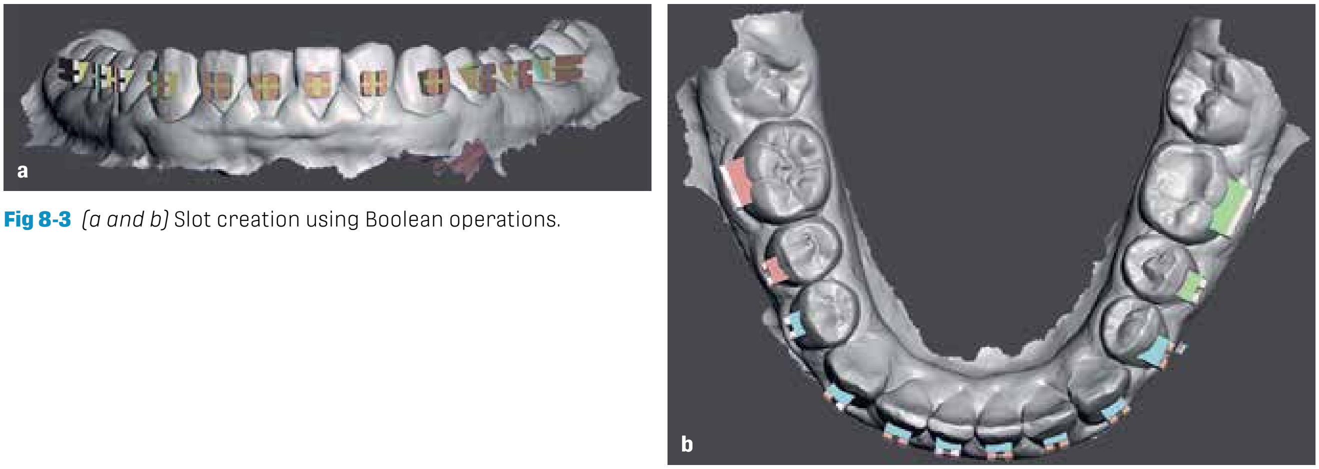

Fig 8-3 *(a and b)* Slot creation using Boolean operations.

(0.018 inch) was added to the slot in-out dimension (Fig 8-3a). The virtual wire was prepositioned in the correct perpendicular dimension of the teeth so that the brackets could be easily designed without touching the gingiva or the opposing teeth. Using object extrusion tools, Boolean operations, and other manipulations, the slot plane was extended to the tooth surface from which the shape of the custom bracket base was determined (Fig 8-3b). The bracket, in essence, is a standard bracket that was adapted to provide a third-order (torque) prescription as defined by the orthodontist at the setup stage and manifested in the bracket's base (Fig 8-4). The in-out thickness of the bracket was also predetermined by the arch that was designed previously.

Difficulties in printing the brackets prevented us from designing four-sided molar tubes. The difficulty and possible inaccuracy in printing a tube in a selective laser melting (SLM) printer forced us to make a bracket-like tube with no buccal sidewall (Fig 8-5). This tube configuration created wire retention problems that were somewhat time-consuming to resolve by ligating the wire into the bracket. In hindsight, some of these design and printing issues could have been solved differently had we been more versed in the software program at the time; but as they say, "Hindsight is 20/20." This brings to mind a quote by a noted Greek philospher, poet, and legislator, Solon the Athenian: "I'm getting older while being taught all the time."

Fig 8-4 Prescription in the bracket base.

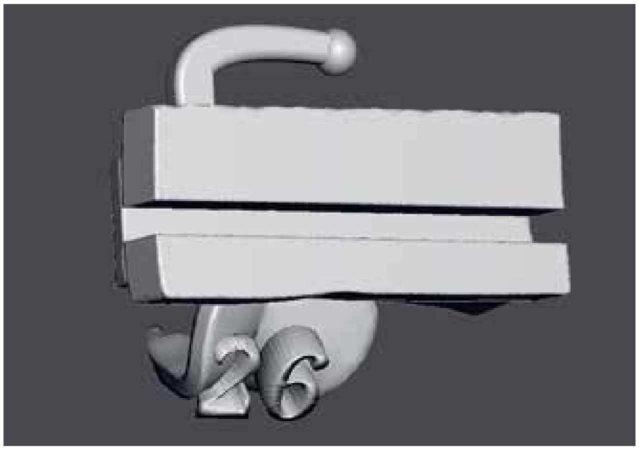

Fig 8-5 “Bracket-type tube” for easier metal printing.

Fig 8-6 Customized brackets.

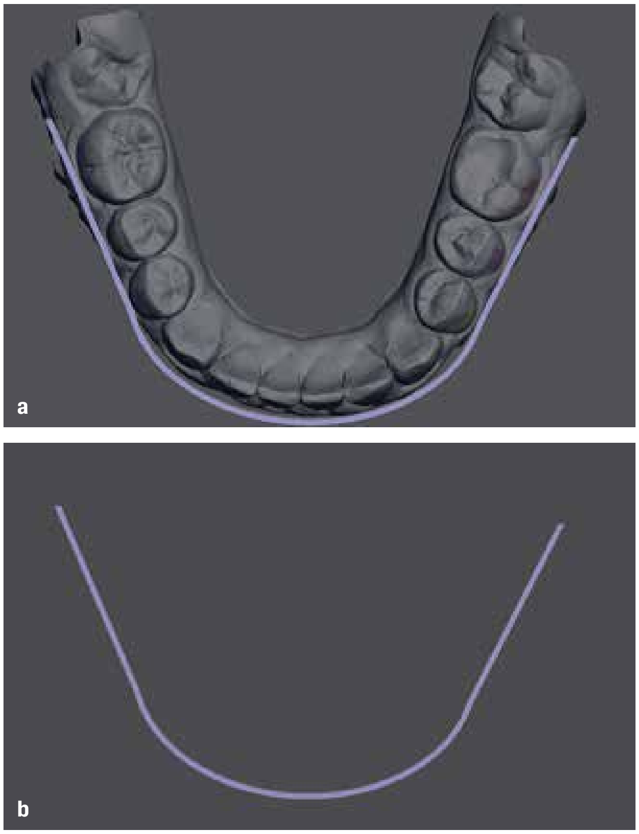

Fig 8-7 *(a and b)* Prototype archwire.

Although designing in the software initially seemed acceptable, due to screen magnification, the bracket dimensions were overestimated, which resulted in the designing of some bracket parts to be too small (Fig 8-6). For instance, although on the computer screen the wing undercut seemed to be adequate for an elastic module, in reality it was deficient, creating the need to engage nearly all of the customized brackets with metal ligature ties. Fortunately, no problems were observed in the exact positioning of the brackets, and most importantly, the dimensions of the slot were accurately printed as designed in the computer, albeit without any technologic means for measuring such small dimensions. This was concluded when after 3 months of treatment, a 0.017 × 0.025–inch multistrand archwire was easily inserted. The archwires were exact copies of the prototype virtual wire that was used to align the slots of the brackets (Fig 8-7). The prototype wire was exported from Meshmixer and 3D-printed for wire replication at each stage of treatment.

It is obvious that a fully customized fixed orthodontic appliance consists of customized brackets and customized archwires. Using nickel-titanium (Ni-Ti) archwires with a preformed shape in a customized orthodontic appliance “destroys” the whole customization concept while weakening the “end in mind” logic.

Algebraic Boolean operations were used extensively to design the brackets, while a mesh was designed at the base of the brackets for bracket anchorage purposes (see Fig 8-1b). At the end of designing, it was realized that the brackets could not have been accurately placed without the use of guide extensions. For that reason, bonding guide extensions were designed on the occlusal surfaces of the teeth and labeled with the tooth number on them (Fig 8-8).

Fig 8-8 Bonding guide extensions.

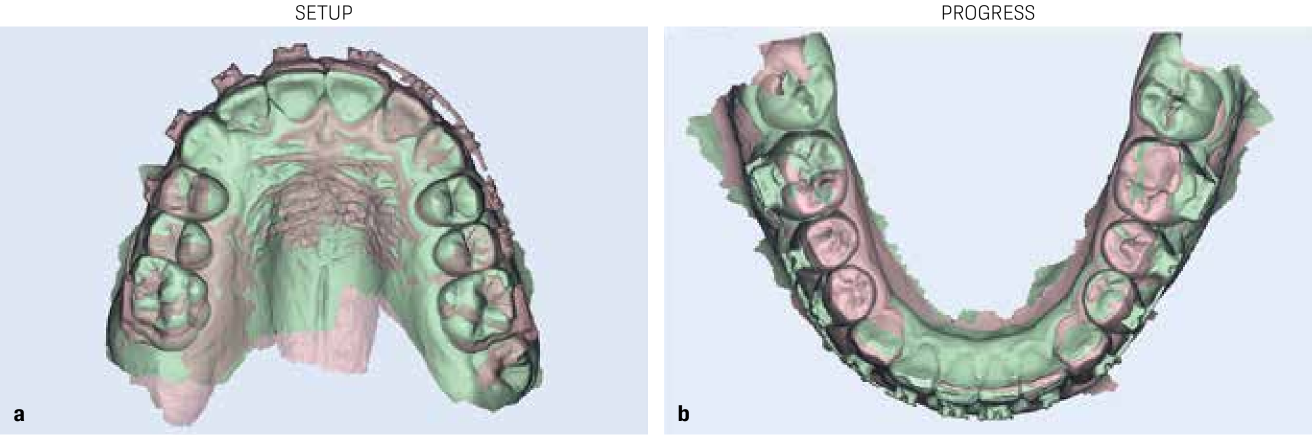

Fig 8-9 *(a and b)* 3D superimpositions of the setup files and the progress scan of the maxillary and mandibular dental arches using Maestro Dental Studio software.

The guide extensions were made to be very thin in order to permit their easy removal after bonding. The printed numerical labels were of poor quality due to their very small size. In addition, there was an attempt to try to design the width and height of the brackets according to general trends of current bracket manufacturing such as making the mandibular incisor brackets smaller in both dimensions. Due to the long time it took to design the brackets, it was not considered to find a way to transfer the brackets to the original malocclusion using an indirect transfer tray.

Printing

Although it initially seemed that the designing of the brackets would be the biggest challenge, printing them was found to be an even greater source of difficulty. However, this too can be related to a necessary learning curve.

Using a laser sintering printer and cobalt-chrome (Co-Cr) is a commonly used technique that was anticipated to allow an easy method to print the brackets. Well, proper positioning of the objects to be printed on the virtual platform of the printer is one of the most important parameters, and this was only realized after the printing procedure was completed and three brackets were printed with deficiencies in one of their wings. Luckily, the base and the slot of the brackets were very well printed. Wire insertion was quite easy, but ligation was a problem. In the end, steel ligation was needed. Photographs and surface scanning were taken every month for treatment progress monitoring. Two bracket failures occurred, and rebonding was done using a partial IDB tray made on a printed dental cast where all the brackets were also printed. Treatment was initiated using a 0.014-inch Ni-Ti wire formed with pliers on the initial wire prototype, which was followed by a 0.016-inch Ni-Ti wire 4 weeks later and a 0.016-inch stainless steel wire 4 weeks thereafter. A multistrand 0.017 × 0.025–inch wire was used after yet another 4 weeks, followed by a 0.017 × 0.025–inch stainless steel wire. A rectangular Ni-Ti or superelastic preformed wire was not used to avoid the deviation from the initial wire prototype arch form.

The most important part of the progress evaluation was the comparison of the several intraoral scans taken using special software—Meshlab and Maestro Dental Studio. The comparisons were made between the initial malocclusion and each treatment stage. The general conclusion is that expansion was avoided and treatment was very fast (although of course there was no control group for comparison). At the end of the alignment phase and before Class II elastics, a comparison was made between the initial setup and the current intraoral scan. Figure 8-9 presents the superimposition of the initial digital setup with the scanning of the dental arches in different colors after 4 months of treatment using the Maestro Dental Studio software. The purpose was to check whether the customized brackets predictably fulfilled the orthodontic result initially planned in the setup. The comparison showed strong similarities between the two virtual dental casts, although treatment was not yet finished. In general, in all intra-arch dimension comparisons, the setup was very much in alignment with the surface scanning. The wires and the customized brackets could not have achieved the Class II correction alone. For this reason, Class II elastics were used over the

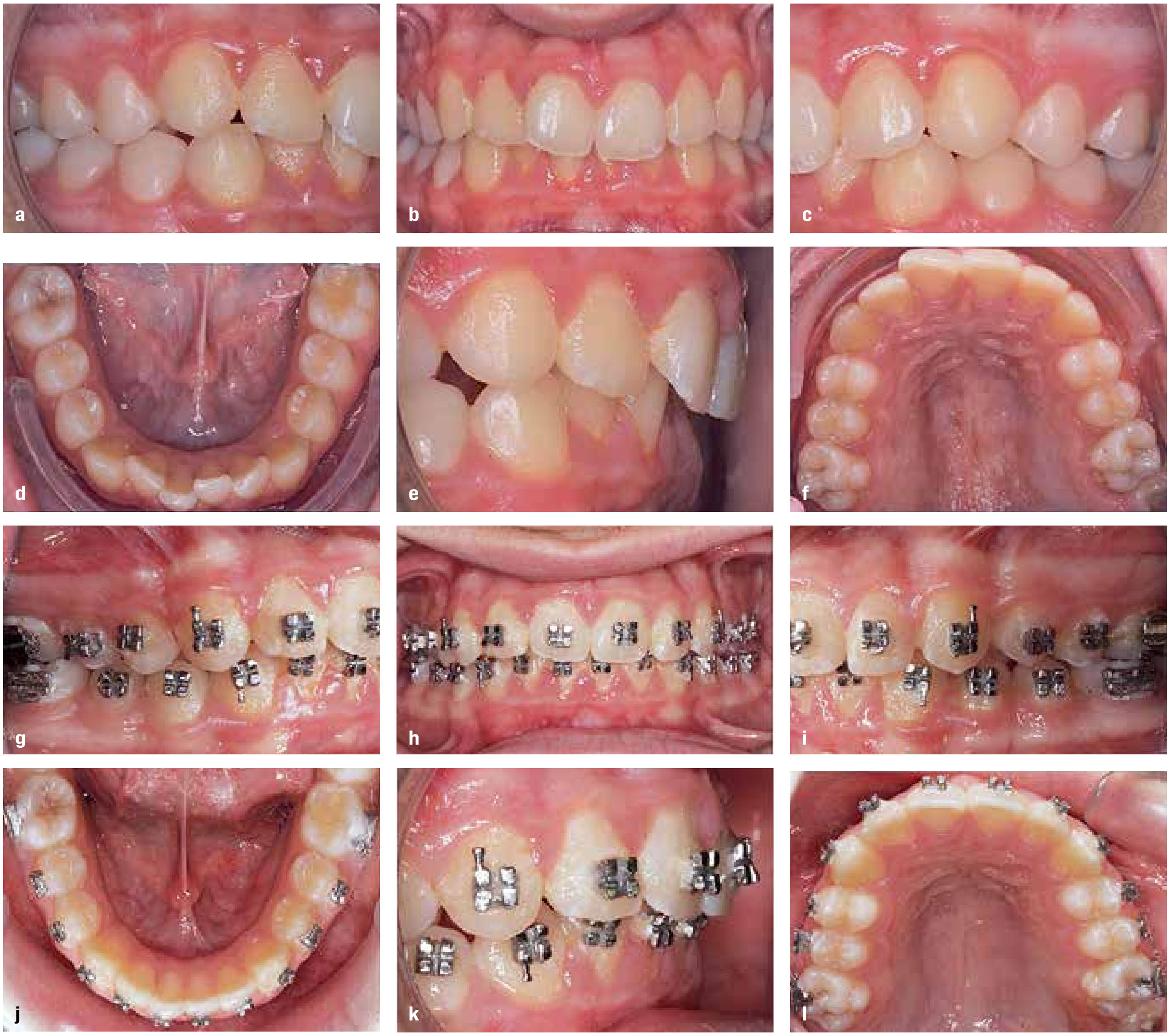

Fig 8-10 *(a to f)* Initial intraoral photographs. *(g to l)* Progress intraoral photographs.

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course of 4 months of treatment with 0.017 × 0.025–inch stainless steel archwires.

Figure 8-10 presents the initial intraoral photographs, the progress photographs after 3 months of treatment, and the final intraoral photographs after treatment. Figure 8-11 shows the comparison of the initial and final 3D scans using the Maestro Dental Studio software. The green color represents the final occlusion. In order to investigate whether the customized brackets accomplished the initial treatment plan based on the digital setup, a comparison was made between the setup 3D files and the final 3D scanning (Fig 8-12). It can be seen that, despite the difficulty in designing and printing, the customized brackets satisfied the initial setup in a shorter than anticipated time with no archwire bends and no use of elastics for occlusal settling needed.

Based on these results, it could be stated that the future of bracket customization is very promising. The combination of a dedicated orthodontic software for bracket customization and accurate printing capabilities will be the next evolution in orthodontics, empowering in-house manufacturing of customized brackets for our patients. Currently the author is working out the kinks of printing brackets in the office using special resin in a high-resolution 3D printer.

Fig 8-10 ***(cont)*** *(m to r)* Final intraoral photographs.

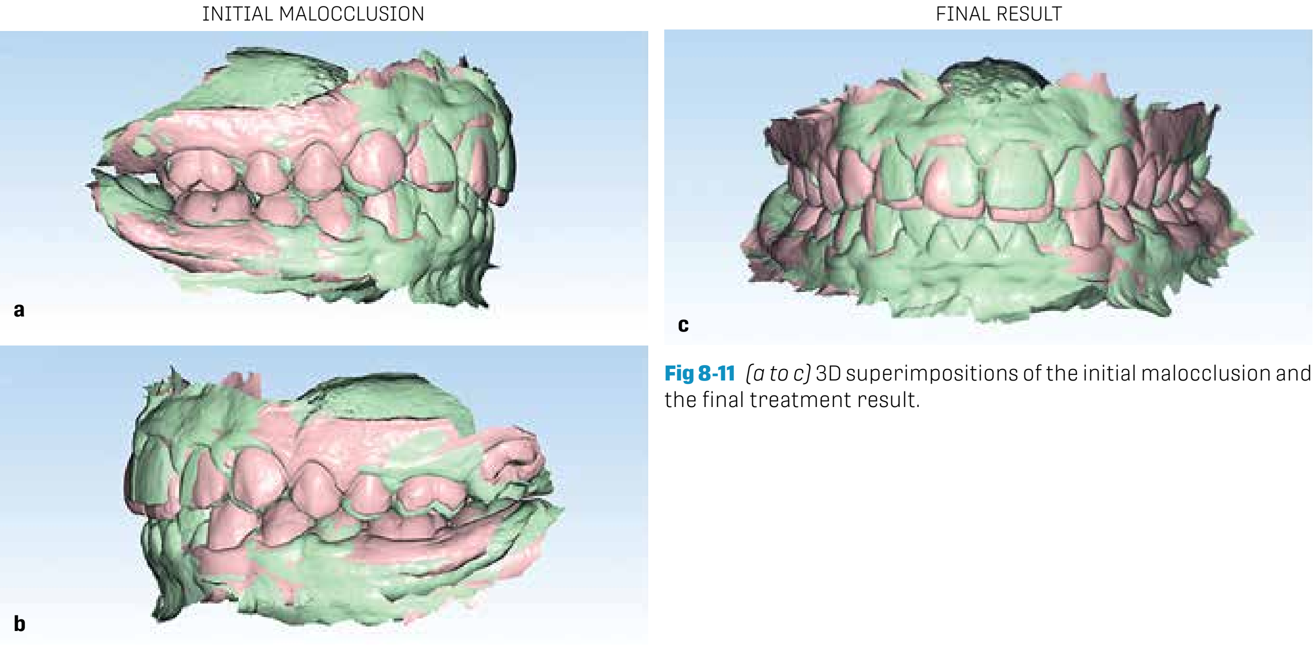


Fig 8-11 *(a to c)* 3D superimpositions of the initial malocclusion and the final treatment result.

Fig 8-12 3D superimposition of the setup virtual file with the final treatment result.

UBrackets Software

A dedicated orthodontic CAD software is needed in order to bring the in-house bracket customization concept to reality. This software must be user-friendly and fast and offer automations and tools for performing the needed bracket customization. Initially, orthodontic CAD company Coruo created DeltaFace software, which was a software for model base and aligner design. Coruo recognized the demand for customization in medicine and dentistry and supported the author in developing and launching the UBrackets software based on in-house customized bracket design. The software is based on existing DeltaFace software, particularly the aligner module. This part is essential to be able to plan the teeth setup. As previously mentioned, at the time of this writing the software is in its beta version, with most of the essential functions included. A few other tools are scheduled to be included to help the operator design customized brackets.

The first stage in bracket customization with UBrackets is to perform a digital setup in the software adhering to the following steps:

1. Maxillary and mandibular dental scan importing
2. Dental model bases design
3. Segmentation
4. Local axes definition
5. Setup procedure

In the next stage, the operator chooses the customization procedure. In the UBrackets software, bracket customization can be performed in two different ways:

1. Customized bracket bases option
2. Customized brackets option

Customized bracket bases

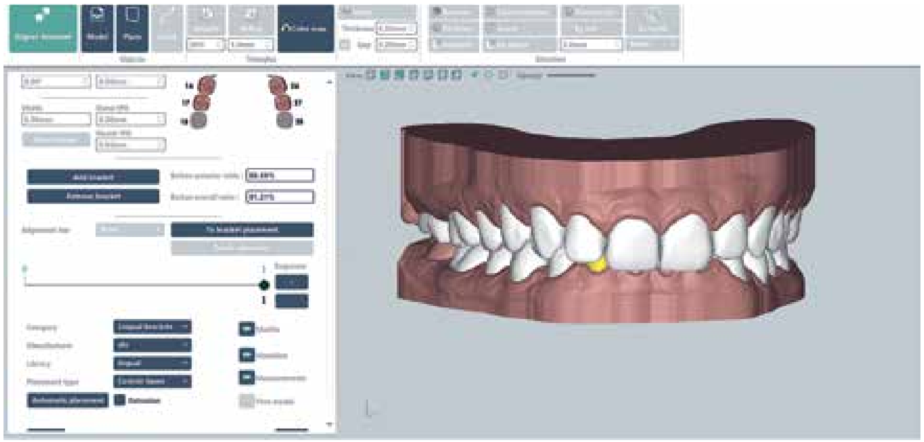
This module enables the orthodontist to design customized orthodontic bases using brackets that are found in the software's library. The idea was first conceived from the design of customized brackets in Meshmixer, as previously described. Printing of a fully customized bracket at this point of development is more difficult to achieve (although attempts are currently underway). In contrast, the concept of customizing the bracket base is easier and more predictable. The bracket's base contains almost all the prescription details for tipping, torquing, and in-out dimensions.

As an alternative to a totally customized bracket, the digitized versions of multiple existing labial or lingual brackets can be used as provided by their manufacturers for inclusion in the software's library. Because the UBrackets software is still in beta version, only one 0.018 × 0.025–inch labial (Delicate, DTC) and lingual (ORG, DTC) orthodontic brackets set types are included (Fig 8-13). These will be supplemented with many more bracket sets, as described above, as product development continues, allowing for clinician preference within the customization procedure.

Figure 8-14 presents the automatic positioning of the ORG lingual brackets. The space between the bracket base and the tooth surface will be filled with the chosen bracket adhesive during the IDB procedure. The operator can move all the brackets together with the virtual wire in a vertical direction or in a left and right differential vertical movement (upward movement for the left buccal segment and downward movement for the right segment or opposite) or choose a center of rotation around which the same can be turned with automatic adjustment of the wire/brackets (Fig 8-15). In addition, each bracket can be moved individually distally or mesially, lingually or buccally, or horizontally rotated, with the wire adapting automatically to these movements (see Fig 8-14). The bases of the brackets can be extruded to the tooth surface with a special tool (Fig 8-16). This manipulation represents the amount and shape of the customized base that will be added using composite by the orthodontist upon IDB, and the software can calculate the volume of adhesive required to perform this task (Table 8-1). The author manually created a special volumetric composite syringe in order to apply the exact composite needed for each bracket base, and soon a dental composite manufacturing company will develop this syringe for commercial use.

A very useful tool is the collision occlusogram that presents possible collisions of brackets with the opposing teeth (Fig 8-17). The software is able to present the dental model in the pre-setup stage (original position) as well as the setup position (Fig 8-18). The next step is to export the initial models with the brackets and the final wire that will serve as a prototype for all the wires to be used in the treatment in STL format (Fig 8-19).

Fig 8-13 UBrackets customized brackets module.



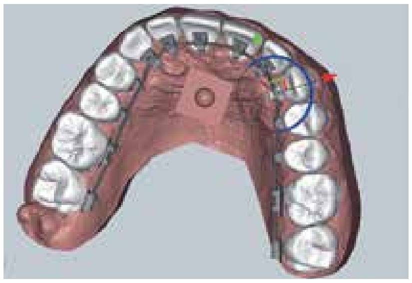


Fig 8-14 Automatic positioning of the ORG lingual brackets in the UBrackets software. Mesiodistal, labiolingual, and rotational movements are possible for each bracket; the wire simply adapts to the movement.

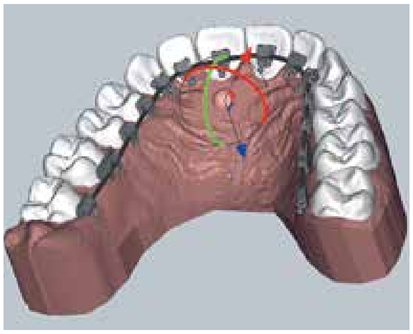


Fig 8-15 Manipulation for the anteroposterior and right-left rotation of the brackets/archwire system.

Fig 8-16 Bracket base extrusion to the teeth surfaces in the final setup.

Fig 8-17 Collision of the brackets on the antagonist teeth is clearly presented in the collision diagram.

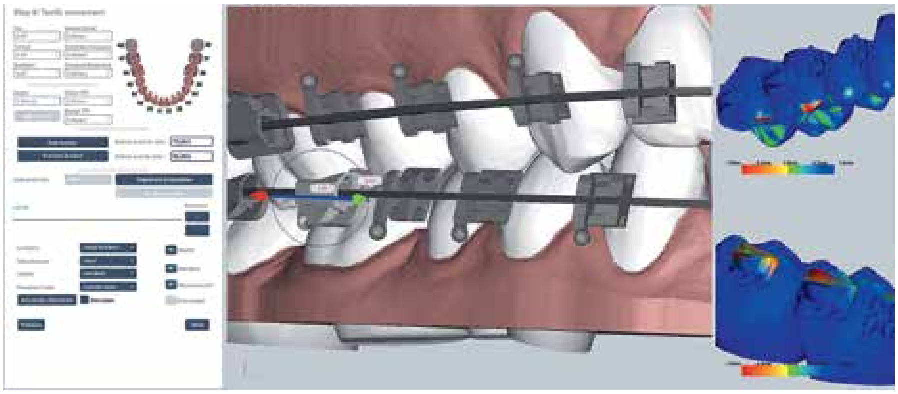
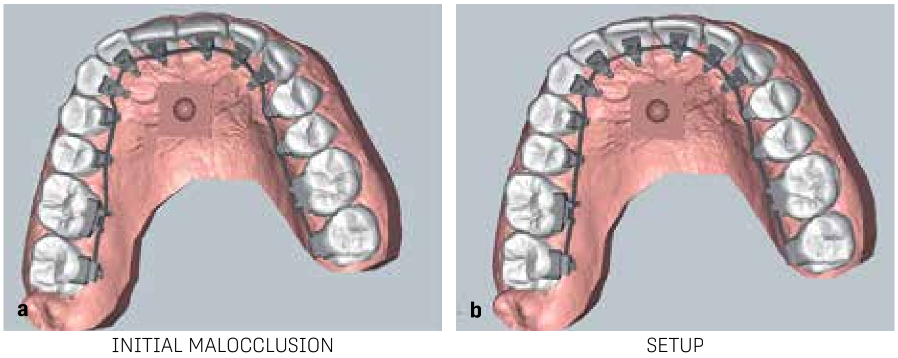


Fig 8-18 *(a)* Dental model with brackets and archwire in original malocclusion. *(b)* Dental model with brackets and archwire in the setup position.



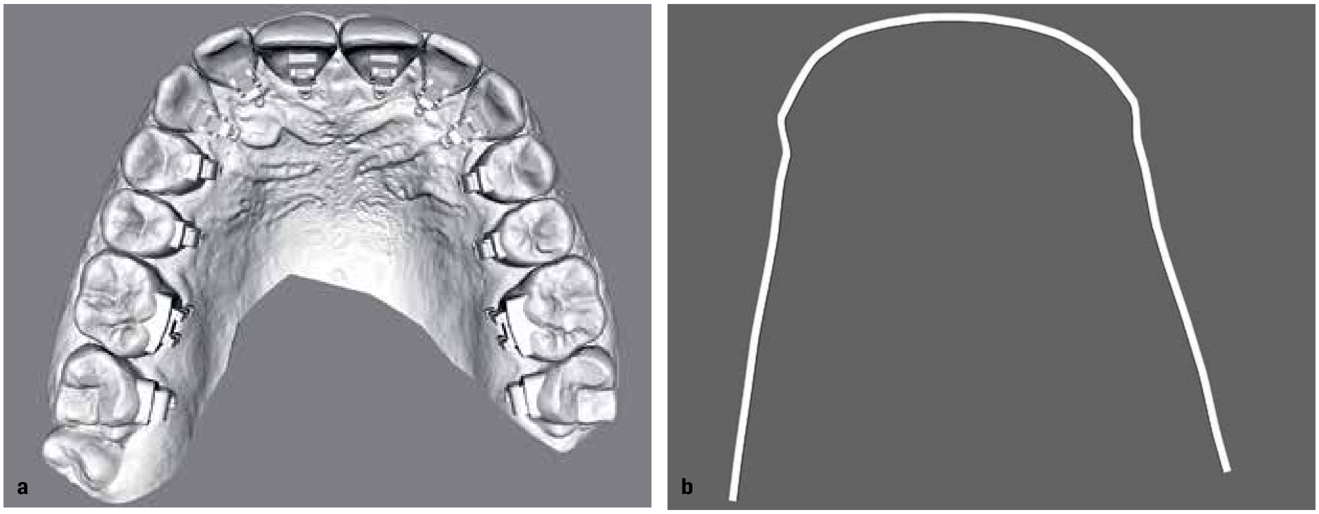


Fig 8-19 *(a)* Export of the initial dental model with the brackets in place. The model can be printed to be used for traditional indirect bonding tray manufacture (ie, Memosil, Kulzer). *(b)* Export of the prototype archwire. The archwire can be printed (and copied on paper) to be used as the prototype archwire for the whole treatment. In a future project, it could be used for in-house wire bending using a wire-bending robot.

Steps in the customized bases module

The interface of the software is user-friendly and simple. There is an occlusal view of the setup of the maxillary and mandibular dental arches where the orthodontist will specify which teeth will be virtually bonded. In addition, there are other functions to help the customization procedure. The steps of the module are as follows:

1. The operator chooses the customized bases option.
2. The orthodontist has to specify which kind of orthodontic treatment will be undertaken—labial or lingual.
3. The bracket manufacturer is selected.
4. The specific bracket is selected.
5. The software automatically aligns the slot of the brackets in a continuing arch-shaped wire (0.018 × 0.025 inch). The brackets are now located at a distance from the teeth. This space will be filled by the composite during IDB (see Fig 8-14).
6. Manipulation of the entire bracket-archwire complex provides the operator the ability to move them in a vertical direction. In addition, each bracket can also be manipulated mesially or distally, buccolingually, or horizontally rotated (see Fig 8-14). The archwire-bracket complex can also be moved around a center of rotation that can be handled manually (see Fig 8-15).
7. By moving a sliding bar, the operator can observe the initial malocclusion or the final setup with the brackets and wires on the dental model (see Fig 8-18).
8. The IDB tray can be designed as one, two, or more units (Fig 8-20).
9. The files that can be exported are:
   - The IDB trays
   - The initial and setup model (brackets and dental model; see Fig 8-19a)
   - The initial and setup model (brackets, dental model, and archwires)
   - The initial and final archwire in STL format and 1:1 image file (see Fig 8-19b)
   - The brackets
   - The volume of the brackets' extrusion (see Table 8-1)

The brackets are inserted into the IDB tray. At the bonding appointment, the predetermined gap between the base of the bracket to the tooth surface is filled with orthodontic composite resin according to the volume calculated by the software. After light curing the bracket adhesive, the IDB tray is removed.

The archwire is formed on the wire image that is exported from the software. The archwire can also be printed using model resin and can be used as a real wire prototype.

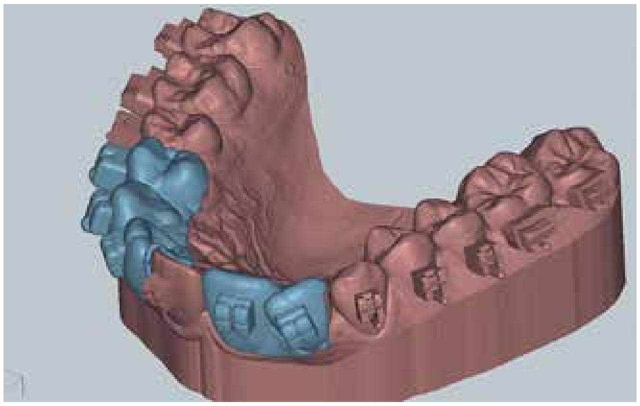


Fig 8-20 IDB tray design in one, two, or multiple pieces.

Alternatively, the IDB tray can be fabricated manually on the initial malocclusion model, which has been printed to contain the digitally positioned brackets. In this method, a transparent silicone impression material (eg, Memosil) is placed over the model, capturing a negative of the intended bracket positions for the patient's malocclusion. This procedure is appropriate for both labial and lingual appliances found in the library of the UBrackets software.

Customized brackets

The digital designing and fabrication of fully customized brackets is certainly more challenging. It entails a procedure that results in printing brackets that only exist as an STL format in a computer, which means that they do not have an analog or physical version of them in existence in the real world. Currently, brackets are predesigned and inserted in the UBrackets software library by the Coruo software company. The company anticipates including new bracket designs and auxiliaries (eg, smaller brackets in the case of excessive mandibular anterior teeth crowding) in the UBrackets software in the near future.

The original idea came from the Meshmixer bracket customization procedure described previously. The software includes a library of existing predesigned orthodontic brackets (labial or lingual), which can be used in the customization procedure. The exported brackets can be printed in laser melting sintering printers using Co-Cr, stainless steel, or titanium. Special biocompatible resins are currently being tested for this category of in-house orthodontic bracket printing using a certain affordable high-resolution SLA 3D printer.

Table 8-1 **Export file presenting the extrusion volume of each bracket base to the tooth surface in mm^3**

Tooth number	Resin volume (mm^3)
37	15.77
36	25.64
35	15.81
34	15.31
33	14.44
32	9.09
31	9.14
41	9.00
42	9.45
43	11.73
44	16.43
45	22.52
46	35.29
47	19.57
17	15.70
16	42.17
15	19.00
14	15.92
13	5.81
12	7.35
11	8.39
21	8.28
22	9.16
23	7.63
24	19.06
25	18.12
26	33.96
27	18.75
Total volume	**458.51**

However, there exists a similar difficulty in printing metal tubes as was discussed previously with regard to the first customization option. Here, too, the author had to reconcile "bracket-type tubes" to be used on the first and second molars. Nevertheless, in contrast to metal SLM printing, tube printing was successful using a high-resolution SLA printer with a special biocompatible resin; however, the resin's mechanical characteristics are not yet thoroughly

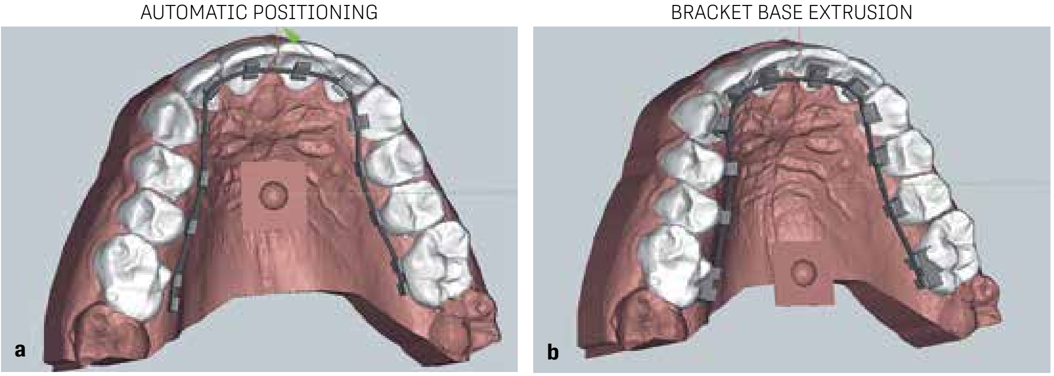


Fig 8-21 *(a)* Automatic positioning of the Coruo lingual brackets by the UBrackets software for the full bracket customization option. *(b)* Bracket base extrusion using the special extrusion tool.

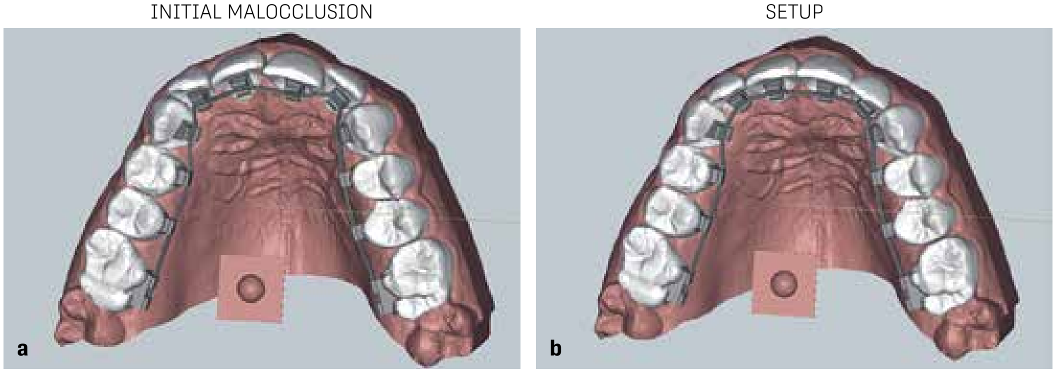


Fig 8-22 *(a)* Dental model, brackets, and archwire in the original malocclusion. *(b)* Dental model, brackets, and archwire at setup.

tested for bracket printing. Comparison testing was done to determine the dimensions of the bases of lingual brackets. A very useful tool, as mentioned before, is the collision occlusogram that presents possible collisions of brackets with the opposing teeth (see Fig 8-17). Other features will soon be included in the module to further aid the orthodontist with bracket customization.

Steps in the customized brackets module

The customized brackets module shares approximately the same interface as the customized bases module. The steps of the module are as follows:

1. The operator chooses the customized brackets option.
2. The orthodontist has to specify which kind of orthodontic treatment will be undertaken—labial or lingual.
3. The bracket brand is selected.
4. The software will automatically align the slots of the brackets in a continuous arch-shaped wire (0.018 × 0.025 inch). The brackets are now at a distance from the teeth, which will be filled by the extrusion of the base to the tooth surface in order to create a customized base (Fig 8-21). The same archwire will be exported as an STL file and a 1:1 image file. This will be the prototype wire that will be replicated for the rest of the archwires throughout the orthodontic treatment.
5. Manipulation of the whole bracket-archwire complex provides the ability to move them in a vertical direction or in a left and right differential vertical movement (upward movement for the left buccal segment and downward movement for the right segment or opposite). In addition, each bracket can be manipulated mesially or distally, labially or lingually, or horizontally rotated, with the slot kept in the same line while sliding on the wire. The operator can also define the center of rotation of the archwire-bracket complex in such a way that the entire complex can be moved around this center of rotation.
6. A tool exists to show the brackets bonded to the setup or to the initial malocclusion (Fig 8-22).
7. Design of the IDB tray can be done in one, two, or multiple units.

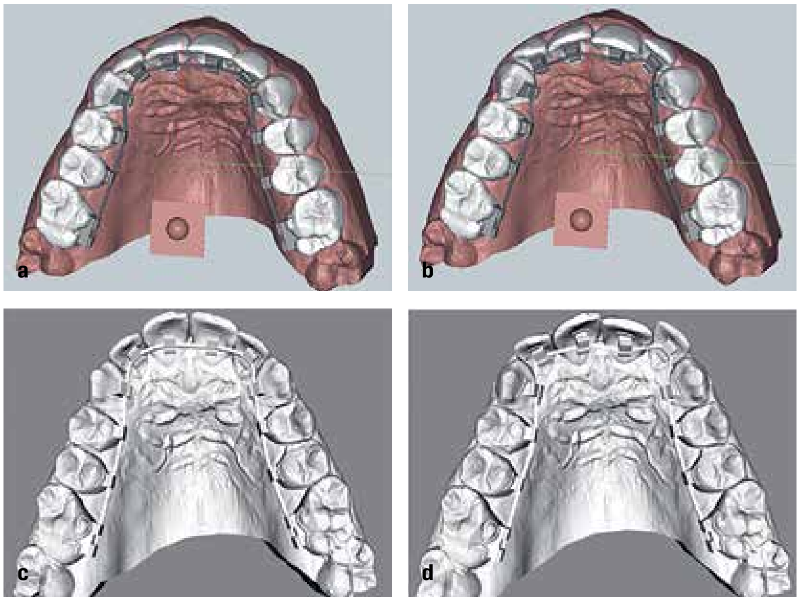


Fig 8-23 *(a to d)* Orthodontic treatment using customized lingual brackets.

8. The software is able to calculate the volume of each bracket in mm^3.
9. The files that can be exported are:
    - The STL files of the brackets
    - The archwire in STL and 1:1 image file
    - The IDB trays
    - The initial and setup model (brackets and dental model)
    - The initial and setup model (brackets, dental model, and archwires)

The brackets are then sent/exported for printing or milling to be printed in metal or resin.

The initial models, including the brackets, can be printed in order to manually create the IDB tray using transparent silicone impression material.

Case Reports

The following four cases were selected to illustrate the capabilities of the UBrackets software for bracket customization. All of these patients' customized orthodontic treatments were designed using the alpha version of the software.

Case 1: Lingual customized brackets

A healthy 25-year-old woman presented to the author's clinic for orthodontic treatment. She presented with a Class II, division 1 malocclusion and a deep bite with mild maxillary and mandibular anterior crowding. She requested maxillary lingual fixed appliances and mandibular fixed labial appliances. Diagnostic records were taken, including optical scans of the dental arches, panoramic and lateral cephalometric radiographs, and intraoral and extraoral photographs. The scans were imported into the UBrackets software, and all the necessary steps were undertaken, starting from tooth segmentation to the setup. The predesigned lingual brackets were selected (Coruo) and automatically placed by the software on the lingual side of the maxillary teeth. The brackets were moved manually using the manipulator in order to achieve the best position regarding the relation to the gingiva and the opposing mandibular dental arch.

Figure 8-23a presents the dental setup with the wire and the lingual brackets bonded, whereas Fig 8-23b shows the initial malocclusion with the brackets and the wire in their place. Figures 8-23c and 8-23d present the export files of the dental setup and initial malocclusion, respectively. The initial malocclusion file (without the wire) was printed and used for the IDB tray forming. Export of the bracket STL files and of the final prototype archwire in STL and image file was also performed. The lingual brackets were sent to an SLM machine for printing using Co-Cr alloy.

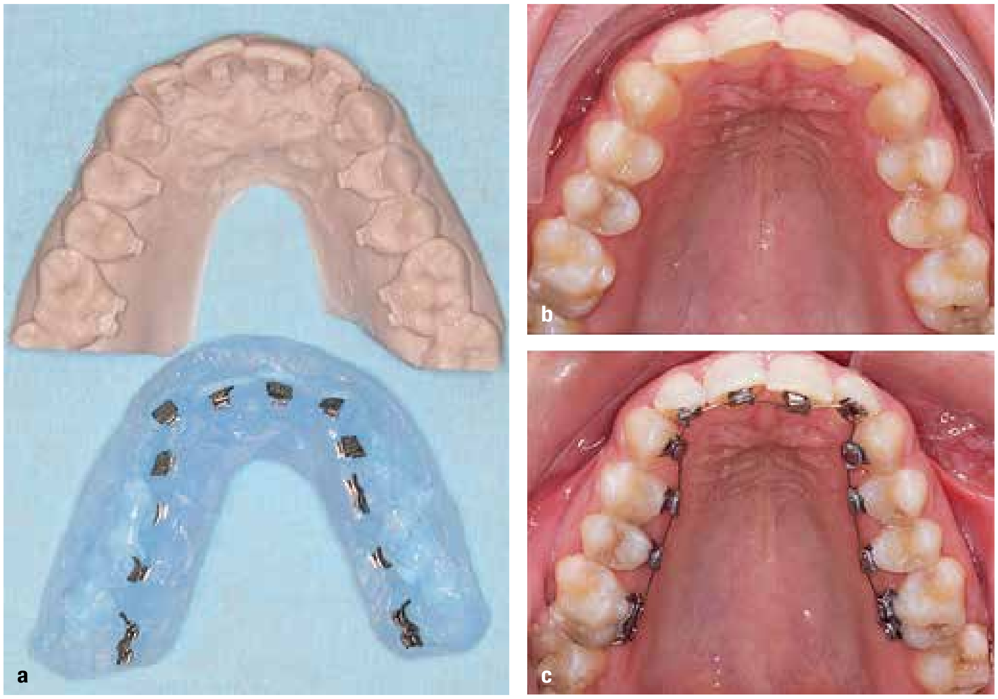


Fig 8-24 *(a)* The original malocclusion dental model with the brackets printed in resin and the IDB tray with the brackets in their corresponding position. *(b and c)* Maxillary arch before and after IDB of the printed lingual brackets.

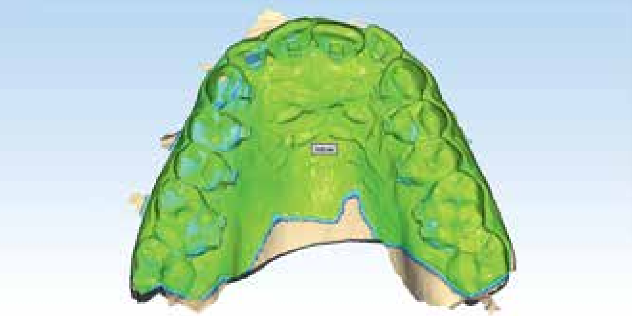


Fig 8-25 Superimposition of the virtual bonding 3D file with the scanning performed after bonding using Maestro Dental Studio software. The bonding error was about 0.2 mm for the majority of the brackets.

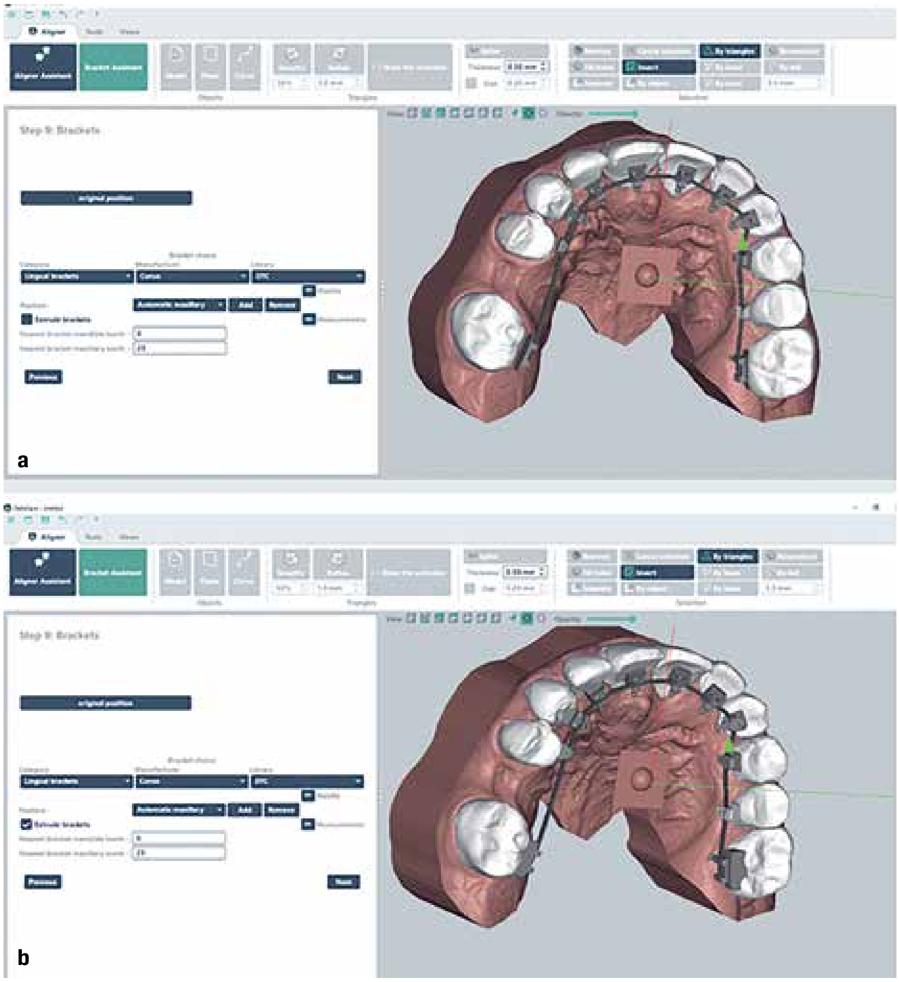
Figure 8-24a presents the initial malocclusion printed dental model and the IDB tray with the lingual brackets in their corresponding place. The IDB tray was manufactured using Memosil; at the time of treatment, the software was not yet able to design a 3D digital IDB tray. Figures 8-24b and 8-24c present the maxillary dental arch before and after IDB. In order to evaluate the bonding accuracy, the maxillary dental arch was scanned after IDB. The 3D file was imported into Maestro Dental Studio software together with the virtual bonding file. A superimposition was done using the software's special module. As can be seen in Fig 8-25, error in bonding was between 0 and 0.2 mm for the majority of the brackets. Nevertheless, the bonding error for one tooth (maxillary right lateral incisor) was 0.6 mm.

The printed lingual brackets were printed as mentioned before in an SLM printer. The slot was slightly smaller than designed due to material shrinkage. This could have been avoided by taking into account the material shrinkage amount and designing the slots bigger according to the shrinkage percentage. This material shrinkage can be overcome by using specific methods proposed by engineers.[29–31]

Case 2: Lingual brackets with customized composite bases

The option of creating customized bracket bases is undoubtedly easier than designing fully customized brackets. To this end, a 30-year-old man presented to the author's clinic requesting lingual orthodontic treatment. He presented with a Class III skeletal malocclusion with mild mandibular anterior crowding. The decision was made to perform orthognathic surgery to resolve the skeletal Class III aspect and to treat the dentition with maxillary arch DTC lingual brackets and mandibular arch labial fixed appliances. The usual digital procedure for performing the setup was followed, and the DTC ORG lingual brackets were selected and automatically virtually positioned by the software on a 0.018 × 0.025–inch lingual archwire (Fig

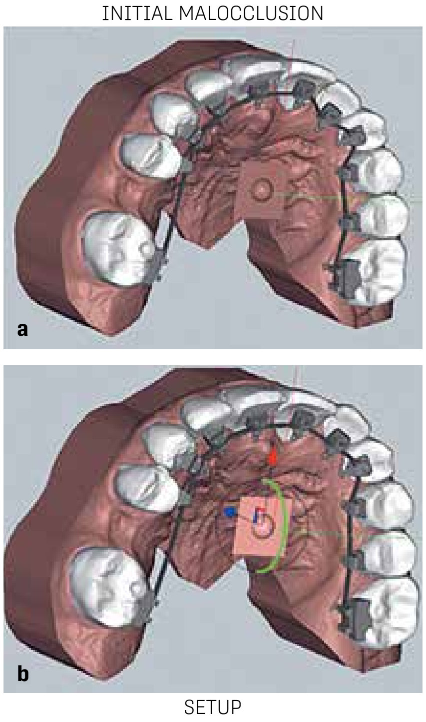
Fig 8-26 Lingual orthodontic treatment using the customized bases option. *(a)* Automatic positioning of the brackets. *(b)* Extrusion of the bracket bases.



8-26a). The brackets were then manually repositioned by the author to the desired ideal position, and extrusion of the appropriate bracket bases was performed to mimic the composite base that would be used during the IDB procedure (Fig 8-26b). Figure 8-27 presents the original malocclusion dental model and setup dental model with the brackets and the wire.

The next step was to export the final prototype wire in STL format and the initial dental models with the brackets (and the extruded base). The initial malocclusion dental model was used to create the IDB tray using Memosil. The brackets were then placed into their corresponding position in the IDB tray. Enlight (Ormco) composite was used to create the customized bases. Continuous IDB was then performed (Fig 8-28).

Fig 8-27 *(a)* The original malocclusion (dental model, brackets, and archwire). *(b)* The final setup (dental model, brackets, and archwire).



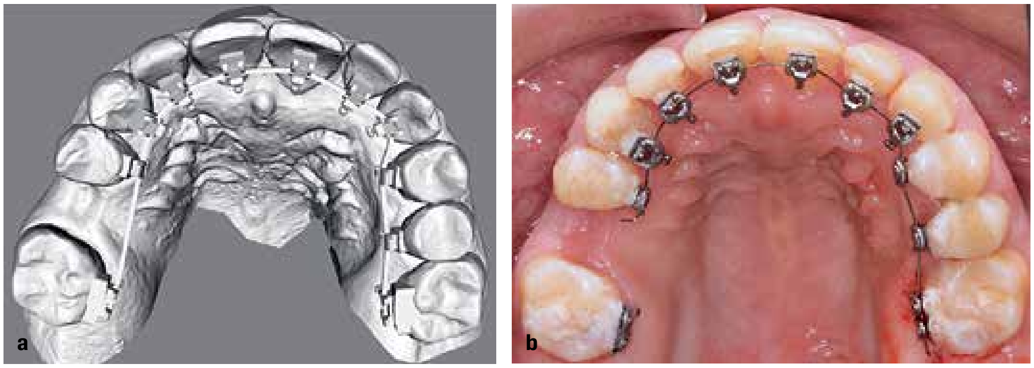


Fig 8-28 The virtual model file *(a)* and IDB of the lingual brackets *(b)*.

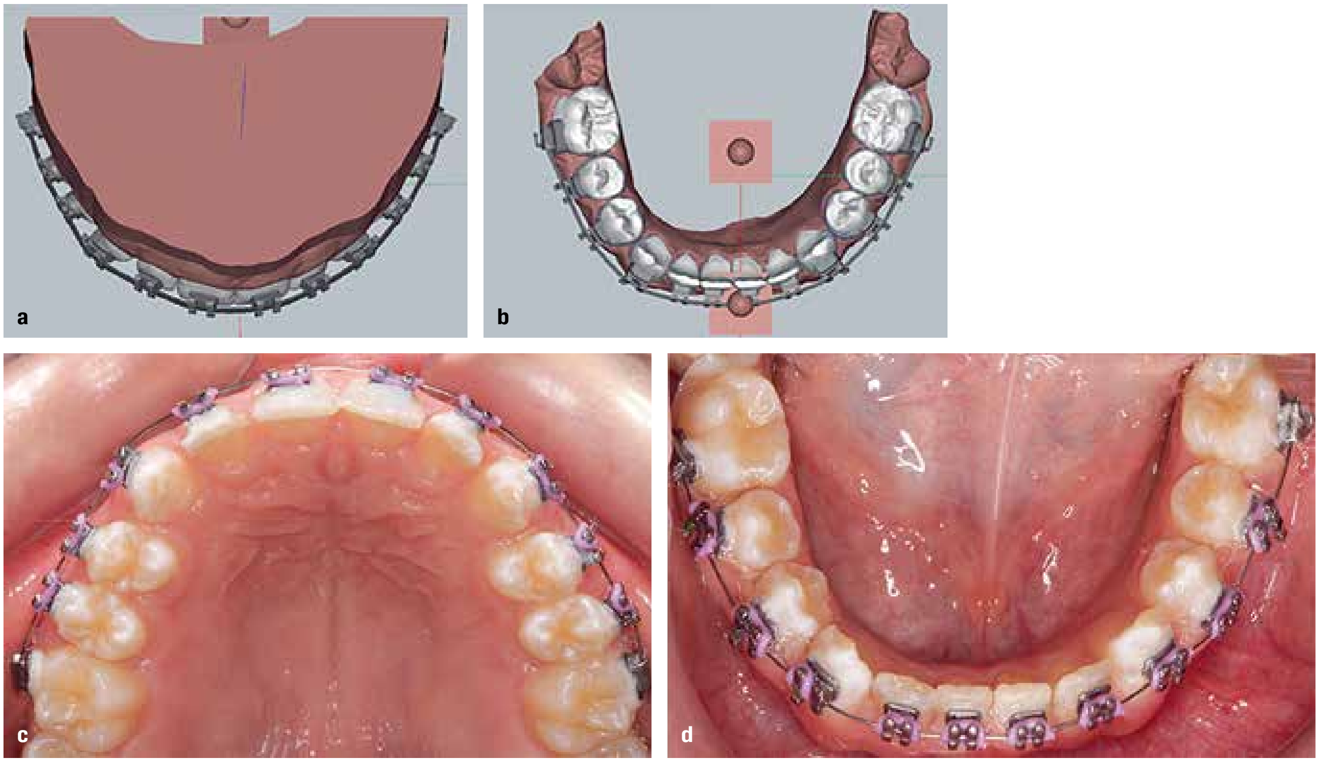


Fig 8-29 *(a and b)* Virtual bonding of Delicate labial brackets. *(c and d)* Indirect bonding of the brackets.

Case 3: Labial brackets with customized composite bases

This healthy 15-year-old adolescent girl agreed to be treated with DTC Delicate brackets (0.018 × 0.025 inch). The same procedure as described in the previous case was followed. The maxillary and mandibular brackets were virtually bonded using the UBrackets software, and virtual customized bases were created (Figs 8-29a and 8-29b). The files were exported, and the maxillary and mandibular dental models with the brackets were 3D-printed in resin. The final maxillary and mandibular wires were also 3D-printed to serve as the prototype wires.

IDB trays were manufactured using Memosil, and the brackets were inserted into their corresponding positions in the IDB trays. The bases of the brackets were filled with Enlight composite, and the trays were delivered to the patient's dentition to function as prescribed in IDB (Figs 8-29c and 8-29d).

After separating the trays from the now bonded brackets, the bonded maxillary and mandibular dental arches were scanned in order to be digitally compared with the virtual

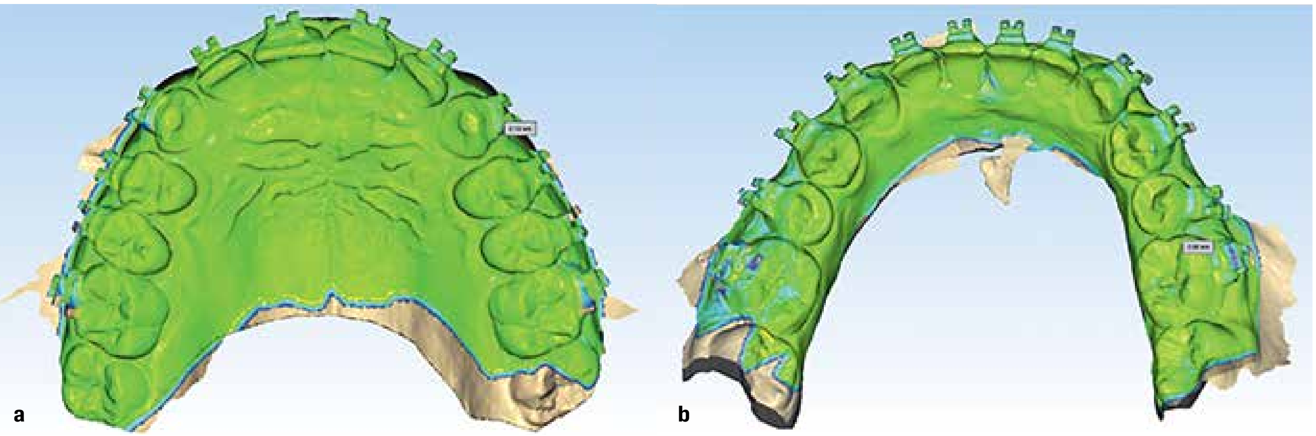


Fig 8-30 *(a and b)* Superimposition of the 3D virtual bonding file with the scanning performed after bonding using Maestro Dental Studio software. Bonding accuracy was very high.

customization 3D file in Maestro Dental Studio. The two files were superimposed in order to evaluate the bonding accuracy (Fig 8-30). Error for the brackets in both arches was between 0 and 0.3 mm, and error for the molar tubes was 0.6 mm.

Case 4: Labial customized brackets

Just before the final editing of this book, it became possible for the author to print labial orthodontic brackets designed in the UBrackets software. The author used Formlabs 3B SLA printer using Formlabs's permanent crown resin in A3 color. This resin is indicated for printing single crowns, inlays, onlays, and veneers. This resin produces high-strength, long-term restorations with an accurate and precise fit. In addition, it has a low tendency to age, discolor, or accumulate plaque. Formlabs suggests following its permanent crown resin application guide for printing and postprinting procedures to ensure a satisfactory outcome.

The author designed the fixed orthodontic appliances in the UBrackets software for a healthy 13-year-old boy. UBrackets in its latest version will include a tool to design positioning tooth keys for each bracket to be bonded. In this way, there is no need for IDB tray manufacture. Another option that is included in the UBrackets software is the connecting bar tool. This tool gives the ability to design bars that connect the bracket keys or any other part of the printed brackets. In this way, all the brackets and positioning keys are connected together, forming a "bracket-keys-bar net." The advantage of this configuration is that we avoid the IDB tray and that less composite is used for bonding, avoiding composite flowing around the bracket (compared to the conventional IDB tray).

The author separated the "net" into three pieces: the four anterior teeth, the right teeth, and the left teeth (canine to molar; Fig 8-31a). In this way, printing was easier and more accurate. Figure 8-31b presents the maxillary incisors' IDB net bonded, while Fig 8-31c shows the brackets without the bar and the keys. The composite used to bond the brackets was Enlight (Ormco). The individual brackets and the bracket-keys-bar net were placed on the Preform software in a specific orientation (Fig 8-31d), and they were printed using the permanent crown resin by Formlabs. Figure 8-31e presents a printed bracket with its supports and base after the postprinting procedure (IPA washing, UV curing, polishing, etc).

The mandibular teeth were bonded using the bracket-positioning key configuration (Figs 8-31f and 8-31g). Continuously, the positioning keys were removed and a 0.012 Ni-Ti wire was inserted (Figs 8-31h and 8-31i).

It is a fact that the permanent crown resin used is not intended to be used as a material for bracket printing. Previous attempts were made to print brackets using other biocompatible materials like temporary crown resin, but due to its low hardness, the author's trials failed. The permanent crown resin is a tooth-colored, ceramic-filled resin that gives high strength to the printed outcome. Formlabs claims that the crowns made by this resin achieve breaking loads that are more than two times higher than the maximum average masticatory forces of 720 N[2]. They also claim that restorations made by the resin are preserved for a long time

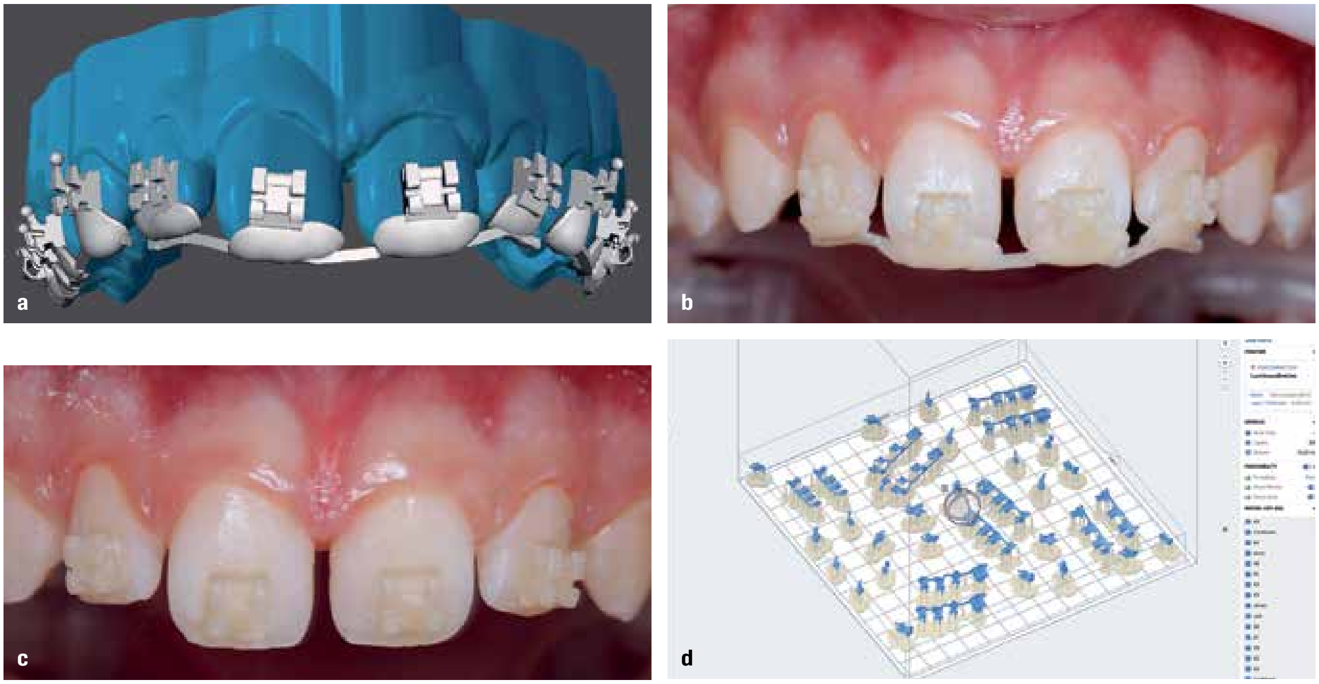


Fig 8-31 *(a)* The IDB net (bracket, positioning key, bar) in three pieces. *(b)* The IDB net (bracket, positioning key, bar) bonded on the teeth. *(c)* The positioning keys and the bars are removed. *(d)* Placement of the virtual brackets on the platform of the Preform software.

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and the existing tooth substance is protected in the best possible manner. Despite the good properties of the resin, this does not necessarily mean that it is suitable for bracket printing. Other factors should be evaluated in order to clarify that the resin can be used for bracket printing. Modulus of elasticity, bending strength, compressive strength, tensile strength, fracture toughness, and friction coefficient are important properties that have to be examined. A study is already designed to investigate all the above factors. On the other hand, the current hybrid-ceramic resin must not be confused with the monocrystalline or polycrystalline alumina that is used for ceramic bracket manufacturing.

Undoubtedly, other issues regarding accurate printing have to be studied. Different 3D printers, different resins, different resin temperatures, and different postprinting curing time and intensity can lead to different bracket printing results. The bracket orientation on the virtual printer platform can have an impact on the dimensions of specific parts of the printed bracket (ie, the slot). Shrinkage should be also considered upon 3D printing. A designed slot of 0.018 × 0.025 inch might be printed accurately or might not. Due to constriction upon printing, we might need to increase by a certain percentage the slot's dimensions in order to have an accurate 0.018 × 0.025–inch slot. It is not the author's intention to discuss the problems that arise upon bracket 3D printing but rather to present the capabilities of 3D technology in bracket 3D printing; further studies are currently being carried out in order to be able to have a consistent bracket printing outcome.

Conclusion

UBrackets software is a tool that can help the orthodontist plan a given treatment and create tailor-made fixed orthodontic appliances by creating customized bracket bases or printing customized brackets found in the software's library. Artificial intelligence, as described in a later chapter, is a technology that could significantly aid the orthodontist in the various stages of customized orthodontic treatment in this software. To accomplish this desired step toward individualized orthodontic treatment, there needs to be cooperation between the interests of orthodontic clinicians and the interests of the technology/manufacturer corporations developing these applications. Achieving this mutual goal will improve patient care and the quality of orthodontic treatment as a whole.

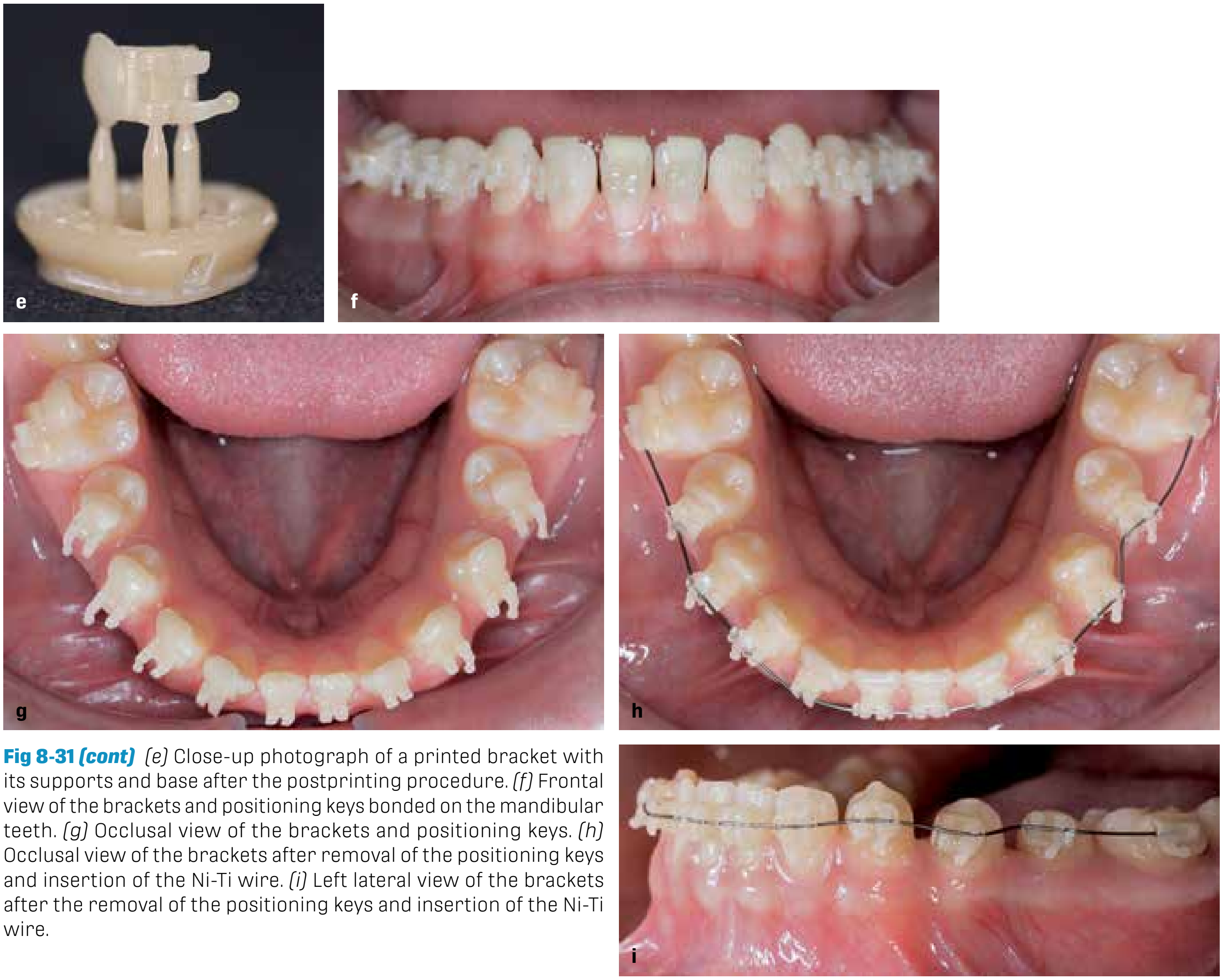

Fig 8-31 ***(cont)*** *(e)* Close-up photograph of a printed bracket with its supports and base after the postprinting procedure. *(f)* Frontal view of the brackets and positioning keys bonded on the mandibular teeth. *(g)* Occlusal view of the brackets and positioning keys. *(h)* Occlusal view of the brackets after removal of the positioning keys and insertion of the Ni-Ti wire. *(i)* Left lateral view of the brackets after the removal of the positioning keys and insertion of the Ni-Ti wire.

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9

In-House Customized Lingual Orthodontic Appliances

Chris Riolo

Innovations in technology are disrupting the orthodontic profession. These changes affect both orthodontic care delivery and the economics of care delivery—the orthodontic marketplace. As Christensen et al explains, "Disruptive Innovation in healthcare involves technologies, products, or services that are cheaper, simpler, and more convenient, making it possible for less expensive professionals to provide advanced services in affordable settings, or even for patients to care for themselves."[1,2] This is not the first time that the orthodontic profession has experienced disruptive innovation. The initiation of the direct bonded appliance or the straight-wire appliance in the 1970s was also disruptive.[3] While orthodontists were concerned that these changes in technology would result in an increase in the number of general dentists and pediatric dentists doing orthodontics, in reality these advances in technology provided benefits to patients and the orthodontic profession as a whole.

The advent of Invisalign (Align Technology) in 1999 again led orthodontists to believe that general dentists and pediatric dentists would begin treating more orthodontic patients. While general dentists have indeed treated more orthodontic patients since the introduction of Invisalign, so have orthodontists! In fact, the "orthodontic pie" has increased in size, and both general dentists as well as orthodontists are providing more orthodontic treatment. Invisalign, through its enormous advertising budget, is almost certainly responsible for the esthetic adult orthodontic market that all of us enjoy today.

Digital technology has advanced at a rapid rate since the introduction of Invisalign, and the production of clear aligners is easier now; as such, treatment planning and the outcomes of clear aligners have improved immensely. As a result of these recent advances, today we are experiencing disruption of the orthodontic marketplace by the "direct to patient care" model through corporations such as Smile Direct Club, Candid Co, Byte, and others due to the appearance of custom orthodontic appliances.[4,5] However, the same digital technology that makes this corporate direct-to-patient care model possible offers orthodontists real opportunities to improve the care they offer their patients. This technology enables the following:

- Proactive treatment planning
- Hybrid orthodontic treatment using two or more custom orthodontic appliances coordinated on a unified digital platform
- The use of 3D printing to take control of our workflow and to provide to the patients true customization of orthodontic treatment at minimum cost

Proactive Treatment Planning

The increase in the popularity of custom appliance systems has resulted in a paradigm shift from "reactive" treatment planning to "proactive" treatment planning. In the traditional reactive treatment planning model, the orthodontist has an extraction or a nonextraction treatment plan in mind. For example, this hypothetical treatment plan may involve Class II mechanics as well as interproximal reduction (IPR) of tooth material during treatment. In this treatment paradigm, the orthodontist delivers the brackets and begins to level and align. As the treatment progresses, the orthodontist makes irreversible treatment decisions sequentially: We may decide to start Class II elastics and procline the mandibular incisors; it is difficult or impossible to reupright these incisors. We may extrude tooth segments; it is very difficult to reintrude these teeth. If we perform IPR, we certainly cannot replace the enamel.

With each of these treatment decisions, we decrease our degrees of freedom. In other words, the universe of possible occlusal outcomes becomes smaller with each treatment decision. As treatment progresses, we eventually decide that we have achieved the best occlusal result possible; thereby, we remove the brackets and deliver retainers. But is this really the best result possible? The answer is we do not know for sure. It may be the best result possible at this point, after making a series of irreversible decisions. But could we have achieved a better treatment outcome if we could return to the start of the treatment? It would be nice to know the amount of mandibular incisor proclination and leveling Class II mechanics may cause.

The traditional reactive paradigm sometimes works well for our adolescent patients, but this model rarely produces the best clinical outcome for our interdisciplinary patients or our adult patients with highly restored, worn, and/or debilitated dentitions. These patients with compromised dentitions require a proactive treatment paradigm in order to achieve an optimal occlusal result. In this “proactive” paradigm, digital records are employed to produce a treatment setup, and the factors that are important for achieving an ideal occlusal result are identified using this setup. A custom appliance can then be fabricated using this same setup in order to maximize the treatment efficiency and the quality of the treatment outcome.

Hybrid Orthodontic Treatment

Hybrid orthodontic treatment entails the use of two or more appliance systems during orthodontic treatment. Hybrid treatment may be coordinated in a sequential or parallel manner. In the sequential model, one treatment modality is employed at a time. The parallel model requires the coordination of multiple appliance systems at the same time to achieve a single plan treatment outcome. This coordination is best achieved using custom appliance systems employing a single treatment setup. At this point in time, the software required to achieve this coordination is limited.

Hybrid treatment has emerged because there are logistical, biomechanical, and esthetic advantages as well as disadvantages associated with various orthodontic appliance systems, such as buccal fixed appliances, lingual fixed appliances, and clear aligners. Many patients are best treated with a combination of these orthodontic appliances. There are obvious and simple examples of sequential hybrid treatment in all our practices. Fixed appliance systems incorporating bands often result in open contacts. These spaces are easily resolved using a short series of one to three clear aligners. Another simple example includes the correction of small rotations with clear aligners after debonding rather than extending treatment time with fixed appliances. However, it is difficult and often expensive to utilize this type of hybrid treatment using commercially produced appliances. The solution is to transition this workflow in-house employing resin 3D printing, staging these small movements and thermoforming a limited series of aligners in-house.

This transition allows more complex sequential hybrid treatment that is the most beneficial treatment option for some patients. The patient in Fig 9-1 presented with a Class I molar relationship, moderate mandibular anterior crowding, history of periodontal disease, and poor oral hygiene. He required the extraction of four premolars during orthodontic treatment. Minimizing the duration of fixed appliance therapy was desirable due to periodontal disease. In addition, this patient desired esthetic orthodontic treatment, ruling out buccal fixed appliances; therefore, a lingual fixed appliance system was elected. However, as a result of the mandibular anterior crowding, the use of lingual fixed appliances was likely to extend treatment time, because it can be very difficult to align mandibular anterior teeth with lingual fixed appliances in patients presenting with significant mandibular anterior crowding. Therefore, we decided to start treatment with clear aligners (before lingual fixed appliance treatment), moving selected tooth segments from the first stage, aligning the dentition, and gaining access to the lingual surfaces of the mandibular anterior teeth. Clear aligners had additional advantages in this case: They are an esthetic treatment option and facilitate oral hygiene. Not only were clear align-

Fig 9-1 Custom appliance treatment combination: lingual fixed appliances and clear aligners. *(a)* Initial presentation of a patient with periodontal disease, severe mandibular anterior crowding, and a desire for esthetic orthodontic treatment. *(b)* Intraoral photographs taken the day that lingual fixed appliances were delivered after a first phase of four premolar extractions, space closure, and alignment using clear aligners.

→

ers most efficient to initiate orthodontic treatment, but they were also the safest treatment tactic with respect to this patient's periodontal health. Lastly, they satisfied the patient's requirement for esthetic orthodontic treatment.

Unfortunately, four-premolar treatment using clear aligners is unpredictable and unlikely to result in an excellent treatment result,[4,5] as it tends to result in tipping of the teeth adjacent to the extraction sites (see Fig 9-1b). Resolution of molar or premolar tipping is very difficult using clear aligners,[5] whereas it is relatively straightforward using a buccal or lingual edgewise fixed appliance system. Therefore, using both custom appliance systems (clear aligners and fixed lingual appliances) was the definitive solution for this patient (Fig 9-1).

Failure to offer our patients esthetic orthodontic treatment options is one of the reasons patients seek esthetic treatment through the direct-to-patient care model and forego the benefits of a more comprehensive treatment plan. After

Fig 9-1 ***(cont)*** *(c)* Progress photographs two appointments after initial delivery of the lingual fixed appliances.

Fig 9-2 *(a and b)* A Class II malocclusion with a deep impinging overbite treated with maxillary buccal and mandibular lingual fixed appliances.

all, many patients have an appreciation for the benefits of esthetic orthodontic treatment but frequently do not have an appreciation for the benefits of comprehensive orthodontic treatment resulting in a healthy stable occlusion.

Hybrid treatment can also be used for logistical and biomechanical reasons. The patient shown in Fig 9-2 presented with a deep impinging overbite and a Class II molar relationship. He was interested in efficient and effective treatment, and he was willing to wear buccal fixed appliances in order to complete his orthodontic correction. Logistically, buccal fixed appliances in the mandibular arch are difficult to manage in a patient with a deep impinging overbite.

On the other hand, there are two primary advantages to using lingual fixed appliances in the mandibular arch in this situation. First, logistically the appliance system is placed out of occlusion. The second advantage is biomechanical due to the location of the point of force application versus the center of resistance (Fig 9-3). The logistical advantage is obvious; by using a lingual appliance, we can avoid placement of posterior occlusal buildups that tend to deepen the bite over time. The biomechanical advantage is also important. Figure 9-3a shows the point of force application using a buccal fixed appliance versus the center of resistance of the root. There is a significant buccal lingual offset between these two points, resulting in a moment and adverse tendency for tooth proclination. This tendency for proclination requires the application of torque in order to resist the proclination. On the other hand, Fig 9-3b shows the point of force application using a lingual fixed appliance system. The lingual fixed appliance system results in a point of force application over or near the center of resistance of the tooth, minimizing or eliminating the need for torque during intrusion.

While it is clear that a hybrid approach is an efficient treatment option, the problems with this treatment approach are twofold:

- Coordination of the different appliance systems can be difficult
- Cost

The solution is to replace commercial appliance systems with "in-house" custom appliance systems. The workflow for design and fabrication of the clear aligner system is well established at this time, but the workflow to design and fabricate a fixed orthodontic appliance system in-house is not well established.[6–9]

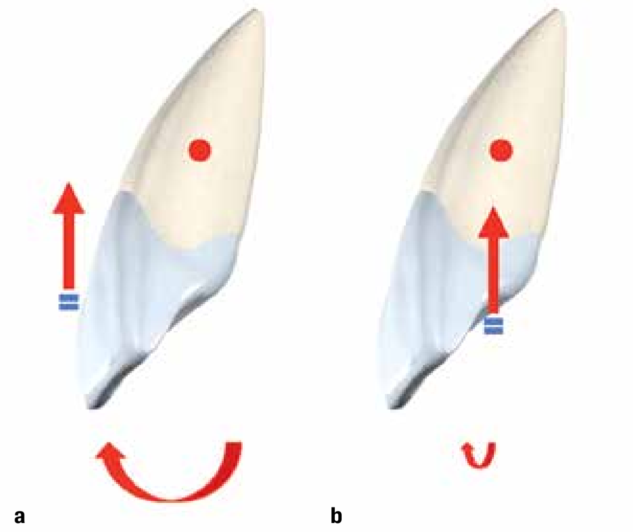


Fig 9-3 *(a and b)* Lingual fixed appliances minimize the tendency for adverse proclination of the tooth during intrusion that happens when buccal fixed appliances are used.

True Customization of Orthodontic Treatment

Clear aligners fabricated in-house employ 3D resin printing, which involves different types of stereolithography (SLA) printing. There are three general types of SLA technologies commonly employed in orthodontic clinical care: laser SLA, digital light processing (DLP), and LCD masking. All of these printing technologies use photosensitive resin, a light source, a membrane, and a build plate. The differences between laser SLA, DLP, and LCD technology is mainly the way light is projected to cure the photosensitive resin (Fig 9-4). These differences affect the accuracy, speed, and cost associated with printers. The accuracy requirements in orthodontic 3D printing is less than dentistry in general,[10] and each of the printing technologies properly employed can be used for the fabrication of in-house aligners.

Designing and printing fixed appliances requires access to software that is not commercially available. Therefore, at this time, the only way to design an in-house custom fixed appliance system is to use "off the shelf" CAD software. The workflow required for the design and fabrication is shown in Fig 9-5.

The design of all custom appliances begins with a setup, and fixed custom systems are no exception. Any software that can be used to move teeth in the digital model of the dentition can be used to create the treatment setup. Once the treatment setup has been completed, it is imported into the CAD software of your choice; Rhino6 (Robert McNeel & Associates) CAD software was employed in this example.[11] The first step in the design process is to establish the "wire plane." The choice of the wire plane is important in terms of design and logistical requirements of the lingual fixed appliance system.[12,13] With regard to the design consequences, there are significant changes in the required first- and third-order compensations as the wire plane migrates apically or occlusally.[12] The lingual anatomical variability is one of the primary factors that make lingual biomechanics difficult.

In addition to the anatomical problems with first- and third-order compensations, there are biomechanical issues with lingual bracket placement related to the point of force application and the center of resistance of the teeth (see Fig 9-3). These biomechanical consequences of bracket position are well established in the literature.[12–15] The logistical advantages are more obvious. In the maxillary arch, cervical positioning of the brackets results in fewer issues of occlusal interference with the mandibular dentition. There is a trade-off between the biomechanical advantage of minimizing the first-order offset with cervical bracket placement with the disadvantage of decreasing the interbracket distance in the mandibular arch. The precision of the bracket slot-wire interface is critical to the perfor-

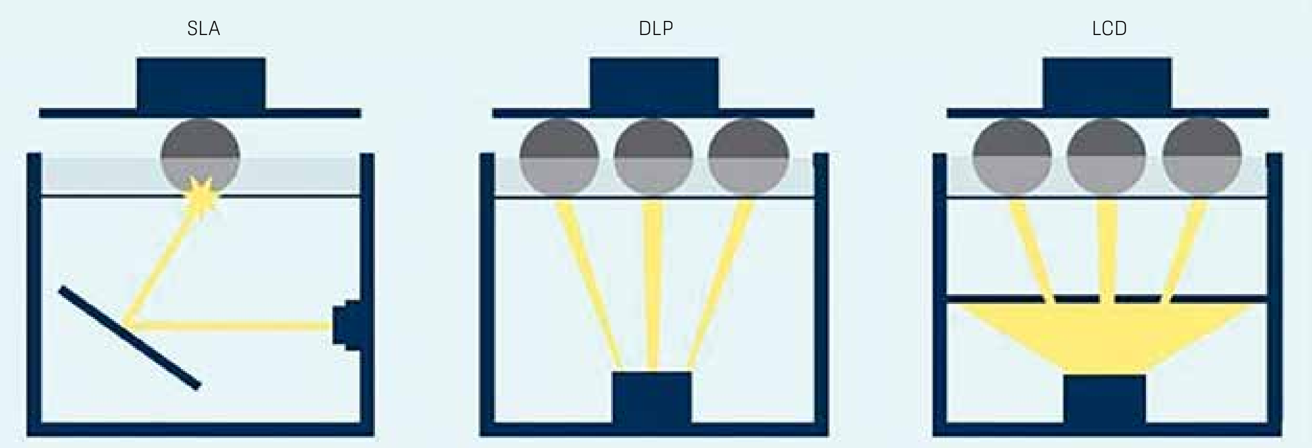


Fig 9-4 SLA printing uses a laser to cure photosensitive resin point by point. DLP uses a digital micromirror device to produce a high-resolution projection and cure photosensitive resin one whole layer at a time. LCD projection uses an LCD light source and a “masking” screen to cure one whole layer of photosensitive resin at a time.

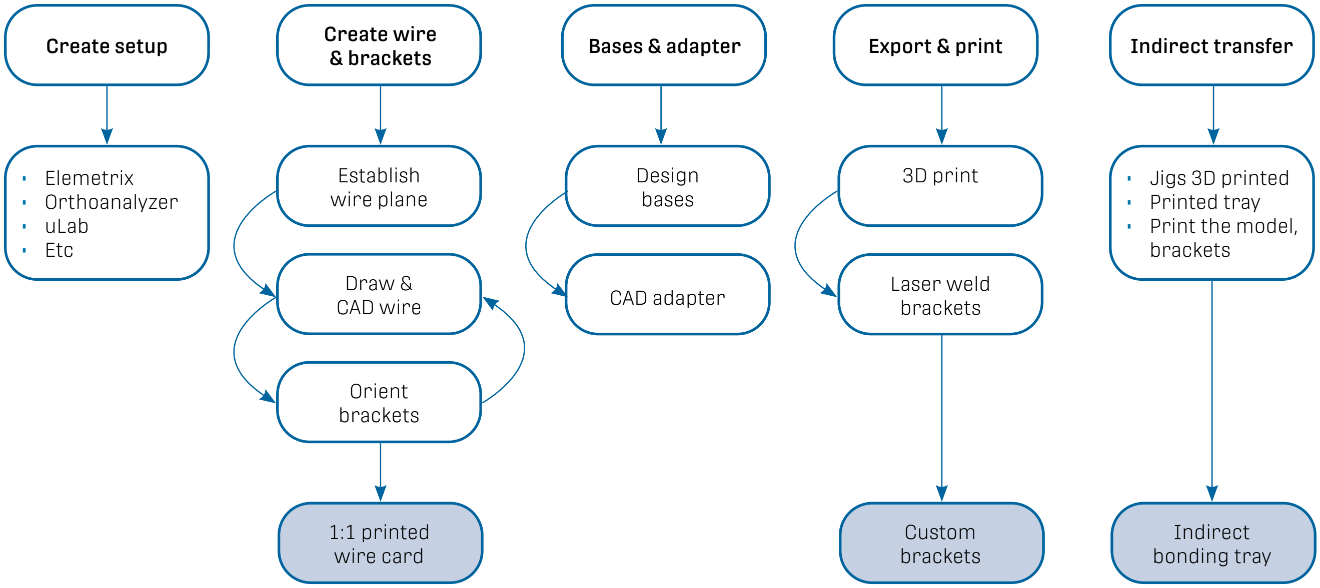


Fig 9-5 The workflow required for the design and fabrication of an in-house custom fixed appliance system.

mance of lingual systems, and factors such as decreased interbracket distance in lingual orthodontics and well-documented lingual biomechanical issues are antithetical.[16–22] This is because there is an increased tendency for torque loss and extrusion of anterior tooth segments under Class II mechanics and space closure.[19] The decrease in lingual interbracket distance results in a threefold increase in wire stiffness for first- and second-order displacements and a 1.5- fold increase for torsion.[23] These factors result in significant clinical difficulties when treating patients using lingual brackets with traditional buccal orthodontic technique.

After the wire plane has been established, a wire conformation must be chosen.[24,25] While the choice of wire form is infinite, there are three main types of wire form: straight, mushroom, and individual (Fig 9-6).

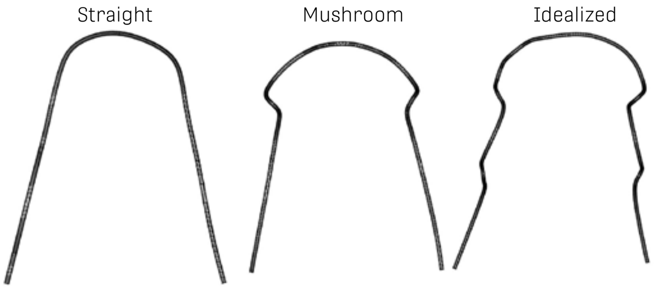
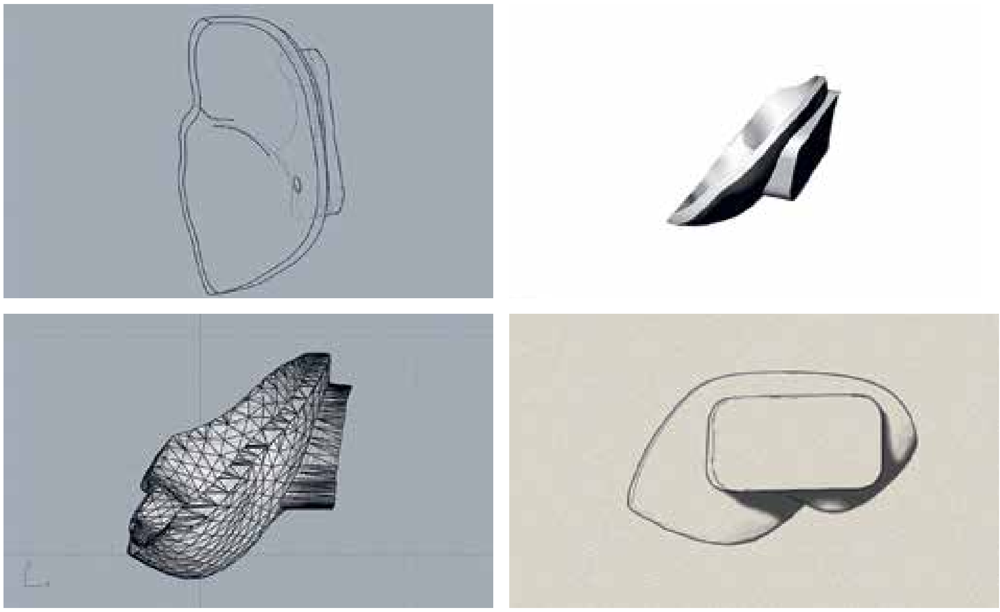


Fig 9-6 The three main types of wire form: straight, mushroom, and individual (or idealized).

Fig 9-7 A digital bracket slot and wings are digitally suspended on the "wire." The wire, bracket slot, and wings are "tools" used to create the custom bracket bases and connector.

Fig 9-8 The custom base with half occlusal coverage and connector; the custom connector provides most of the prescription used to align the dentition.



The straight wire form is convenient with respect to sliding mechanics; however, it will result in brackets with a larger profile to account for the first-order compensations. On the other hand, the mushroom arch form reduces the required first-order compensation in the area of the canines and still allows for some sliding mechanics in the anterior and posterior. The mushroom arch form is an intermediate solution between the straight and individual wire conformation. The individual wire conformation leads to bracket slots that are as close as possible to the lingual surface of the tooth. This facilitates both biomechanics and patient comfort.[26]

Once the wire plane and wire conformation have been established, customization of the bracket can begin. The bracket is digitally suspended on the "wire" close to but not in contact with the lingual surfaces of the teeth (Fig 9-7).

The closest distance from the bracket to the lingual surface of the tooth must be greater than or equal to the anticipated custom pad thickness. Empirically, we have found this minimum distance to be no less than 0.2 mm. There is tremendous flexibility in custom pad design (Fig 9-8).

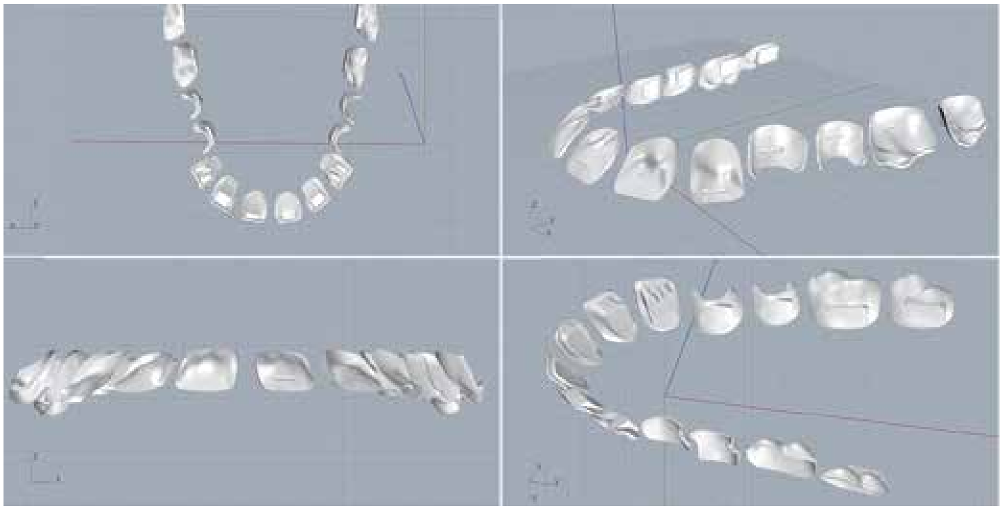


Fig 9-9 Complete set of custom bases and connectors. Each of these custom bases has a connector with a unique shape that mimics the shape of the slot and wing component to facilitate accurate laser welding.

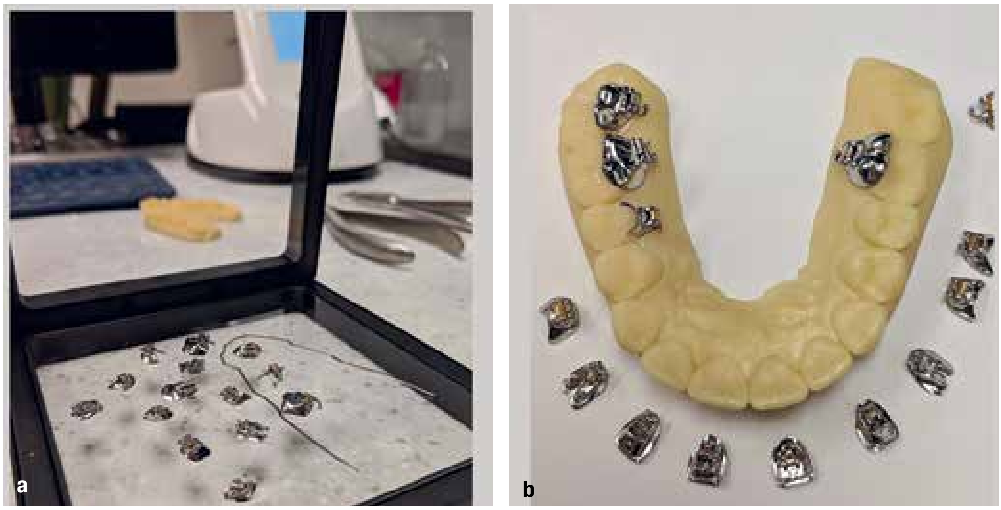


Fig 9-10 *(a and b)* The complete set of lingual brackets with their cobalt-chrome custom-printed bases and the custom wire hand-bent from a 2D 1:1 printed wire card.

The bracket slot and wings are positioned on the wire opposite each tooth. The bracket slot and wings are then connected to the custom base by the "connector." It is this "connector" that encodes the portion of the system prescription provided by the bracket. The wires provide the remaining portion of the prescription. The proportion of the information contained in the bracket and in the wire changes as wire complexity increases from "straight" to "mushroom" and to "individual." The custom bases with their connector can be seen in Fig 9-9. In the example shown here, the custom pad and connector are 3D-printed (cobalt-chrome), and then the bracket slot and wings are laser welded to the connector. Note that the shape of the connector mirrors the shape of the bracket base of the slot and wing portion in order to facilitate positioning for laser welding. The completed custom brackets after assembly are shown in Fig 9-10.

Once we have a set of custom brackets with the encoded prescription, we need to be able to accurately apply them to the patient. In order to accomplish this, we need to fabricate a bracket transfer system. This transfer system could entail jigs to transfer brackets directly or the fabrication of an indirect transfer tray. Jigs for direct transfer can be designed using the same CAD software used to design the brackets themselves. These jig STLs are then exported, and the jigs can be printed using a resin printer. However,

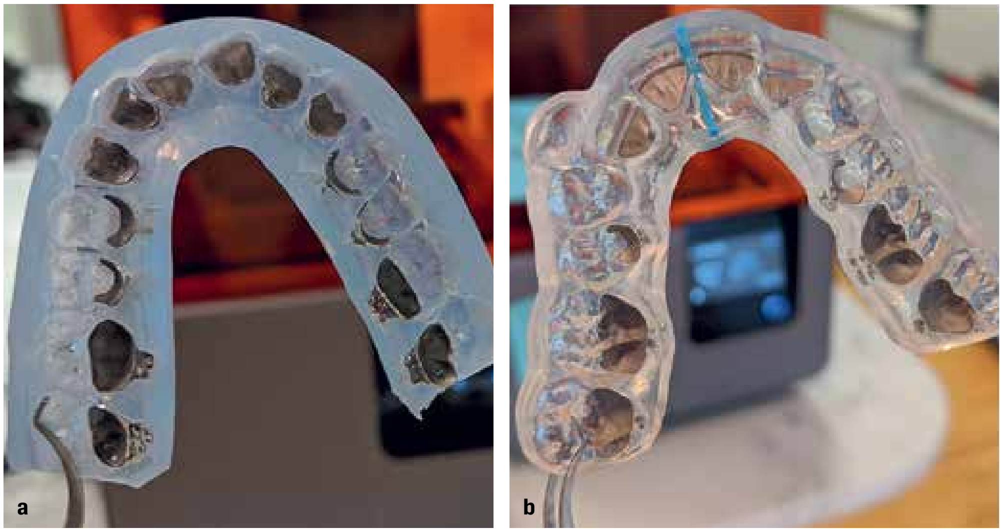


Fig 9-11 *(a)* The custom indirect transfer tray fabricated for our custom lingual appliance system. *(b)* An indirect transfer tray used with the Incognito lingual appliance system offered by 3M Unitek.

digital design of individual jigs can be time-consuming, and the accuracy of these jigs for bracket placement can be dependent on the type of jig designed and operator experience.

Alternatively, there are two methods for fabrication of an indirect transfer tray. In the first method, the tooth movement used to create the setup can be backed out of the setup model with the brackets in place. This results in the digital malocclusion model with digital custom brackets in place on the lingual surface. Brackets that have penetrations with tooth structure or another bracket can be digitally removed from the malocclusion model. Then the transfer tray can be digitally designed and then STL exported and printed by a resin printer. Afterward, the physical brackets are inserted into the tray for transfer to the patient.

The second method involves direct printing of the digital malocclusion model with the custom brackets followed by fabrication of an indirect tray on this printed malocclusion model. The physical custom brackets can afterward again be inserted into the transfer tray for delivery to the patient. An indirect tray fabricated using polyvinyl siloxane can be seen in Fig 9-11.

Conclusion

The advent of digital orthodontics and 3D printing has the potential to change the way orthodontists practice by moving the workflow associated with the design and fabrication of custom appliances in-house. In-house custom appliance design and fabrication allows orthodontists to truly customize appliance systems for their patients, coordinate the use of these appliances, and minimize cost, making these appliances more accessible for our patients. Printer technology is improving at an incredible rate; the limiting factor in this transition is software. Commercial software for aligner staging defeats the goal of returning 100% control of the design and fabrication of orthodontic appliances to the orthodontist. As a profession, we should strive for control of both our data and workflow by working together as a community to develop software for staging aligners. One possibility is for the American Association of Orthodontists (AAO) to develop aligner staging software and offer it to AAO members at little or no charge.

An alternative model for the development of the software requires orthodontists as a community to develop the software for designing and printing custom fixed appliances with an open-source license, only demanding that those who make improvements share those improvements with the community at no cost. The trend in clinical care over the last dozen years has been for corporations to market directly to our patients. More recently, some corporations have even begun to provide care directly to patients. Orthodontists have in many cases become tied to corporations as “providers” of these corporate appliance systems; these relationships vary from direct employees to loose affiliations as unofficial salespeople for their appliance systems. 3D printing has the potential to upend the power dynamic at play between orthodontists and corporate orthodontic entities. By working together, orthodontists can ensure the future of independent practice and full control over the care we offer our patients.

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10

In-House Clear Aligners

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Manolis Mavrikis
Evangelos Akli

Patient demand for esthetic orthodontic appliances has catapulted clear aligners into the mainstream of modern orthodontics. But the story of clear aligners actually began in 1926 with Orrin Remensnyder's "Flex-O-Tite" gum massage appliance, which had the side effect of tooth movement. Twenty years later, H. D. Kesling used this concept to create his tooth positioner made of vulcanized rubber. Henry I. Nahoum took Kesling's vision one step further in designing a vacuum-formed dental contour appliance, and in 1993 J. J. Sheridan invented the esthetic Essix appliance for retention. Just 4 years later, Zia Chishti and Kelsey Wirth combined the Essix appliance with the idea of the tooth positioner in what we know today as clear aligners, founding Align Technologies. Ever since, Invisalign (Align Technology) has maintained the most significant portion of the clear aligner market, but multiple companies have introduced their own clear aligner systems as well. In addition, within the last decade, direct-to-consumer aligner companies like Smile Direct Club have attempted to sidestep the orthodontist entirely and offer aligners without the chairside supervision of a professional. Advances in technology have enabled this sea change in orthodontics (see chapters 2 to 4).

Aligner Design and Manufacturing

The past several years have seen the development of multiple orthodontic CAD software packages for in-house aligner design and fabrication (Fig 10-1). All of these share, more or less, the same method of aligner design, varying only in the sophistication of the design options they provide—for example, the possibility of importing CBCT scans and other tools to help the operator design the aligners. Some of these programs require a one-time license purchase (ie, 3Shape Orthoanalyzer, DeltaFace, Onyx Ceph, and Maestro Dental Studio). Others like BlueSkyPlan are free to install but require payment according to the study models that are exported. No matter the fee schedule, all of these software packages provide the operator with various tools that improve the quality of treatment planning, such as precise values of every scheduled tooth movement, the ability to stage each movement separately, and visualization of the anticipated occlusal contacts.

Currently, the vast majority of clear aligners are planned and fabricated by submitting patient records (dental impressions, radiographs, clinical examination, and photographs, etc) to an external laboratory for appliance design and fabrication. This workflow describes companies like Invisalign, which also maintains all the data submitted to it for analysis to improve their treatment-planning algorithms and to refine the services and products it offers. In addition, traditional orthodontic laboratories have started using CAD aligner software to design and produce aligners as well. In this case, the orthodontist is more involved in the designing of the aligner, but most of the procedure is performed by the dental technician. This option can be said to be between full in-house aligner fabrication and an Invisalign-like company aligner fabrication (Fig 10-2).

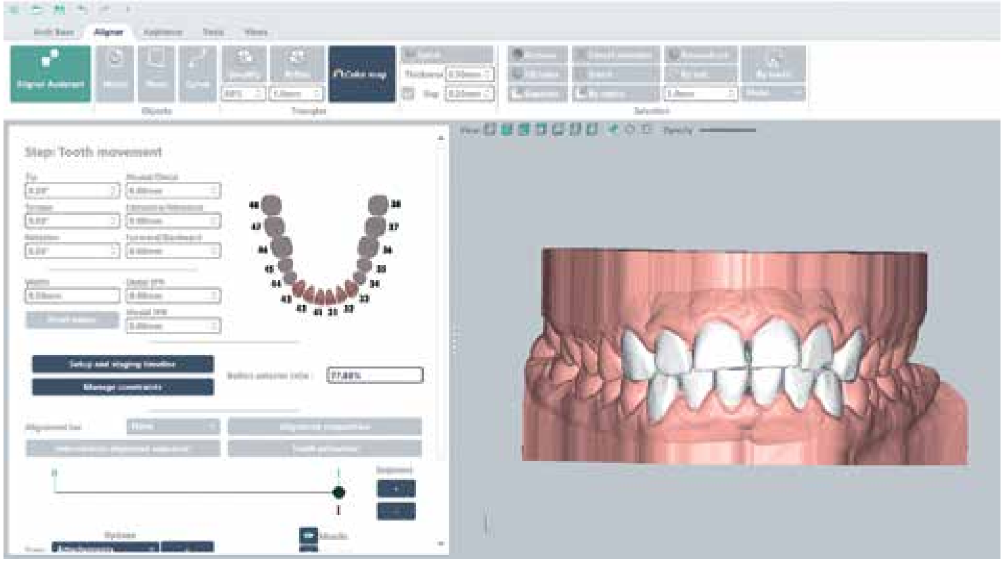


Fig 10-1 DeltaFace orthodontic CAD software (Coruo).

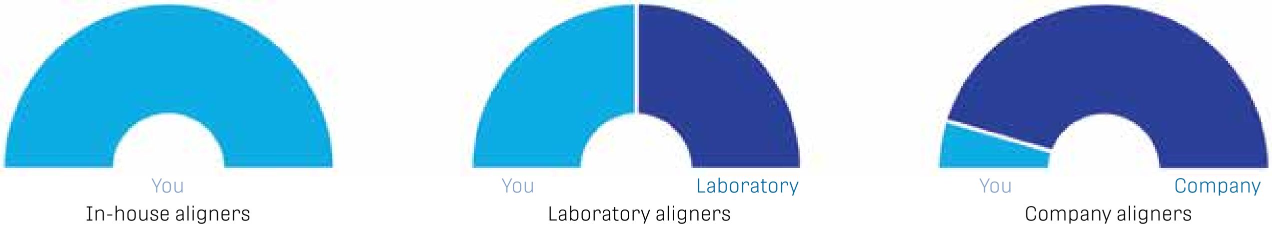


Fig 10-2 The contribution of the orthodontist in designing and manufacturing aligners in three different workflows.

A big advantage of Invisalign is the availability to the orthodontist of treatment libraries, which could be a guide for viewing similar aligner cases. On the other hand, the cost is significantly higher compared to in-house aligner design and fabrication. Presently, the cost of the necessary equipment for in-house aligner manufacturing (3D printer, thermoforming machine, intraoral scanner) is decreasing. Furthermore, with Invisalign and similar companies the orthodontist does not have the flexibility to easily alter the treatment plan or provide supplemental aligners when using outsourced clear aligner fabrication. In-house aligner treatment affords the orthodontist the ability to check each stage of treatment using the CAD software and change its course accordingly. The ability to perform an intraoral scan as it is deemed necessary permits treatment assessment by superimposing the data on previous scans, as seen in Fig 10-3.

Another advantage of in-house aligner design is that some CAD software programs like Maestro Dental Studio offer an option to fuse a CBCT (converted to an STL format file) with the intraoral scan (Fig 10-4). This helps the orthodontist to visualize the dental roots while moving the crowns in the setup procedure. The number of aligners that can be developed in the office is practically unlimited. The opposite is the case with aligner companies, where either a high price permits unlimited aligners or paying a lower fee allows only a limited number of aligners.

While in-house aligner fabrication requires the dedication of more doctor time and perhaps additional staff for aligner design and fabrication, in situations or clinical settings where access to external aligner companies is discontinued or limited (for example, during a pandemic lockdown), then the self-sufficiency of in-house aligner production is even more advantageous. However, each method of arriving at clear aligner appliances to treat patients has its advantages and disadvantages, which should be weighed in order to choose the most appropriate choice for each clinician.

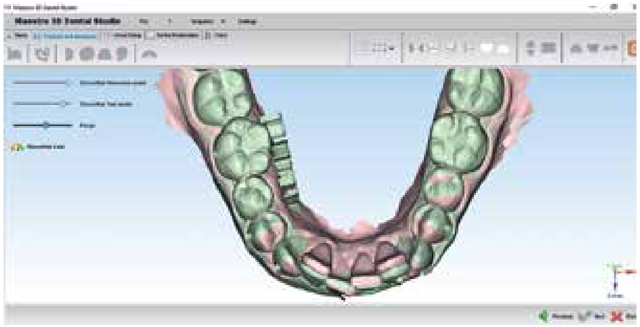


Fig 10-3 Superimposition of the initial malocclusion with a new intraoral scan of the patient during the orthodontic treatment in Maestro Dental Studio software.

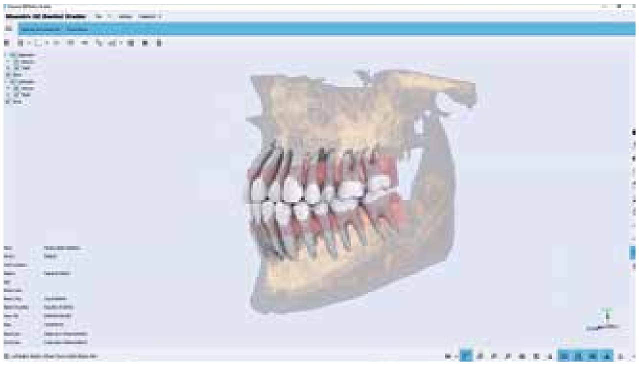


Fig 10-4 Fusion of a volume scan with a surface scan of a patient.

Mechanical Properties of Aligners

The mechanical characteristics of aligners should mean they behave similarly to orthodontic wires.[1–4] Appropriate stiffness is mandatory in order to minimize the breakage of the aligners due to occlusal bite forces. Flexibility, shape memory, and a high range of activation are other physical properties that are essential in clear aligners so that they can be easily inserted around crowded teeth. However, for the most part, the plastic aligner material does not behave entirely like the metal alloys used to shape traditional orthodontic wires either in stiffness, shape memory, or elastic range.[5,6] Stress relaxation and water absorption of aligner material are other behaviors that can affect their ability to move teeth. Whereas wires are made with different materials and come in different shapes and/or thicknesses in order to perform specific tasks during orthodontic treatment, all aligners throughout treatment are fabricated from the same material, which is expected to perform all its stages. The use of bonded composite protrusions (ie, attachments) are an effort to overcome the deficiencies of the plastic material compared to metal archwires to produce retention and directed forces and moments.

It is worth mentioning that aligner treatment, unlike fixed appliance treatment, is unrelated to the manual skills of the clinician. During aligner therapy, the patients are constantly disoccluded due to the occlusal coverage caused by them, which provides an advantage when treatment requires crossbite correction or the elimination of dentoalveolar compensations during mandibular growth of Class II patients, etc. This added layer of material between the posterior teeth has been reported to aid in the resolution of anterior open bite due to a posterior bite plate effect. However, this is controversial because aligner thickness ranges from 0.35 to 0.7 mm, which, even if worn on both arches is still less than the average freeway space.[7–10] The claim that aligner coverage of mandibular incisors controls their proclination is similarly unclear.[11] What has been satisfactorily demonstrated is that aligner treatment entails fewer visits, reduced chair time, and fewer emergencies than treatment with fixed appliances.[12,13]

Virtual Aligner Treatment and Real-Life Aligner Treatment

Aligner therapy has transferred a lot of chairside time to screen time, requiring the clinician to first treat the “avatar” and then transition to the “real-life patient.” Many times, however, the outcomes that are designed on the “avatar” are not attained by the “real-life patient.” The most common reasons that this occurs are lack of tracking, the play of the plastic material, and the insufficient mechanical properties of the foil. Equally important is that the virtual setup procedure does not take into account the tissues around the tooth, such as bone and soft tissue, which play a major role in tooth movement. Root dimensions, shape, and position relative to the compact bone are also disregarded.

Lack of aligner tracking can occur due to biologic constraints that avatars are not bound to, such as slower-than-anticipated bone remodeling or proximity of a molar root to a sinus wall, all of which might compromise the algorithm-based anticipated tooth movement. Also, as mentioned earlier, designing tooth movements on an avatar does not take into account Newton’s third law, which the clinician needs to consider. Finally, the same way that a

0.019 × 0.025–inch stainless steel wire has twelve degrees of play in a 0.022-inch slot bracket, the tooth has multiple degrees of play within an aligner due to its mechanical properties. Therefore, an aligner might perfectly fit the teeth, but the patient's dentition might behave in a manner different from that created on its avatar.

The aligner thermoforming foil is one of the most important components of a clear aligner treatment (CAT). This foil is the media that will exert the forces and the moments for tooth movement. Invisalign uses its patented SmartTrack foil to perform smaller tooth movements (0.1–0.2 mm) while utilizing only a single aligner for each setup. Clear Aligner system (Scheu Dental) uses larger setup steps. In each setup, usually three foils are used based on the Duran foil (0.5, 0.625, and 0.75 mm). Other aligner thermoplastic material companies in the market are Essix (Dentsply Raintree Essix), Zentura (Bay Materials), and Biolon (Dreve Dentamid). Studies comparing the various thermoplastic materials have been reported, most importantly concerning the mechanical properties of the aligners.[14–18] Other factors that either affect the aligner treatment or can be affected by the treatment (eg, root resorption, aligner material cytotoxicity, color stability, attachments, etc) have also been reported.[19–26]

Trying to compare fixed orthodontic appliances with removable clear aligners has become a focus of academic and clinical research, as evidenced by the significant number of articles dedicated to this subject. Particularly, comparison of the effectiveness, the prevalence of apical root resorption, incidence of spot lesions, oral hygiene, pain level, periodontal health, pulpal blood flow, and relapse between fixed and removable clear appliances exist in the literature.[6,27–36] While fixed orthodontic appliances are still the main tool used to treat all kinds of malocclusions, the technologic advancements harnessed by Invisalign in the early 2000s have opened the door for this appliance to provide comprehensive treatment.

Case Selection for Aligner Treatment

Case selection is a crucial part of aligner treatment success. Class I cases with an ideal overbite to moderate open bite are considered highly predictable, whereas Class I or Class II, division 2 cases with moderate to severe overbite and minimal crowding or spacing are less predictable. The main reason for this is that aligners are very best applied when dental movements require that the plastic push the teeth, but the opposite is true with extrusive/pulling movements.[10,37] Leveling a deep curve of Spee with no crowding is challenging, considering that most of the correction is anticipated by premolar extrusion. If, however, this is combined with resolving mandibular incisor crowding by their proclination, a concomitant leveling of the curve of Spee can be more easily achieved.

Treatments requiring dental extractions are considered beyond the capacity of clear aligners due to the tooth movements required during space closure. However, Invisalign recommends initiating orthodontic treatment from the mixed dentition stage to reduce the need for extractions or to limit the amount of tooth movement required should extractions become necessary. In addition, a mandibular advancement aligner appliance has also been introduced by Invisalign to treat teen Class II patients in the manner that functional appliances are designed to do.

Attachments and Interproximal Reduction

The success of aligner therapy is inextricably bound with the use of the appropriate attachments. *Attachments* are a term used to describe specifically shaped composite resin protrusions that are "attached" to strategic locations on specified tooth surfaces. These protrusions serve two main purposes: to introduce higher generated moments and to increase retention.

Attachments can increase the moments by increasing the available surface that the aligner pushes against in order to express the wanted tooth movement. Therefore, attachments are designed in such a way that their long axis is perpendicular to the force vector that the aligner generates.[38] Predetermined attachment forms are provided within various orthodontic CAD software, but they can also be designed individually in other software (eg, Meshmixer) and imported into the CAD software.

Retention is increased when extrusion attachments are placed, which means that their long axis is perpendicular to the long axis of the tooth.[26] These serve the purpose of locking the teeth in the plastic while couples of forces are applied to their crowns (eg, rotation, torque, angulation). They therefore prevent any loss of tracking that could be caused due to consequential intrusive forces ("watermelon seed effect"). Extrusion attachments are also placed in "anchor units," on which the intended biomechanics will have expressed the equilibrium forces generated during intrusion of the "active" nonanchorage unit (Newton's third law of motion). For example, when leveling the curve of Spee where the digital plan might only include intrusion of the mandibular incisors, extrusion of the premolars is to be expected; otherwise, loss of tracking in the premolar region will be observed. In addition, retention attachments are often placed on molars to ensure that the distal end of the aligner is locked in place over the crowns, on which slits are added to the aligners for elastic use. The vertical component of the elastic force has a dislodging effect on the aligner, necessitating the placement of a retention attachment to prevent this occurrence.

Supplemental specially designed pliers can be used to achieve simple tooth movements or to create undercuts for elastic placement. These tools are designed to place reproducible accurate modifications of an area of an aligner to create vertical indentations for individual tooth rotations, circular indentations for increased retention, or horizontal indentations for root torque. In addition, these can be used to create angulated cuts that serve as a place to hook an elastic around.

Most aligner treatments require interproximal reduction (IPR) in order to create adequate space to resolve aspects of a given malocclusion. IPR was first mentioned by M. L. Ballard but was popularized as an idea 40 years later by J. J. Sheridan.[39,40] Reports published in the literature during the 1990s supported the validity of this method and dispelled attitudes of any detrimental effects as a causative factor in elevated caries rate and/or periodontal complications.[41,42] Zachrisson et al concluded in 2007 that this treatment option was highly unlikely to induce any untoward tooth sensitivity and that IPR was a safe and reliable treatment tool.[43]

The use of IPR is an essential part of aligner therapy for several reasons. Firstly, the level of forces generated by the plastic aligner material on the dentition greatly reduces its ability to alter the transverse dimension of a patient's arch form through expansion. Therefore, the space needed to level and align the dentition is accomplished by incisor flaring and IPR. Secondly, clinicians often utilize IPR to loosen the contacts between crowded teeth during alignment in order to decrease friction. Finally, IPR is required to avoid adjacent tooth contact during alignment in order to facilitate tracking of the teeth in the aligners.

Staging the Aligner Treatment

Staging the tooth movements is another crucial part when designing aligner treatment, and with aligner CAD software, staging is a procedure that often has to be included in the aligner design. Frequently, a combination of movements is required for each tooth to level and align. Often clinicians tend to design aligner treatments where these are all performed simultaneously. However, in certain clinical situations, it has been shown to be more predictable to isolate these movements and execute them separately in a procedure called "staging." Nevertheless, this staging concept requires more aligners to be fabricated. For example, dental movements may be planned that result in areas of undercuts in order to serve as push surfaces for the plastic to generate forces. Think about bodily translation of a tooth. This can be broken into two separate movements: crown tipping and root uprighting. This is already an established concept used as the basis of the Begg technique and the modern Begg technique[44,45] (Fig 10-5). When closing an extraction space with aligners, the plastic has no room to wrap around both interproximal surfaces of each tooth that will be bodily translated in the extraction space. If this is attempted, poor angulation control and poor tracking are observed. However, when this is done by first tipping the teeth into the extraction space, the plastic can then engage both their now-exposed mesial and distal interproximal surfaces, which will then be used to generate the couples to upright their roots (Fig 10-6). A similar design can be implemented when distalizing a molar by letting it tip back first, enough for the plastic to be able to wrap around its mesial surface, and then uprighting its root. These tooth movements can be accompanied by just an extrusive attachment on the tooth to keep it within the plastic while these moments are applied.

Another example of staging tooth movements is shown in Fig 10-7 in the DeltaFace CAD software, where posterior segment distalization for correcting a Class II relationship or gaining space for anterior crowding is split into stages. First, the terminal molar is moved distally, then each tooth anterior to it is staged to be moved individually in a similar manner. In reality, what transpires is that there is an overlapping of movements where, before the last tooth takes its final position, the next tooth to be moved starts to move distally.

Staging combination movements can also be discussed in the context of their synergistic or antagonistic nature. For

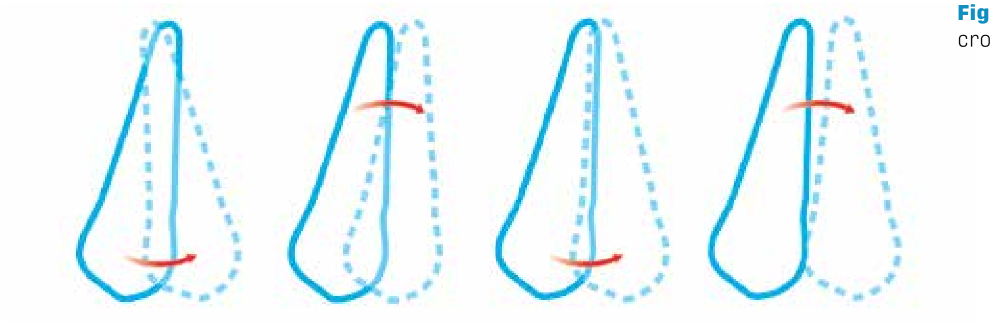


Fig 10-5 Tip-Edge philosophy for crown tipping and root uprighting.

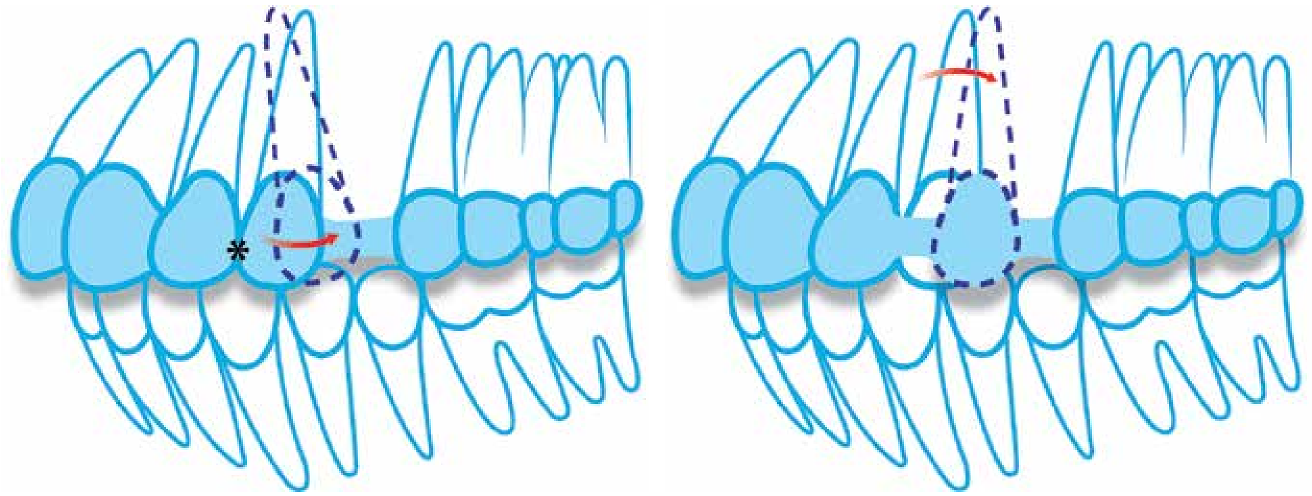


Fig 10-6 Tip-Edge philosophy applied in aligner orthodontic treatment (staging).

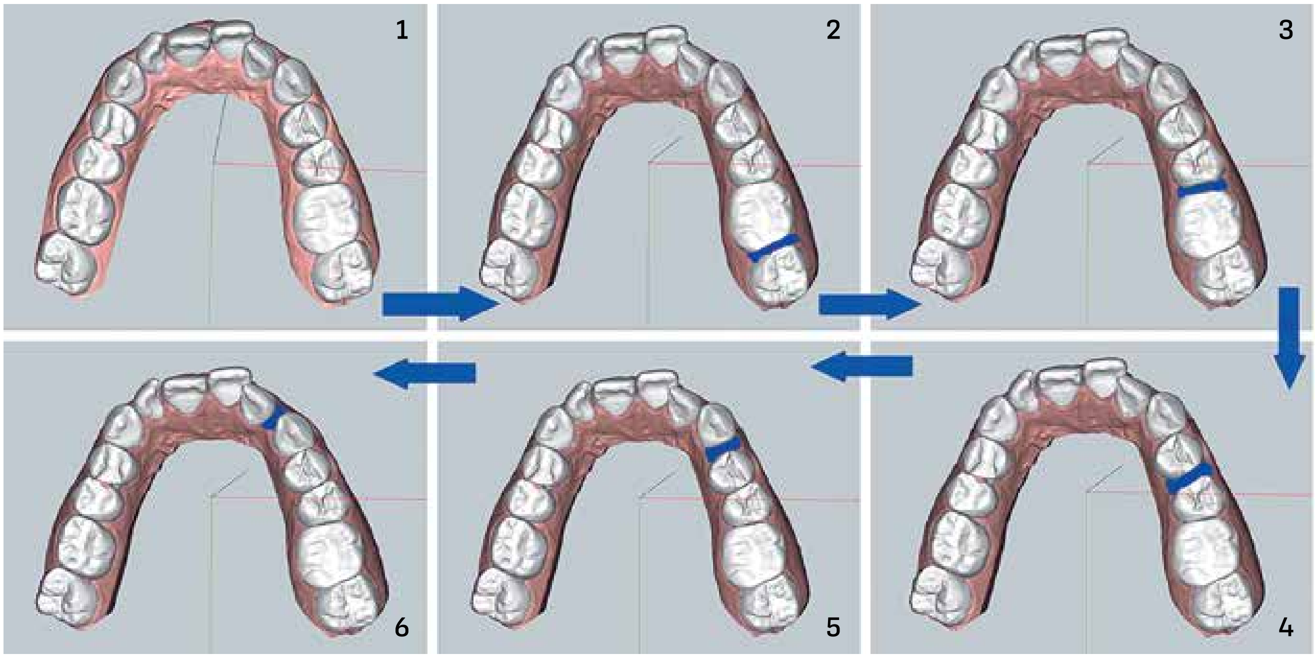


Fig 10-7 Correction of a Class II malocclusion or space gaining in stages.

example, rotation has been shown to have intrusive effects ("watermelon seed effect"), and therefore rotation and intrusion are two synergistic movements. In other words, they work well together and can be performed simultaneously with great success. If, however, rotation and extrusion are required on the same tooth, their antagonistic relationship might require that they be staged separately. Staging these two movements would mean that first rotation will be performed and then extrusion on the same tooth, or vice versa.

The clinical use of aligners and the research conducted on their use have elucidated their potential weaknesses as a treatment option. These studies have provided an evidence-based description of the inefficiency of this treatment tool in achieving numerous tooth movements.[4,46–50] Informed clinicians can improve their success by accepting the need for multiple additional aligners to improve treatment outcome. In addition, it might be recommended to perform a short preliminary stage of fixed appliance treatment before transitioning to aligner therapy in order to tackle some tooth movements that either would require a large number of aligners or are questionable as to whether they can be achieved with aligners at all. This can reduce treatment time and effort for the patient. Some preliminary actions can entail the use of an expander (conventional or TAD-supported), a Class II corrector, a distalizer (conventional or TAD-supported), a transpalatal arch to derotate molars, or a TAD-supported uprighting spring (for severely tipped molars), among other supplementary appliances.

In-House Aligner Design

Generally, aligner treatment can be divided into three categories:

1. Full aligner treatment
2. Hybrid aligner treatment, where treatment starts with fixed appliances and finishes using aligners (or the opposite)
3. Aligner treatment for relapse cases

All orthodontic CAD software programs share a similar workflow in clear aligner design. Some software packages also offer the ability to design aligners for direct 3D digital printing using aligner resin. The procedure of designing aligners will be described using DeltaFace software without getting into details concerning biomechanical considerations. This software is easy and efficient to use, with plenty of tools to help the orthodontist design the necessary study models for aligner manufacturing or to design the aligners for direct 3D printing.

Aligner Design Workflow Using an Orthodontic CAD Software

1. Intraoral scan importing

The first step is the digitization of the dental arches, usually using an intraoral scanner (Fig 10-8). A desktop scanner could be used in cases where polyvinyl siloxane impressions were taken. The impressions could be directly scanned, or plaster casts could be poured and scanned. All the necessary patient data are written down in the chart, and the intraoral scan of the dental arches is imported. Tools for capping, deleting, and smoothing can be used to clean up the scans of the dental arches.

2. Occlusion adjustment

The second step is to adjust the occlusion if needed (Fig 10-9). Nevertheless, most of the time the occlusion is defined correctly during intraoral scanning. Three points are selected on each arch to define and orient the occlusion plane to ensure that the digital model is in the right reference plane.

3. Border cleaning and model base generation

In this stage, the borders of the virtual dental models are cleaned automatically or manually, and the model bases are created to give the dental model its final form (Figs 10-10 and 10-11).

4. Tooth numbering and segmentation

The fourth step is to define the teeth that will undergo segmentation by enabling them (Fig 10-12). After that, the software asks the operator to define the mesial and distal surfaces of each tooth (Fig 10-13). In this way, the software separates each tooth from its adjacent neighbor(s) and sets the default angle (rotation around Z) of the teeth. The

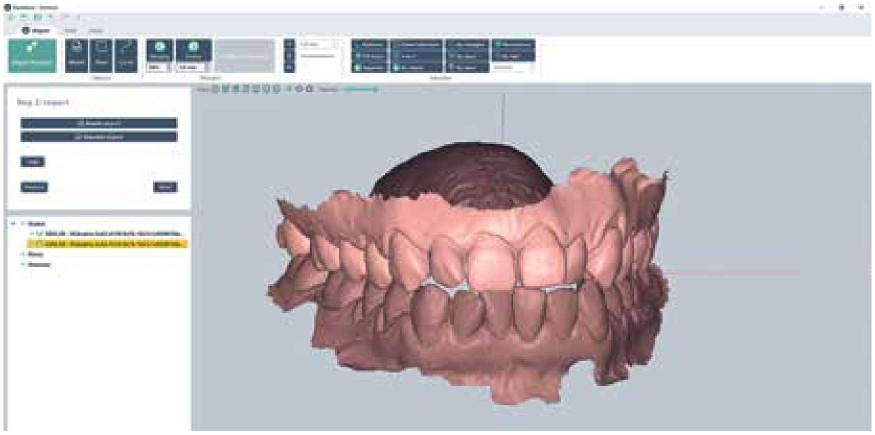


Fig 10-8 Intraoral scan importing in Delta-Face software.

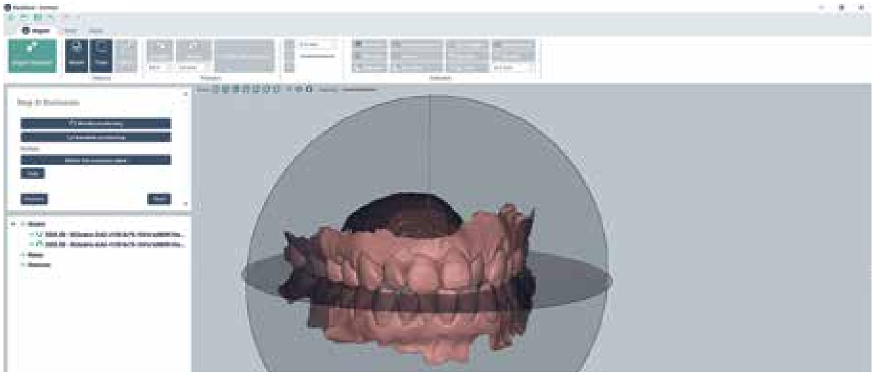


Fig 10-9 Occlusion adjustment using the manipulator.

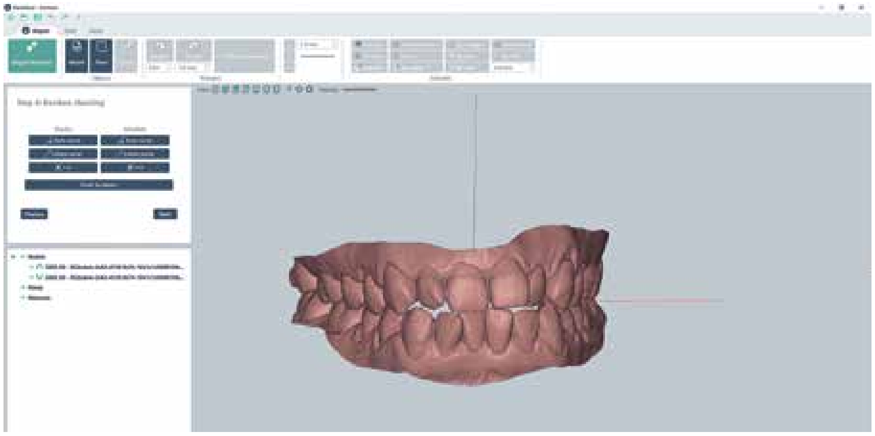


Fig 10-10 Cleaning of the virtual model borders.

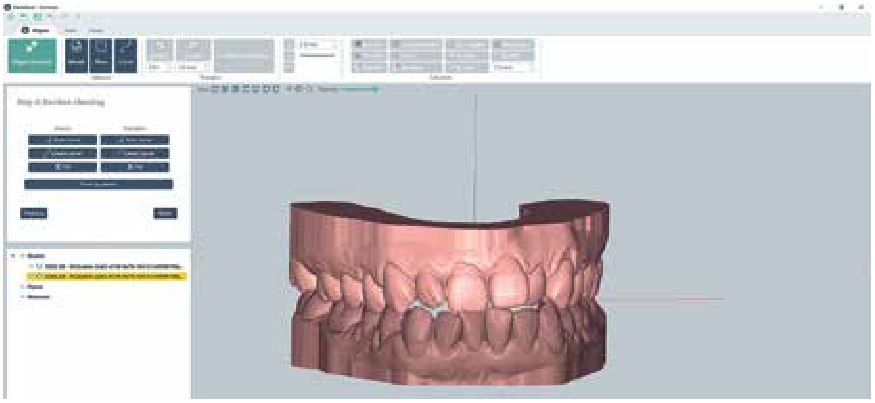


Fig 10-11 Closing of the models.

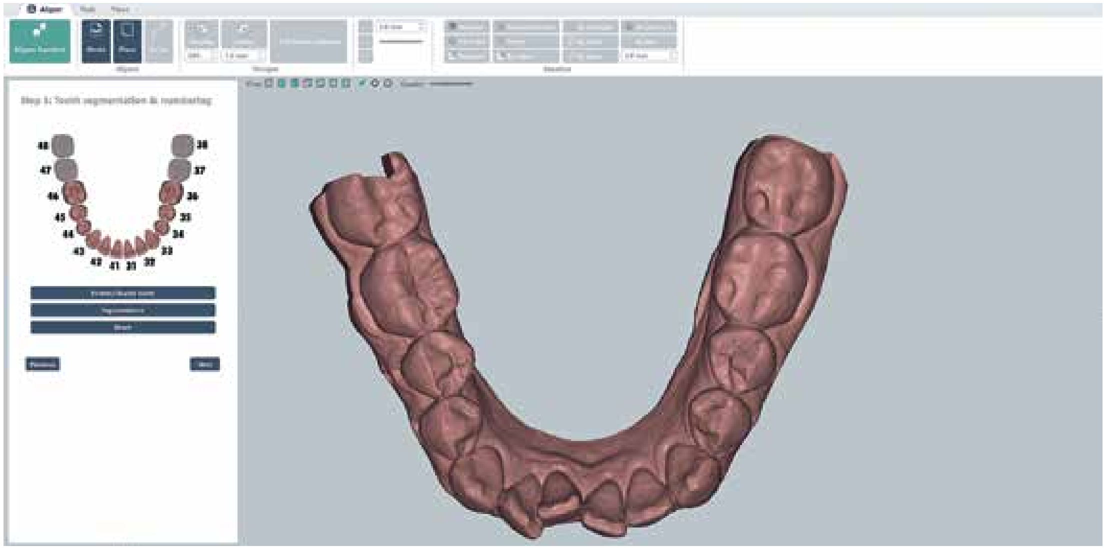


Fig 10-12 Enabling-disabling the teeth to be segmented.

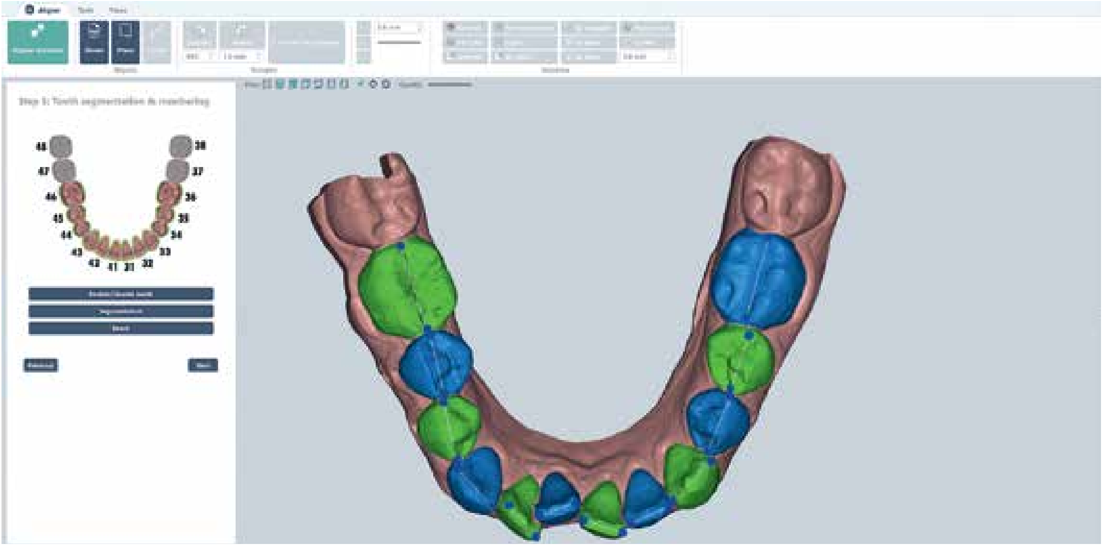


Fig 10-13 Defining the mesial and distal occlusal surfaces of the teeth: automatic segmentation.

last stage is segmentation. The software calculates and presents in different colors each tooth that is going to be moved in the setup stage. It is absolutely crucial to check every tooth. In case of incorrect segmentation, the operator can manually correct the problem (Fig 10-14).

5. Defining tooth reference axes

In this step, the operator adjusts the central point of the teeth (Fig 10-15). The central point of each tooth (red point) is the reference point used to measure all the rotations and translations in the setup stage. The software itself, through calculations, tries to define the approximate position of the root of each tooth in the space. Most of the time, this is not accurate. In two studies by Athanasiou and Halazonetis, it was shown that commercially available software cannot estimate the anterior tooth root inclination of digital models.[51,52] For this reason, manual correction of the tooth axes must be performed (Fig 10-16). Importing the patient's CBCT data is helpful in order to visualize the exact position of the roots. Unfortunately, radiation is an obstacle for CBCT scanning for many patients, unless it is needed for other medical reasons.

6. Virtual setup

The next step is the virtual setup of the dental arches. All software programs of this type have similar tools, and the

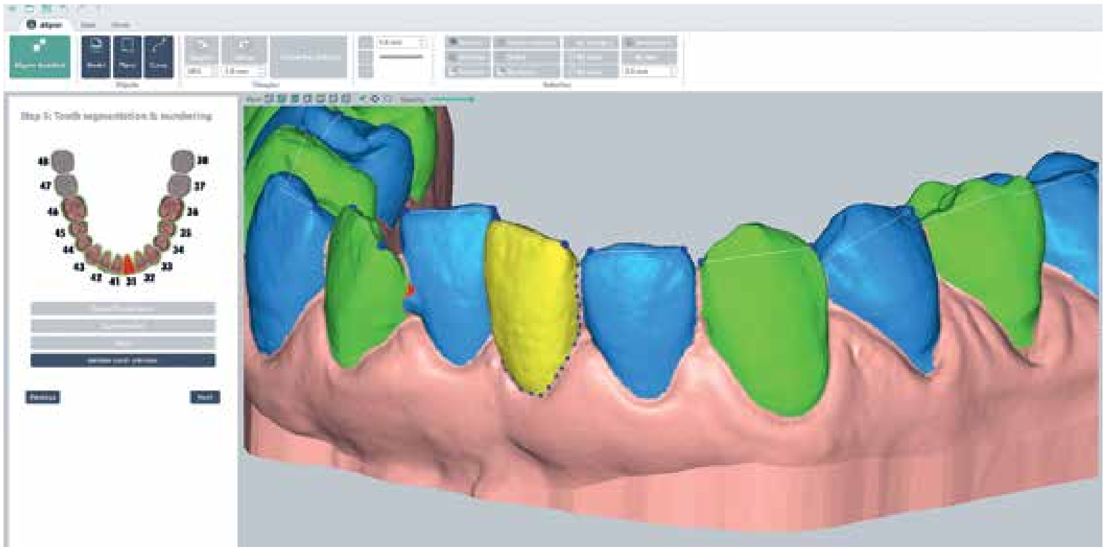


Fig 10-14 Manual segmentation.

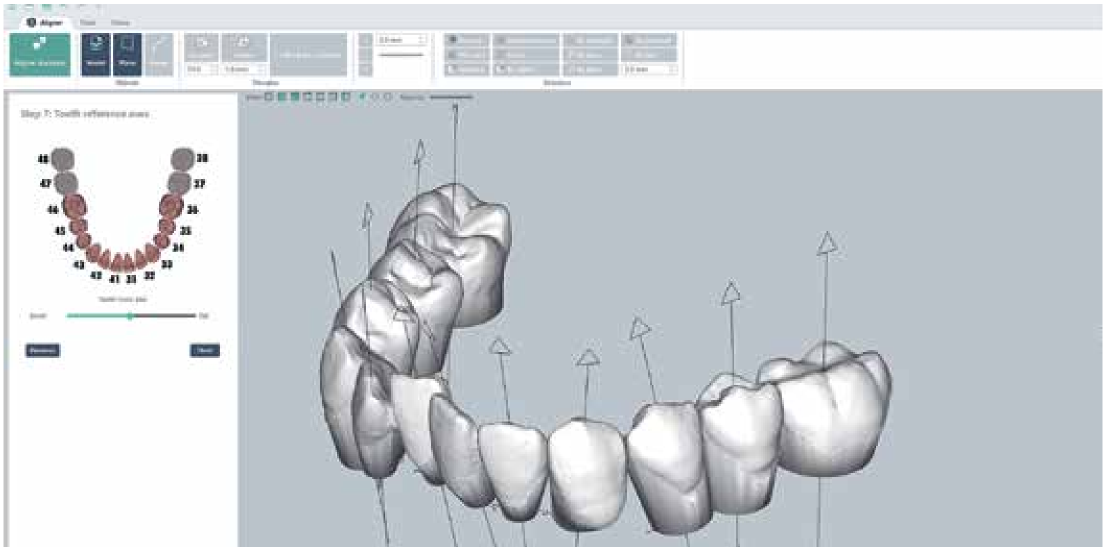


Fig 10-15 Defining the tooth axes.

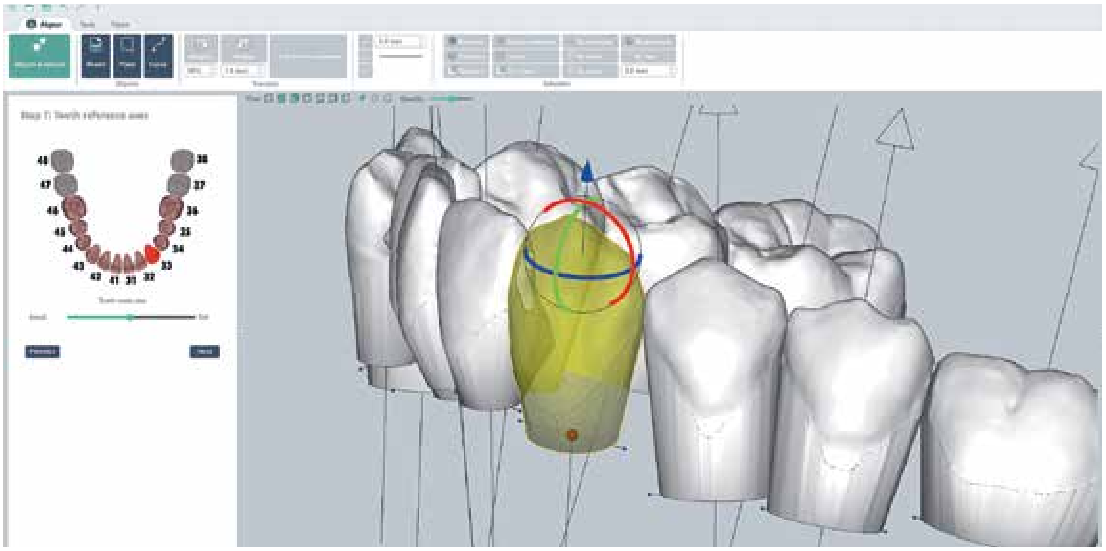


Fig 10-16 Manual correction of the root orientation axes.

Fig 10-17 Setup using a manipulator.

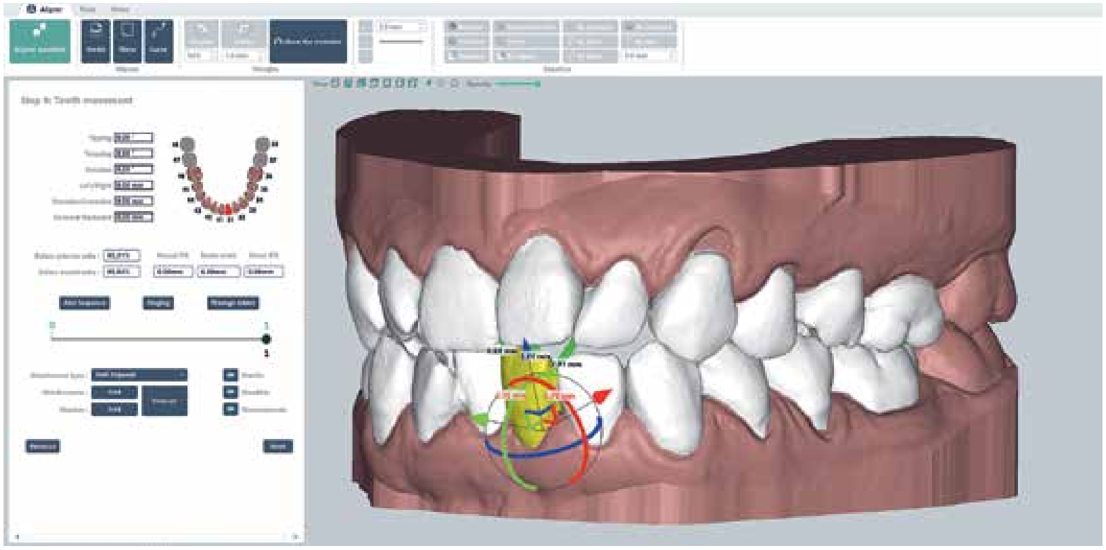
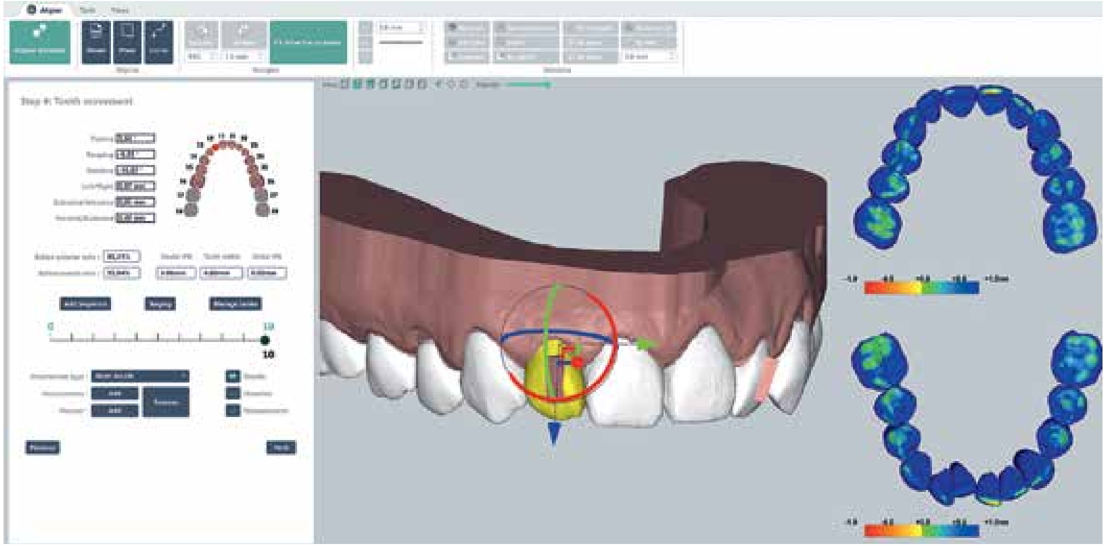


Fig 10-18 Setup and occlusion inspection.



teeth can be moved separately with the tooth manipulator or by defining the amount of movement or angulation change numerically (Figs 10-17 and 10-18). When teeth are virtually moved into an area lacking space, then IPR will be needed. When this is attempted, the software calculates and displays on the mesial and/or distal side of the tooth the space needed (Fig 10-19). The amount of IPR needed must be marked in the appropriate place within the software.

One of the most important parts of CAT design is separating the teeth movements into stages. It is an error to do so in a single stage. The software cannot distinguish which teeth have to be moved first in order to have an efficient and smooth course of treatment. For instance, if we want to create space by distalizing the maxillary molars, we have to create different stages of movements. Movement of the molars has to be the first stage of the movement. Then a second stage has to be added where the crowded teeth are moved in the space created by the distalized molars (see Fig 10-7). In the current software, this can be done by using the "Add sequence" button.

Careful planning and staging of individual and all tooth movements has to be performed in order to correctly guide the software. Staging can be visualized on the computer screen or printed onto paper in a PDF format (Fig 10-20). During the setup process, the attachments needed for

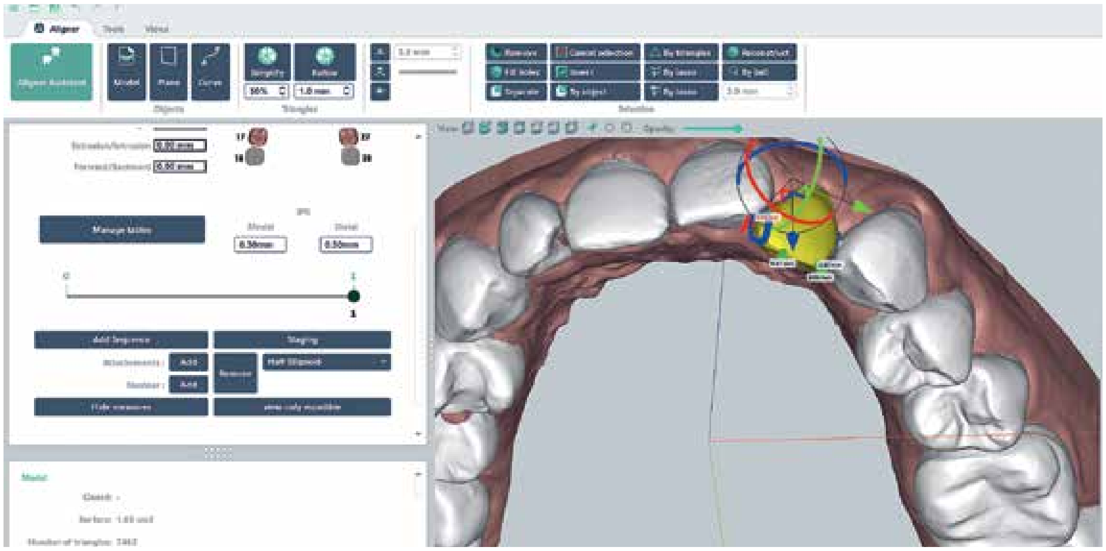


Fig 10-19 Setup and IPR calculation.

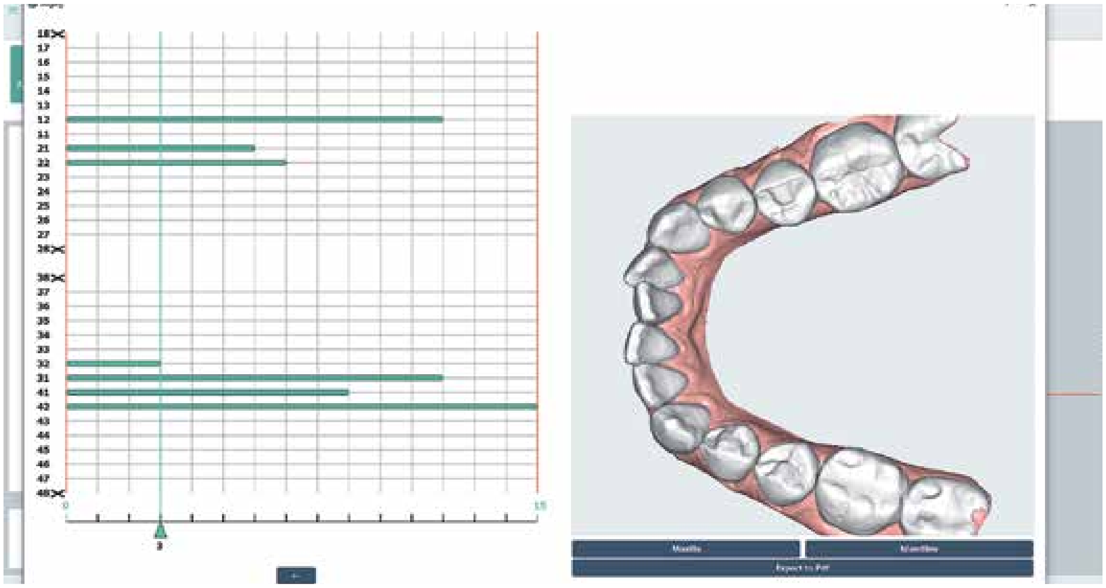


Fig 10-20 Movement staging table.

these movements must be placed. A variety of attachments (elliptical, half-sphere, etc) are found in the appropriate library within the software. Their dimensions can be easily changed depending on the patient's needs. Attachments can be placed on the teeth or "in" the teeth (negative attachment). Outsourced designed attachments can also be imported for use in the software. Furthermore, the strategic use of attachments as aligner anchorage points to stabilize the aligners during tooth movement is a critical role they play. Furthermore, the ability to use all the teeth as an anchorage against the movement of one or two teeth is a significant advantage of aligner treatment.

The last stage is to add sequential labeling to each virtual model to be printed. It is useful to write the number on the buccal surface of the last molar that will not be moved so that each aligner will have its number printed. Once this sequence of setup stages has occurred, the operator can visualize the number of aligners that will be needed for the treatment. The maximum amount of movements (linear or angular change) that an aligner can perform is the same for every case. Nevertheless, there is an option to change the default numbers using a table provided. Concurrently, at this stage, a Bolton analysis is automatically created by the software.[53]

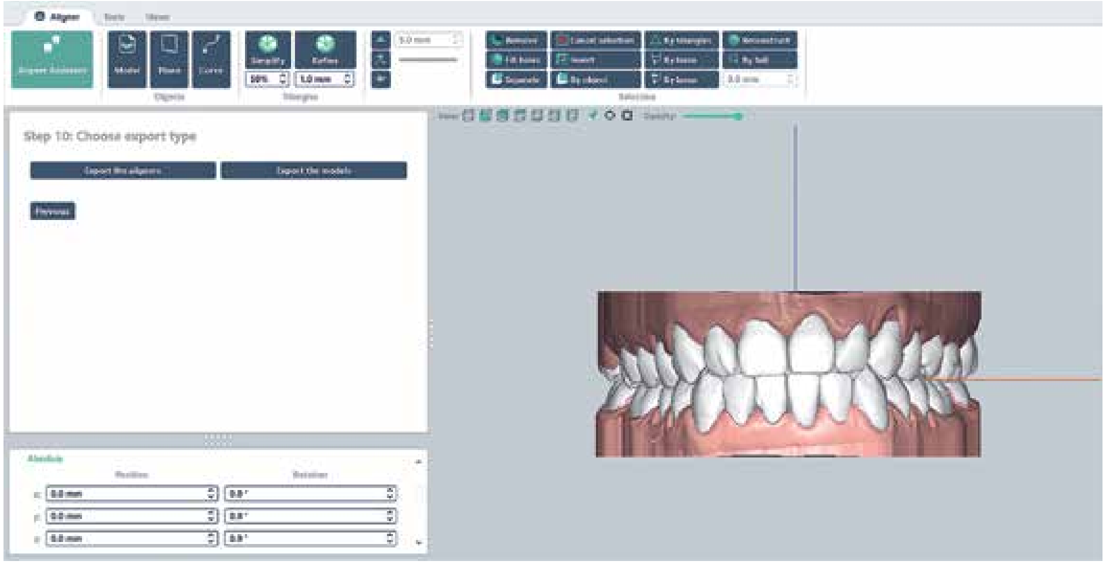

Step 10: Choose export type

Fig 10-21 The operator must select between exporting the models or the aligners themselves.

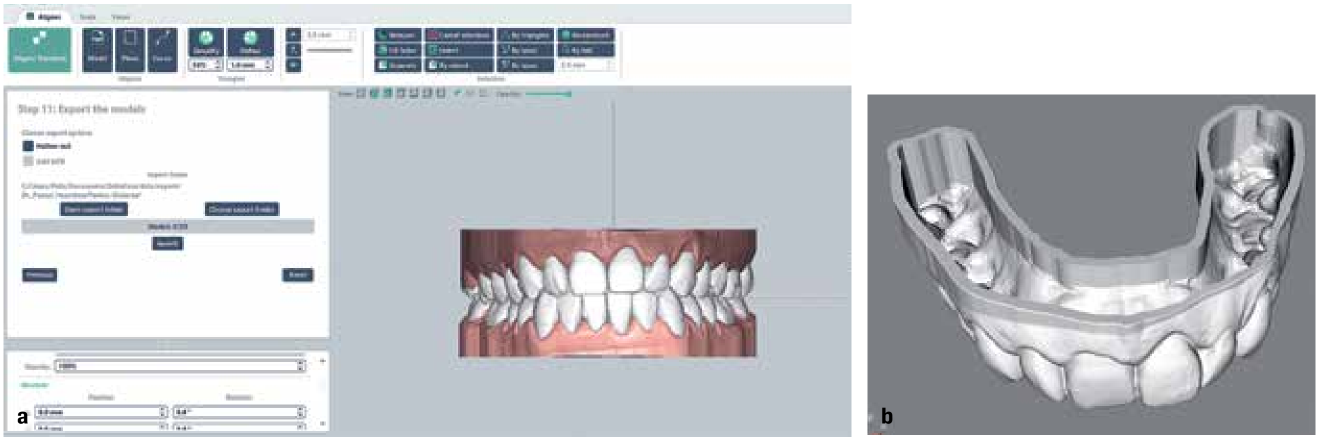

Step 11: Export the models

Fig 10-22 *(a)* Exporting the models to fabricate a hollow dental model. *(b)* Hollow dental model.

7. Exporting of files

At this stage, the orthodontist has to define if the aligners will be printed on a 3D printer directly (to be discussed later), or if dental casts are to be printed from which aligners will be fabricated (Fig 10-21). If the latter is performed, the printed working models can be fabricated to be hollow and without bases in order to conserve material (Fig 10-22). However, care must be taken to avoid model breakage when removing it from the printer's platform due to its reduced structural strength. In addition, models fabricated to be too thin may also distort during aligner thermoforming due to the heat involved in softening the aligner plastic material. In a study reported by Camardella et al, printing accuracy was compared between printed models from intraoral scans with different designs of model bases and different 3D printers: a regular base, a horseshoe base, and a horseshoe base with a bar connecting the posterior region using a polyjet and a 3D SLA (stereolithography) printer. The results showed that printing models using the polyjet printing technique were accurate regardless of the model base design. On the other hand, horseshoe-shaped base printed models using the SLA 3D printer were found to be transversely constricted. Horseshoe-shaped bases with a posterior connection bar printed with an SLA 3D printer were accurate when compared with the printed models with a regular base.[54]

8. Dental model printing: Undigitization

The setup virtual dental models can now be printed—or undigitized and converted to a real object. Regarding the printing accuracy of study models, a study by Rebong et al showed that FDM (fused deposition modeling) casts had the fewest dimensional changes compared to plaster casts, while SLA and polyjet models had a tendency for expansion at the inter- and intra-arch measurements and a tendency for shrinkage at the vertical dimension.[55] These results apply only to the specific resin, FDM filament, and to the particular printers that were used in the study.

Generally, printing is done using SLA, DLP (digital light processing), or MSLA (masked stereolithography) printers, which all use dental model resin and a UV light source for polymerization (laser beam, light projector, or LCD light source). The printing procedure is followed by the cleaning of the dental cast using isopropyl alcohol 91% and postprinting curing. FDM printers are less frequently used for working model printing. However, they have the advantage of a lower cost compared to the resin printing systems, and there is also no need for further postprinting procedures. Isopropyl alcohol is also an irritant chemical substance, and therefore proper room ventilation is required. A disadvantage of FDM printer usage is the need for a special filament that can withstand the high temperature of the thermoforming procedure where deformation of the dental cast could lead to inaccurate aligner fabrication.

9. Aligner thermoforming

Following working model printing, aligner thermoforming is the next step. This procedure entails the use of vacuum or positive pressure thermoforming machines with various thermoforming plastic foils. Vacuum thermoforming machines cannot apply pressure of more than one bar (between 0–1 bar), which is the normal air pressure at sea level. However, positive thermoforming pressure machines have no limit on the amount of pressure they can exert. It is crucial to have a thermoforming machine that can deliver the proper pressure to create the aligners accurately. In cases where attachments are going to be placed on the teeth, a separate template aligner is developed by the software in order to facilitate attachment bonding. Usually, this is made of a thinner foil (eg, Duran 0.5 mm) to make template removal easier.

Tracking

In any stage of the aligner treatment, the orthodontist can acquire a new intraoral scan to compare it with the initial intraoral scan using the superimposition feature. Superimposition can also be done between the new intraoral scan and the corresponding virtual dental cast. In this way, the orthodontist can check whether the specific aligner at this stage is moving the teeth exactly as it was designed. In the case that refinement aligners are needed, the orthodontist can proceed to the setup tool and add a new “stage” of treatment, which will allow for further tooth movements.

In-house aligner design and fabrication is a multiple-step procedure that the orthodontist has to fulfill. Intraoral scanning, clinical examination, the taking of radiographs and clinical photographs, CAD software use, dental model 3D printing, and thermoforming of the aligners are the stages that are essential for a successful treatment outcome. On the other hand, in an orthodontic laboratory, the technician assumes a more significant role in aligner design and fabrication while the orthodontist plays a lesser role. Aligner companies unavoidably take the biggest piece of the pie in the design and fabrication of the aligners (see Fig 10-2). It is the clinician’s decision whether to be in charge of all the aligner design-printing procedure, have a laboratory do a part of this, or have an aligner company provide complete service in this endeavor.

Case Presentation

CAD software capabilities in designing aligner treatment are enormous. Frequently all the CAD software programs undergo updates, which make the software more intelligent and helpful for the operator. Nevertheless, the orthodontist has to choose which cases to treat using aligners and which to reject.

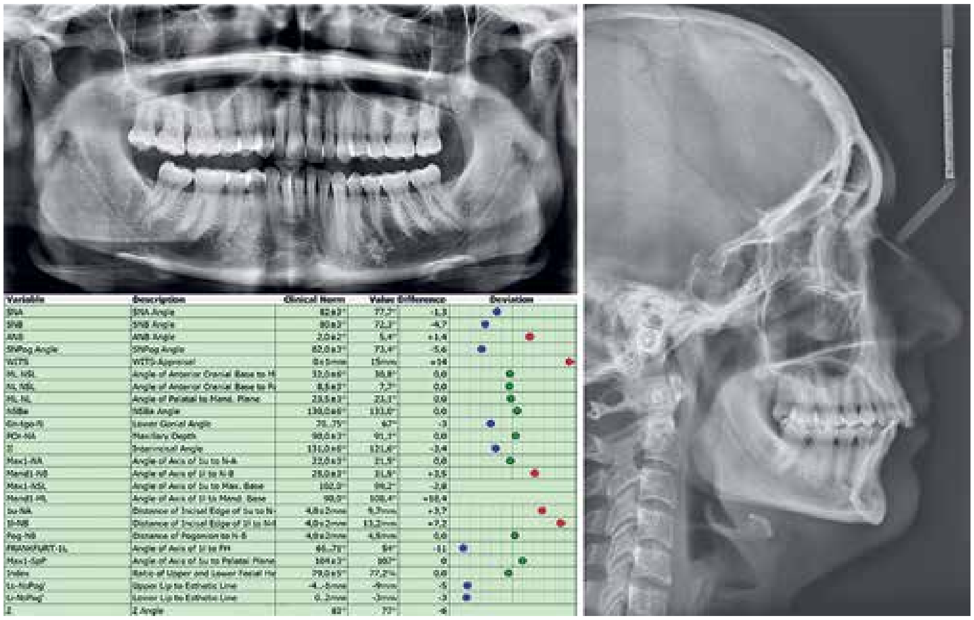
Starting with relatively easy orthodontic cases and gradually advancing to more complex ones is highly recommended in order to parallel fabrication with treatment goals. But no matter the difficulty level of the case, certain essential steps are required for any CAT (Box 10-1). In this section, a relatively easy case is presented to show that in-house aligner design workflow can be simple and that the treatment results after careful planning are satisfactory.

The patient in Fig 10-23a presented with a Class II skeletal and dental malocclusion with mild maxillary and mandibular anterior dental crowding. Anterior Bolton discrepancy

Box 10-1 Essential steps of a successful in-house aligner treatment

1. Complete treatment records
2. Proper treatment planning
3. Correct aligner design steps
4. Correct setup
5. Appropriate attachment selection
6. Correct attachment placement
7. Aligner staging
8. Accurate dental working model printing and aligner fabrication
9. Use of auxiliaries to facilitate treatment

Fig 10-23a Pretreatment patient photographs.



Variable	Description	Clinical Norm	Value	Difference	Deviation
SNA	SNA Angle	82±2°	77,7°	-1,3	●
SNB	SNB Angle	80±3°	72,3°	-4,7	●
ANB	ANB Angle	2,0±2°	5,4°	+1,4	●
SNPog Angle	SNPog Angle	82,0±3°	73,4°	-5,6	●
WITS	WITS Appraisal	0±5mm	15mm	+14	●
ML NSL	Angle of Anterior Cranial Base to M	32,0±6°	30,8°	0,0	●
NL NSL	Angle of Anterior Cranial Base to N	8,5±3°	7,7°	0,0	●
ML NL	Angle of Palatal to Mand. Plane	23,5±3°	23,1°	0,0	●
NSBa	NSBa Angle	130,0±6°	131,0°	0,0	●
Gn-tgo-N	Lower Gonial Angle	70..75°	67°	-3	●
PO-NA	Maxillary Depth	90,0±3°	91,3°	0,0	●
II	Interincisal Angle	131,0±6°	121,6°	-3,4	●
Max1-NA	Angle of Axis of Iu to N-A	22,0±3°	21,5°	0,0	●
Mand1-NB	Angle of Axis of Il to N-B	25,0±3°	31,5°	+3,5	●
Max1-NSL	Angle of Axis of Iu to Max. Base	102,0°	99,2°	-2,8	
Mand1-ML	Angle of Axis of Il to Mand. Base	90,0°	108,4°	+18,4	
Iu-NA	Distance of Incisal Edge of Iu to N-	4,0±2mm	9,7mm	+3,7	●
Il-NB	Distance of Incisal Edge of Il to N-B	4,0±2mm	13,2mm	+7,2	●
Pog-NB	Distance of Pogonion to N-B	4,0±2mm	4,5mm	0,0	●
FRANKFURT-IL	Angle of Axis of Il to FH	65..75°	54°	-11	●
Max1-SpP	Angle of Axis of Iu to Palatal Plane	109±3°	107°	0	●
Index	Ratio of Upper and Lower Facial He	79,0±5°	77,2%	0,0	●
Ls-NsPog'	Upper Lip to Esthetic Line	-4..-5mm	-9mm	-5	●
Li-NsPog'	Lower Lip to Esthetic Line	0..2mm	-3mm	-3	●
Z	Z Angle	80°	73°	-8	

Fig 10-23b Panoramic and lateral cephalometric radiographs and cephalometric analysis.

was present as manifested in the area of the maxillary lateral incisors (mandibular anterior excess material). The lateral cephalometric radiographic analysis revealed a retrognathic mandible, normodivergent face, mandibular incisor proclination, and mild maxillary incisor proclination (Fig 10-23b). She also had gingival recessions mainly of the labial and lingual sides of the mandibular incisors and a generalized recession of the interdental papilla on both dental arches. She had a history of previous periodontal treatment for periodontitis. The panoramic radiograph revealed a general mild horizontal bone loss (see Fig 10-23b). The patient's main complaint was the presence of black triangles between the teeth due to the blunting or loss of interdental papilla.

It was agreed to proceed with in-house CAT together with IPR to reduce the black triangles. Intraoral scanning was performed, and the files were transferred to DeltaFace Orthodontic CAD software. All the steps for the design of the aligners were followed in the software. The software calculated the need for seven maxillary and five mandibular aligners. Duran foils (0.5, 0.625, and 0.75 mm) were used for each of the stages. Composite attachments were also placed using an aligner template designed by the software. Treatment time was 8.5 months, during which time the patient wore the clear aligners for 22 hours per day. Progress photographs were taken 5 months after the beginning of treatment (Fig 10-23c). At the end of the treatment, maxillary and mandibular fixed retainers were bonded. The goals of the orthodontic treatment were achieved together with patient satisfaction, and there was no need for supplemental refinement aligners. The treatment results are shown in Fig 10-23d, and the final panoramic and lateral radiographs are presented in Fig 10-23e.

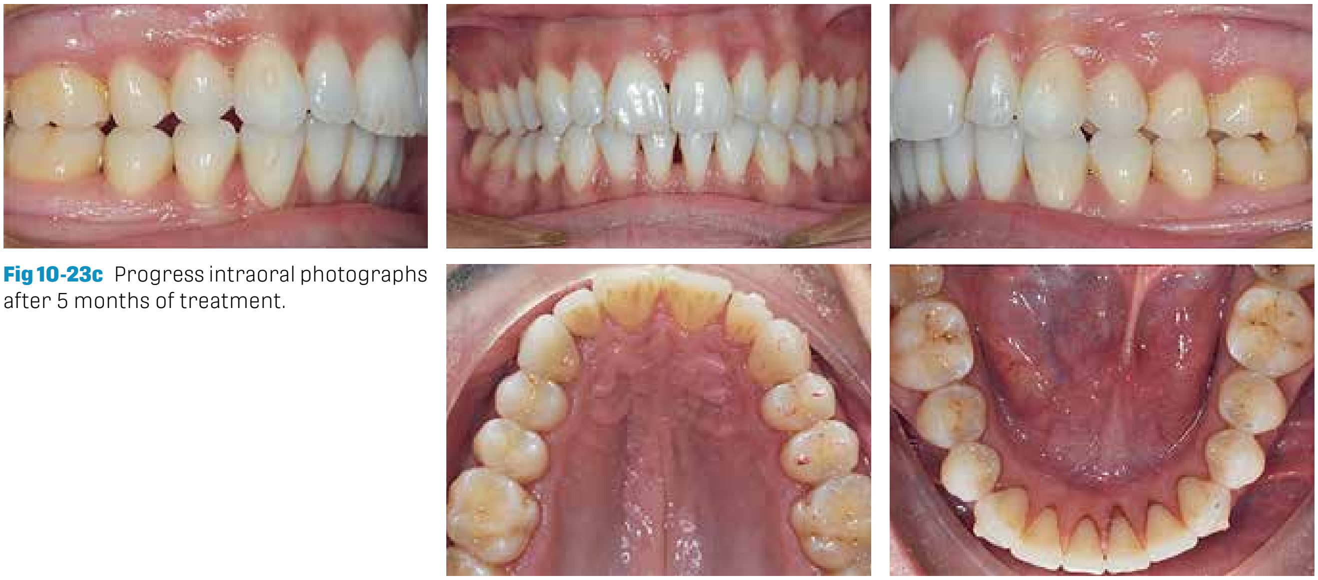
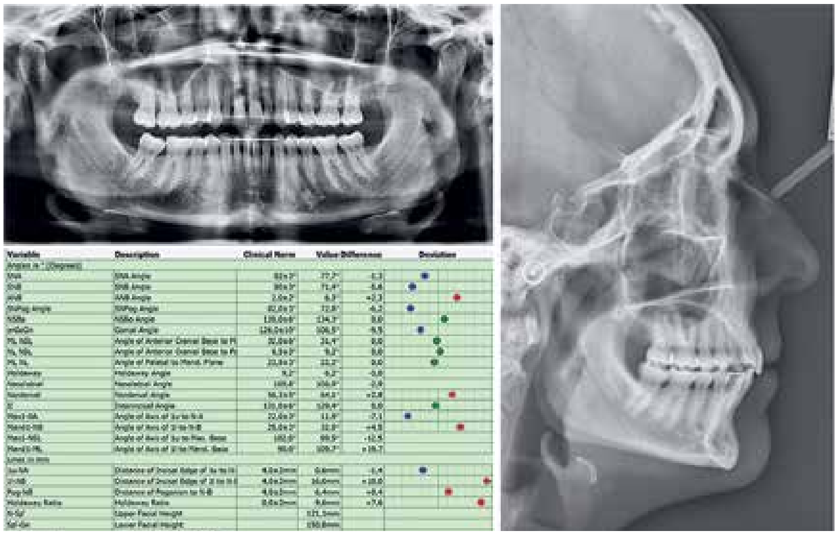


Fig 10-23c Progress intraoral photographs after 5 months of treatment.

Fig 10-23d Intraoral photographs after orthodontic treatment.

Fig 10-23e Final panoramic and lateral cephalometric radiographs.



Direct Aligner Printing

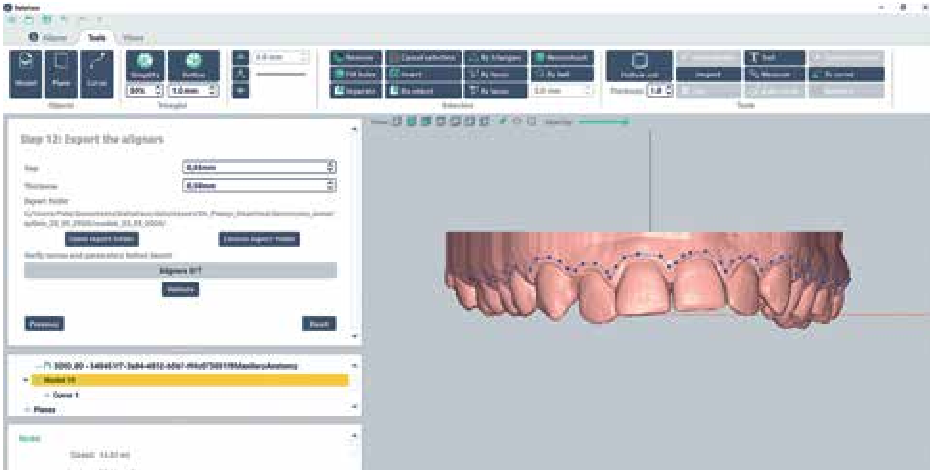
3D additive technology has evolved significantly during the last few years. The number of companies developing new 3D printers or materials for printing is continuing to increase. This is evidenced in the size and number of technology exhibition conferences planned and taking place all over the world. These have presented a trend for almost all 3D printing companies now turning their interests to dentistry, and especially to orthodontics. New 3D printers and materials for printing with better properties for dental model printing, surgical guides, indirect bonding trays, casting, denture bases, semipermanent crowns or bridges, etc, are constantly being invented, not all of which are biocompatible. Of note is that materials for direct aligner printing are also just beginning to make their appearance at these exhibitions. Presently, this is being pursued only by a small number of companies (eg, Graphy). The challenge in developing this material lies in its inability, once cured, to provide comparable mechanical properties to thermoformed aligners.

Excluding aligner resins, all other polymeric materials are used to print appliances that do not exert any forces on the teeth. They are passive appliances that fit into the mouth for various purposes (occlusal splints, surgical splints, surgical guides, etc). Aligner resin, on the other hand, is a material that is used to build active appliances. It is a resin that will be transformed in the 3D printer from a liquid into an active appliance. That is the main reason why there is a difficulty in creating an aligner resin that will have all the properties of an orthodontic archwire or at least be able to mimic the properties of the commonly used thermoformed aligner, namely the appropriate stiffness, shape memory, high elastic range, and flexibility. Biocompatibility is another important issue, because aligners might sometimes be worn for more than 2 years. Minimal moisture absorption and color stability (transparency) are also important. Nevertheless, we should not be discouraged by their unavailability at this time. In less than 20 years, aligners evolved from an appliance for correcting simple relapse problems to an appliance that can correct complex malocclusions. In the same way, direct aligner printing resin will evolve through research, case trials, and new technology.

The postprinting procedure is another aspect that will hopefully evolve as well. At this time, a printed aligner is not ready for patient use until it undergoes relevant postcuring procedures. Specifically, cleaning of the residual resin is essential after printing. With all other resins, it is done with isopropyl alcohol, followed by a further cycle of curing to ensure complete internal polymerization and removal of residual uncured resin. These postprinting procedures are currently essential to produce required appliance physical and mechanical properties.

Direct-print aligner resin differs from the above, among other things in needing different postcuring processing. Graphy is a company that has developed such an aligner resin and has recently made it commercially available; hence, there is presently no independent confirmation of its performance. Manufacturer directions require postprinting of this resin by centrifugation. They also developed a high-power UV curing machine (Cure M) that cures the remaining resin faster and more efficiently. Insufficient resin curing, as they state, can affect the properties of the aligner. All these direct aligner printing and postprinting parameters increase the complexity of developing an aligner that would be satisfactory for orthodontic treatment; however, they have not deterred its being made available. There is no intention here to analyze the resin's properties and possible uses but rather to trigger orthodontists, researchers, and other companies to test such resins, study them, and evolve them.

Orthodontic CAD software like Maestro Dental Studio and DeltaFace already have a function to design directly printed aligners. The procedure to design these aligners with these software programs is the same as those needed for thermoforming aligners. As can be seen in Fig 10-24, in the DeltaFace software the orthodontist has to mark the limits and define the offset and thickness of the aligners on the dental cast, which is currently uniform throughout a given aligner but is due to become variable at operator-specified aligner areas. Theoretically, this means that higher or lower forces could be exerted on a specific area of a tooth's surface or within areas of the dental arch. Different amounts of forces translate into differential amounts and directions of tooth movement. In addition, necessary moments for tooth movement could be more easily created while the number of attachments could be decreased. The effect of modifying aligner thickness is another aspect requiring investigation.



Step 12: Export the aligners

Fig 10-24 Aligner virtual design in DeltaFace.

Workflow for Directly Printed Aligners

Printed aligner design

The workflow for designing the printed aligners is the same as that for thermoforming aligners. At the point of export, the orthodontist must select to export the aligners directly (see Fig 10-21). After setup has finished, the aligner has to be designed by marking its limits and defining the offset and its thickness (see Fig 10-24). The next step is exporting the files, which later will be printed in a 3D printer (Fig 10-25).

Aligner printing and postprinting procedures

The guidelines for the printing and postprinting procedure will differ for different resins. Graphy has a specific protocol for the aligner printing and postprinting process. In order to reach a successful outcome, the author had to experiment with all the stages of the procedure. It is a multistep process in which every step should be accurately performed in order to have the desired outcome.

The printing process starts by placing the aligners on the 3D printer's virtual platform (Fig 10-26). Due to the big span of the aligners (for printing), many supports (like internal struts or a skeleton) have to be added. A horizontal position of the aligners was preferred, and the aligners were flipped upside down in order to position the supports on the outer part of the aligner. In a recent new protocol, Graphy proposes to position the aligners in a vertical position; this helps to create smoother aligners with fewer supports. The resin used for printing was Tera Harz TC-85DAC by Graphy. It exudes a pleasant odor and is nontoxic and hypoallergenic. The company suggests using a specific 3D printer that is calibrated for this specific resin, although the orthodontist could use his or her own printer and calibrate it appropriately. Perhaps the most important part of the process is the postprinting curing procedure. Graphy suggests using its own high-powered curing unit, the Cure M, which produces the best results because it is tested and calibrated for the specific resin. Nevertheless, in the case presented, a 3D DLP printer was already installed in the office and that was the one used for printing. Settings for the office printer were sent by Graphy to be installed, and the curing unit was similar in power output to the company's unit.

In order to test the resin in direct aligner printing, a case where no attachments were needed was chosen, while movements to be performed were minimal. The aligners were designed using DeltaFace software and exported to the office 3D printer. Printing was done using a resolution of 100 μm, and it took 50 minutes to print (Fig 10-27).

The postprinting procedure is different than for other printed appliances or dental casts. The manufacturer informs that the typical isopropyl alcohol bath should not be used because it destroys the aligner. Instead, and because the resin is biocompatible, a centrifuge procedure to remove the excess resin needs to be performed. A hand-operated centrifuge machine is shown in Fig 10-28. Nevertheless, an automatic centrifuge machine is offered by Graphy for this reason. The aligners are positioned perpen-

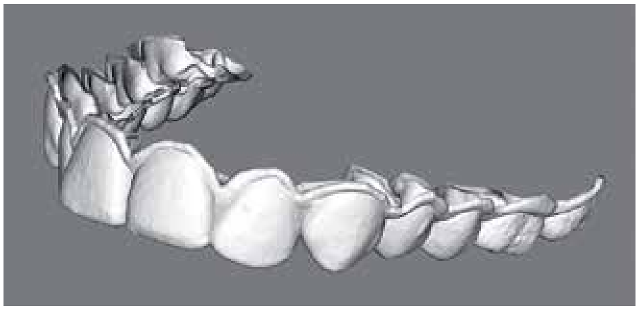


Fig 10-25 Virtual aligner to be exported to a 3D printer.

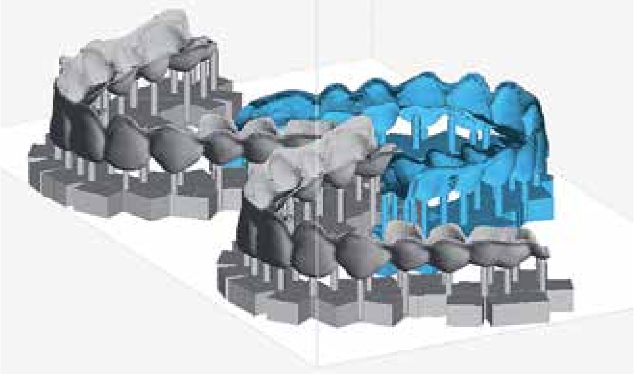


Fig 10-26 The aligners on the printer's virtual platform.

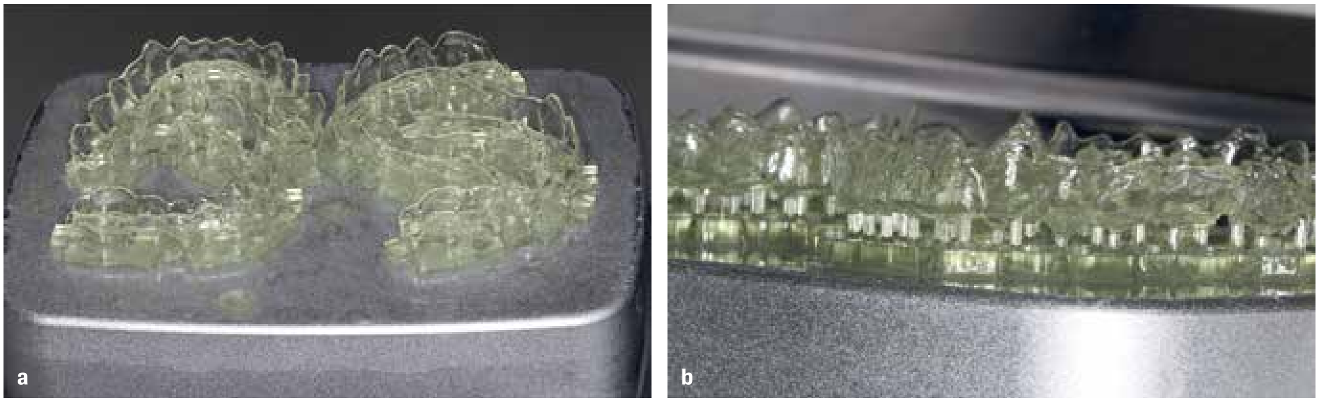


Fig 10-27 *(a)* The aligners printed. *(b)* The aligners' supports.

dicular with the internal surfaces facing outward so that the centrifugal force removes the residual resin from the inside part of the aligner. The manufacturer proposes a centrifugal protocol of 350 rpm for 3 minutes, or 700 rpm for 2 minutes. The aligners have to be processed in this fashion immediately after printing because there is a risk of ambient light curing the residual resin, which will alter the internal dimensions of the aligner that can result in poor fitting. This error was experienced by the author.

After printing, the aligners are very soft and have good shape memory. Prior to UV postcuring, the supports must be removed. Removal after curing may result in aligner breakage because the aligners and the supports become harder. The aligners then have to be inserted into the UV curing machine (Fig 10-29). It is not possible to have clear guidelines about the time or the power of UV light needed to cure the aligners properly using a universal curing machine. The only known response is that the longer the aligner is cured, the harder and more brittle it gets. For these reasons, the author performed several trials with varied curing duration and UV power exposure. On the contrary, when Graphy's curing unit is used, curing is done in exactly 10 minutes (5 minutes on the aligner's internal side and 5 minutes on the outer side) with excellent results.

After curing, the aligners have to be washed with warm water, and then the support sites have to be polished. It is proposed by the company to apply a thin layer of resin on the outer surface of the aligner and recure it for a few minutes in order to give the aligner a more glossy and smooth surface.

The 3D-printed aligners were found to be less flexible than the thermoplastically formed aligners, but they have quite good shape memory. They are more fragile, but, if printed according to the guidelines, tend to fit better than thermoformed aligners. The thickness of the printed aligner using this specific resin can be between 0.3 and 0.4 mm. Attachments can be included, but their surfaces should

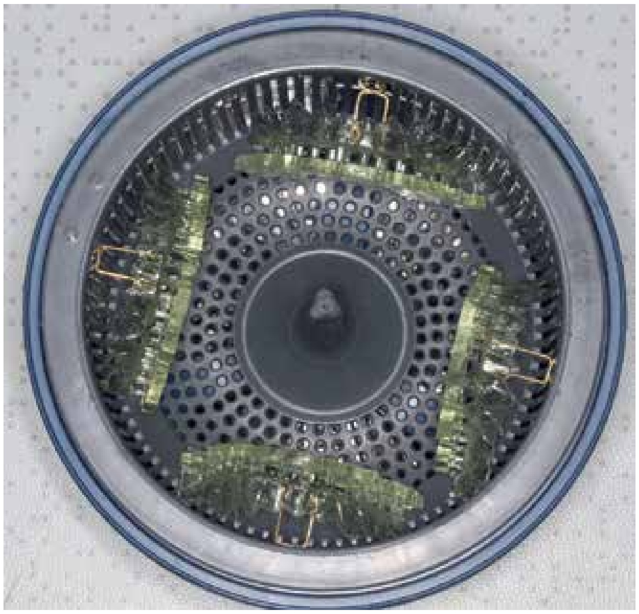


Fig 10-28 Manually operated centrifuge for excess resin removal.

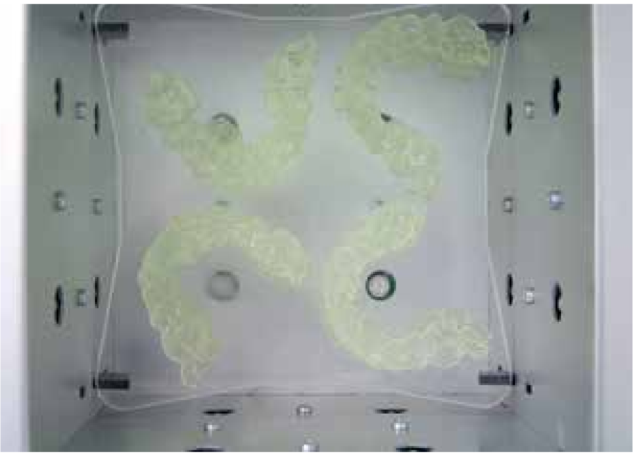


Fig 10-29 Aligners in the UV curing machine.

not be steep or with undercuts but rather rounded for easy removal and insertion. (Note that these statements are our direct observations and were not arrived at using any scientific method.) Specific attachments are currently being investigated for their potential to further ease insertion and removal of the aligners. It is our firm belief that direct aligner printing resin will undoubtedly be the future of aligner manufacturing. Nevertheless, it will need some improvements in order to make it superior to the current thermoformed aligners.

The insertion of the first aligner was not so difficult, and due to its elasticity, it fit quite well. The company proposes to immerse the aligner in hot water before insertion in order to make it softer and facilitate insertion in cases of insertion difficulty.

The case presented was treated using five aligners of 0.4-mm thickness that were changed every week. The patient desired to align only the maxillary anterior teeth. Figure 10-30a presents the aligner fitted on the maxillary dental arch, and Figs 10-30b to 10-30e compare the maxillary dental arch before and after 5 weeks of CAT.

After treating the above case, it was decided to purchase and use the Cure M curing unit in order to get the best results in aligner printing (Fig 10-31). A new, easy orthodontic case was planned for aligner treatment, and the aligners were designed in DeltaFace software. The aligners were successfully printed using Graphy's aligner resin using the office 3D printer and the same procedure as previously described. The difference was that the aligners were centrifuged in a new electric centrifuge unit for 3 minutes according to Graphy's guidelines. In addition, they were cured in the Cure M unit for 10 minutes per the manufacturer's instructions (Fig 10-32a). The results of curing were excellent. The color of the aligners was transparent (Fig 10-32b), compared to the semitransparent or slightly yellowish when the regular curing unit was used, the fit in the patient's mouth was more accurate, and the feeling of force exertion and shape memory was similar to that of the thermoforming aligners. Moreover, the aligners did not have the sticky feeling of uncured resin, which was evident when the universal curing unit of the office was used. It is clear that an incomplete aligner curing results in an aligner with insufficient mechanical properties.

It is obvious that accurate aligner printing is a procedure that depends on many factors: the CAD software, the aligner resin properties, the 3D printer, the aligner cleaning from residual resin, and the curing process. In contrast, the accurate production of thermoforming aligners does not depend on so many factors. For those reasons, direct aligner printing is a sensitive procedure that has to be performed accurately at each separate stage. The author's impression is that designing, printing, and aligner cleaning can be easily performed. On the contrary, aligner curing is difficult to handle. Undercuring results in insufficient

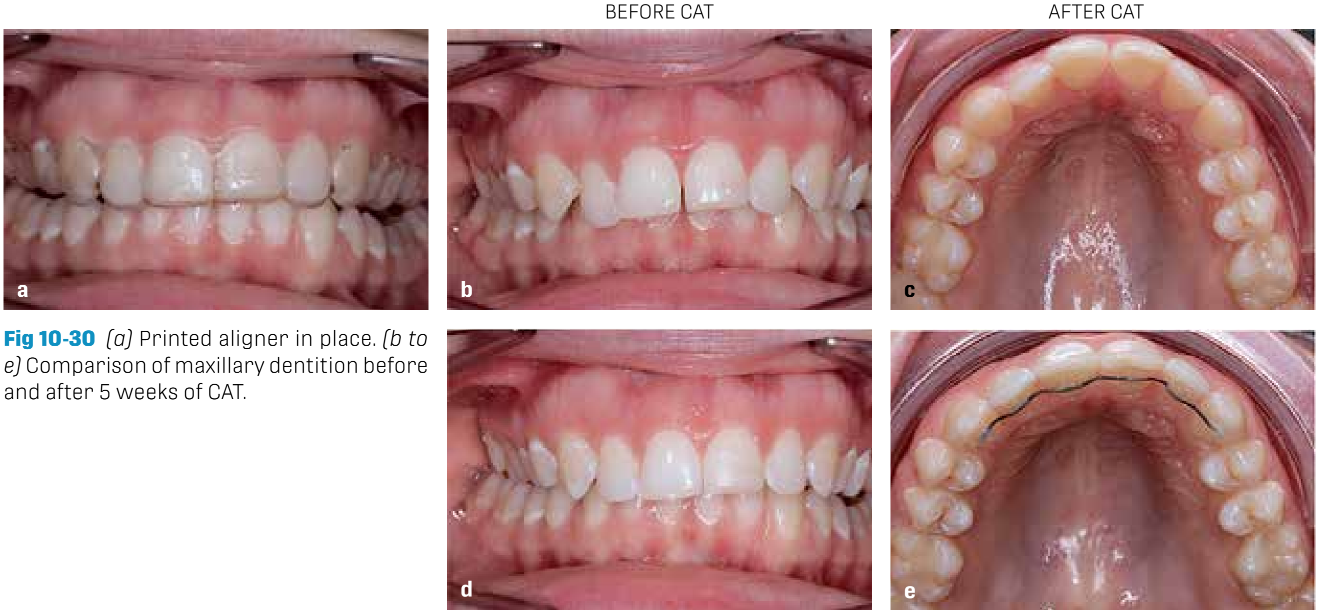


Fig 10-30 *(a)* Printed aligner in place. *(b to e)* Comparison of maxillary dentition before and after 5 weeks of CAT.

Fig 10-31 Cure M curing unit.

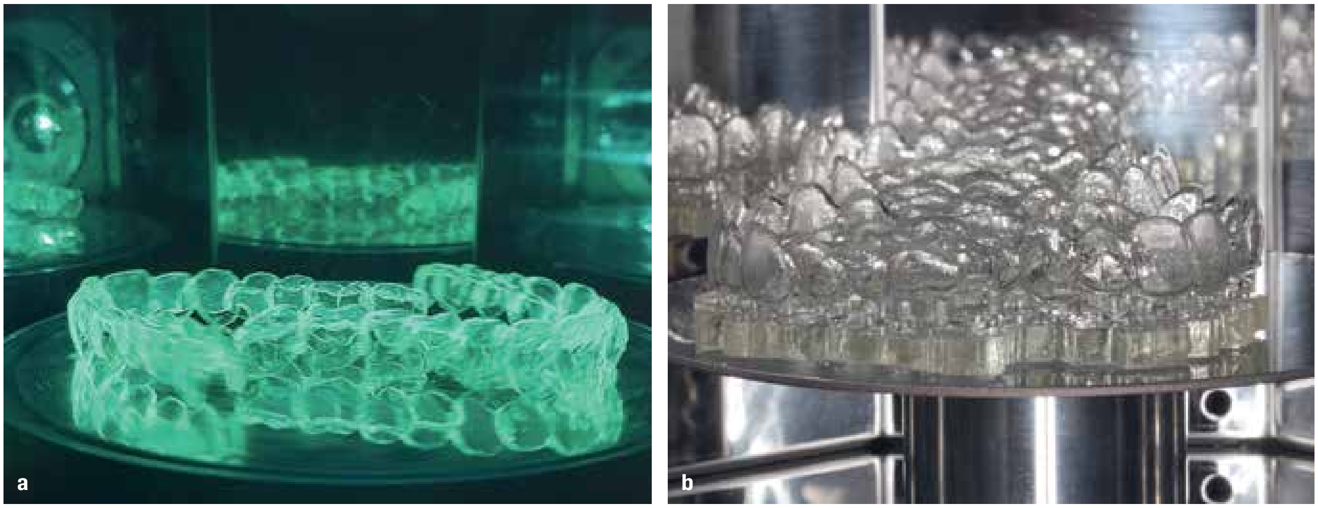


Fig 10-32 *(a)* Aligners in Cure M curing unit. *(b)* Cured aligners.

aligner properties, as mentioned before, while overcuring creates a brittle, hard aligner with no elastic properties. Therefore, the final properties of the aligner are established in the postprinting curing process. For this reason, it is suggested that, at least for Graphy's resin, the specific Cure M curing unit should be used.

Recent evidence demonstrated that 3D-printed aligners retrieved after 1 week of intraoral service had no difference in key mechanical properties (ie, hardness, modulus of elasticity, and elastic index) compared to thermoformed aligners.[56] The aligners were identified as aliphatic ester urethane dimethacrylate–based resin with a high degree of carbon double-bond conversion. The clinical implications of the maintenance of the mechanical properties of 3D-printed aligners during service relate to the lack of a material-driven force relaxation, which warrants that the application of force will not show a reduction in its magnitude over time because of material parameters; this profile is different from the Invisalign resin, which has demonstrated reduction of the mechanical properties with time.[57] On the other hand, the 3D-printed aligners in the as-received condition indicated values close to the lower margin of those of PETG-based clear aligners and certainly lower than those of Invisalign, possibly suggesting that the 3D-printed ones may undergo higher wear. In a study that is submitted for publication, a comparison was made regarding the mechanical properties of printed aligners derived from five different 3D printers. It was clearly shown that the mechanical properties of 3D-printed aligners was dependent on the 3D printer used. New studies regarding direct aligner printing are currently underway by the same team.

Conclusion

In-house aligner design and printing provide numerous advantages. It is time for orthodontists to avail themselves of these and be fully in charge of the aligner orthodontic treatment. There is a movement toward in-house aligner design and printing that is reflected by the emergence of new companies that develop aligner CAD software, dental 3D printers, intraoral scanners, new thermoforming materials, and as of late, resin for direct aligner printing. Nevertheless, even with the plethora of materials and machines for aligner designing and printing, aligner treatment is still minimally investigated. Biology is kept out of the designing procedure, which is carried out without taking into account the surrounding tissues and the tooth-root structure itself. Tooth movement–simulating software works as if there is no underlying tissue, no bone, no roots, no gingiva, and no occlusion. Future studies should focus on these inadequately investigated parameters. Nevertheless, Professor Leonardi et al, in a study that has been accepted for publication in the *American Journal of Orthodontics and Dentofacial Orthopedics*, describes a procedure whereby the sinonasal cavity and the pharyngeal airway are automatically segmented using convolutional neural networks (artificial intelligence).[58] The inclusion of artificial intelligence in CAD software aligner design will include in the near future both crown and root movement, thus taking into account the root's position upon orthodontic setup. Perhaps in the future, deep learning machines will be able to predict the treatment results not by treatment simulation but by addressing the influence of each parameter on the orthodontic problem and suggesting the solution for the patient's malocclusion.

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11

In-House Digital Indirect Bonding

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What Is Indirect Bonding?

Indirect bonding (IDB) is a technique applied in clinical orthodontics to determine bracket positions from dental casts, which are then transferred in these orientations to the patient's dentition using a transfer tray. Digital IDB uses orthodontic CAD software to perform the same task using 3D digitized dental models to virtually place orthodontic brackets on said models from which a transfer tray is virtually designed and 3D printed. Actual brackets are placed into the printed tray according to their digitally planned locations to be transferred to the dentition.

Indirect orthodontic bracket bonding is a procedure first described by Silverman et al in 1972.[1] The technique involved bonding of metal and plastic brackets using cement onto working plaster casts and transferring them to the mouth using thermoplastic transfer trays. The same authors later reported on the procedure, including light-cured adhesives for indirect bracket bonding.[2,3] This technique became popularized with increasing studies reporting on aspects such as differences in bonding accuracy between direct and indirect bonding, bonding failure rates, reproducibility of bracket positioning, the development of techniques for transferring the brackets, agents for bracket bonding, materials for transfer tray fabrication, and the level of efficiency of IDB.[4–10]

In the early 1980s, adhesives that were thermally activated were introduced. These were advocated for use in placing metallic orthodontic brackets onto dental casts by auxiliary staff, which could be left uncured until inspected by the doctor in care and then cured by heating the casts to 250°F to 300°F for 15 to 20 minutes. This would form a resin custom base but would require the removal of plaster. The temperature required to prepare these setups precludes the possibility of doing so with plastic brackets.[11] In order to attach these brackets to a working model, or if custom bases are not required, some clinicians utilize water-soluble adhesives, sugar-based mediums, or sticky waxes.[12,13]

Commonly, Bis-GMA materials were used in chemically cured adhesives, but with the introduction of light-cured adhesive, polymerization was catalyzed using a two-part adhesive activated by a UV-sensitive component.[1] In 1991, Hamula reported on the advantages of light-cured adhesives for orthodontic IDB.[14] Not long thereafter, 3M Unitek introduced adhesive precoated brackets (APC), which were used by Cooper et al for IDB. They described the advantages of this delivery method as ease of cleanup, consistency of coating, and elimination of waste.[15]

While light-cured composite provides beneficial alternatives to chemically cured adhesive, they present a problem when construction of bracket custom bases is required. Each has a limited working time due to the effect of the ambient light and the time of activator and base reaction. For this reason, some thermally cured composites were developed as described above.[16]

The materials used for transfer tray composition have also evolved since first introduced by Silverman and Cohen. For example, clear transfer trays were described in 1979 by Thomas in his postdoctoral thesis concerning vacuum-formed clear placement tray material.[17] Other such "clear"

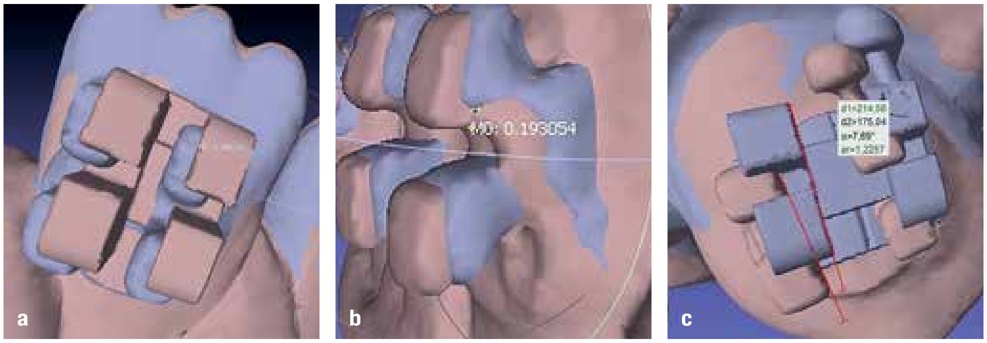


Fig 11-1 *(a)* Superimposition of two 3D scans: IDB file and direct vision file. *(b)* Superimposition of two 3D scans: loupes-assisted bonding scanning and direct vision bonding scanning. *(c)* Superimposition of two 3D scans: IDB file and loupes-assisted bonding scanning.

materials that have been used for transfer tray fabrication are polyvinyl siloxane (PVS), clear impression compounds (eg, Memosil, Kulzer), and hybrid systems made of resin and silicone.[18] Nakaji and Sheffield found it effective and accurate to use double-layer trays made of a softer inner tray material to reduce the risk of the tray debonding the bracket(s) due to stiffness and a more rigid outside layer to provide stability of form for the underlying softer material.[19]

The orientation of orthodontic brackets on working models for IDB has been a point of contention. In 1980, in an interview, Philips discussed the use of a vertical axis line drawn onto the dental cast as a method to improve the accuracy of indirect over direct bonding, because this aid cannot be performed intraorally.[20] Reichheld et al advocated for the use of height gauges to improve the precision of bracket positioning on dental casts.[21] Kalange described the placement and use of horizontal and vertical lines on dental casts to reference the levels of marginal ridges, esthetic surfaces, and functional occlusal contacts.[22] Creekmore developed a unique machine called the Slot Machine (Creekmore Enterprises) for use in customizing individual bracket placements in IDB.[23] The importance of relating the positions of brackets on models as part of an indirect setup to the marginal ridges instead of aspects of the clinical crown was also stressed by Eliades et al. They argued that relying on the center of the clinical crown as a reference point could result in marginal ridge height discrepancy between molars and premolars and lack of occlusal contacts with the opposing dentition.[24]

The differences in bond strength between direct and indirect bonding has also been investigated. In an in vivo study, Zachrisson and Brobakken found that bonding failures were greater in IDB (13.9%) compared to the direct method (2.5%)[4]; however, Polat et al found similar bonding strengths in both of these methods.[25] In vitro studies reported by Yi et al concluded that both indirect and direct bonding strengths were similar and found no statistically significant differences between the two methods.[26] Similarly, Milne et al, in a study comparing tensile and shear bond strengths on previously extracted incisors and premolars, showed no statistically significant difference between direct and indirect bonding.[27]

Comparisons between direct and indirect bonding in terms of accuracy should be one of the most important aspects for investigation. Surprisingly, this has received far less attention than it deserves, with the current literature including a report from Hodge et al finding that there were no differences in accuracy. Findings such as these are partial at best because they do not include bonding to posterior teeth, which is the most difficult area for bracket bonding using direct vision, or teeth with mesiodistal, angular irregularities and severe crowding.[28]

The author used an intraoral scanner (Carestream 3600), digital IDB software (Maestro Dental Studio), and CAD software (MeshLab) to compare mesiodistal (MD) bracket bonding accuracy, occlusogingival dimensions (OCG), and mesiodistal angulation (MDAng) between direct (using direct vision and loupes) and digital indirect bonding. Superimposition was done between direct vision bonding scanning (E), magnifying loupes–assisted bonding scanning (L), and the IDB file (I) derived from an orthodontic IDB CAD software (Fig 11-1).[29] Scanning of the dental arches was performed before bonding (Fig 11-2a), and then the brackets were positioned using direct vision (E) and scanned without light curing. Then using loupes (L), any possible errors were corrected, and the third scan was performed. The first scan (I) was imported into Maestro

Dental Studio software, where we digitally bonded the brackets and then exported the brackets-dental cast file as an STL file. Figure 11-2b presents the three files: direct vision bonding, loupes bonding, and digital IDB. Continuously the 3D scans were superimposed in pairs using MeshLab, and MD, MDAng, and OCG dimensions were measured and compared. Intra-observer and interobserver variability was also checked.

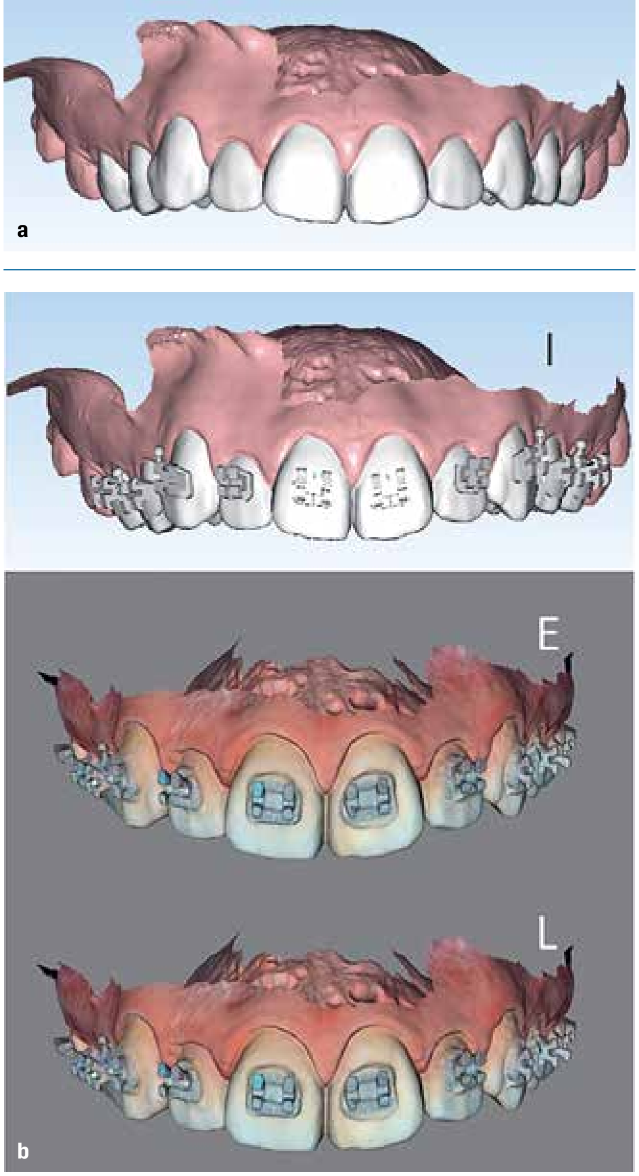


Fig 11-2 *(a)* Intraoral scanning before bonding for virtual IDB (I). *(b)* Three 3D files for comparison: virtual IDB (I), direct vision (E), and loupes-assisted direct bonding (L).

IDB was predefined as the ideal bonding due to the fact that it was done in a virtual environment of a computer with high magnification, with a 3D visualization of the teeth, without the influence of gravity (adhesive slumping), and no need to guard against contamination by saliva, which are factors affecting outcomes of direct bonding. Loupes-assisted bonding was compared to direct vision bonding and IDB. No significant differences in accuracy were found when loupes-assisted direct bonding and direct vision bonding were compared. IDB was found to be statistically significantly more accurate than loupes-assisted direct bonding. On all teeth and particularly on the posterior teeth, there was a high statistical difference in bonding accuracy between indirect and direct bonding in all three planes. These differences become more significant when it is understood that each type of bonding was performed with the operator having knowledge of its inclusion in the study. Therefore, it is possible that greater care was taken when any of the direct bonding techniques were applied, which further emphasizes the differences between direct and indirect bonding accuracy.

It has also been shown that errors in direct bonding occurred more on specific teeth and in specific dimensions measured. For example, Balut et al examined the accuracy of bracket placement with the direct bonding technique and reported statistically significant vertical and mesiodistal angulation bonding errors. These findings are similar to the results found by us as stated above.[30] Furthermore, several authors have reported that errors in direct bracket bonding could lead to incorrect tooth movements during orthodontic treatment. For instance, Thurow found that (two) different vertical bracket positions will cause two different buccolingual axial inclinations (torque).[31] In another study by Miethke and Melsen, it was shown that there was a modest influence on the tooth torque with a change of the vertical position of the bracket of less than 0.4 mm, while the displacement of more than 0.4 mm had a higher influence on the tooth torque.[32] Germane et al studied the influence of bracket positioning and concluded that 1 mm of bracket vertical displacement can result in a torque change of 10 degrees.[33] Furthermore, in a study by Mestriner et al on the effect on torque with a change in the vertical position of the brackets by 0.5 mm and −0.5 mm from the crown center in mandibular teeth, it was found that torque changed progressively from the incisors to the molars from 2 to 8 degrees.[34] It is evident that small errors in bracket positioning in one dimension can have an effect on the tooth position in another dimension provided that full wire engagement is undertaken.

The successful use of lingual orthodontic fixed appliances and their fewer complications are directly related to the significant role indirect bonding plays in their placement. The morphology of the lingual surfaces varies for each tooth, and the limited direct visual access presenting on the lingual aspect does not allow for accurate direct bonding of lingual orthodontic brackets. The former condition precludes a universal standardized preadjusted bracket prescription, thus enhancing the benefits offered by indirectly preparing an individualized lingual appliance setup. This increases the chances for a more accurate appliance bonding and predictable treatment outcomes. Several companies provide this service to the orthodontist from dental setup to appliance arrangement to fabrication of the lingual IDB tray.[35–37]

According to several reports, the advantages of indirect over direct bonding include better accuracy in bracket positioning (especially where lingual appliances are bonded), reduced chair time, and more predictable bonding of the posterior dentition.[11,12,17,38–40] On the other hand, the need for extra materials or appliances (silicone impressions, intraoral scanner), additional laboratory working time, as well as personnel attach added time and monetary investment to this procedure. Furthermore, direct bonding, although a lengthier chairside procedure, is simpler to perform, does not require additional laboratory or trained staff, and there is no need for supplemental materials or appliances. The preference for one or the other bonding technique has been a clinic management decision, where the added time and cost of IDB can be offset by clinical efficiency.

Currently, the use of computers in performing virtual IDB has eliminated the need for manual manipulation of the dental cast or attaching of the brackets to the working model. The ability to also incorporate CBCT data has elevated the resolution of the digital setup so that root positions can also be included in bracket positioning decisions (see Fig 10-4).

Traditional Indirect Bonding

The predigital traditional method of preparing an IDB process starts with an accurate impression of the teeth in each jaw. It is recommended to use a highly accurate impression material such as polyvinyl siloxane (PVS). A plaster or stone cast of the dentition is poured using this impression. The set working model is then marked using a pencil to add reference lines indicating the height of contour vertically along the dental crown long axis, as well as a horizontal line bisecting the greatest curvature of the tooth, and additionally lines to demarcate the marginal ridges. A separating medium is painted onto the working cast to facilitate removal of attached appliances at the finish of this procedure. The brackets that will be delivered to the patient are then positioned on the teeth of the working model according to the reference lines and adhered with light-cured composite resin. A height gauge can be used as well to measure bracket placement accuracy.

The next step is to fabricate the transfer tray so that the orientations of the bracket positions on the working model can be “transferred” to the patient. Initially, this procedure was done using similar PVS material as that used to take the initial impression. These materials were impervious to light and necessitated the use of chemically cured bracket adhesive. Transparent silicone materials like Memosil (Kulzer) have since been developed that allow the use of light-cured composite for indirect bracket bonding (Fig 11-3). The set silicone trays together with the brackets they encase are separated from the working model either by immersion in water or by mechanical force. Once removed, they are trimmed to remove excess silicone material, debrided of any plaster, and sectioned according to clinician preferences.

Bonding of the prepared setup onto the patient’s dentition requires the same measures as in direct bonding. Firstly, the patient’s teeth are prophied, isolated, then dried with oil-free air. Acid etching is performed according to manufacturer recommendations, and the teeth are rinsed and dried as above. A thin layer of bonding primer is applied to the etched surfaces and allowed to cure. If the transfer tray is fabricated from a light-impermeable material, then a chemical cure resin must be used (Reliance Custom IQ A and B). If the transfer tray is transparent, light-cured composite adhesive can be used, which is polymerized using a specific visible light wavelength.

Due to the flexibility of the transparent transfer tray, it has been recommended by some clinicians to add support to the tray by adapting a rigid 0.5- to 1.0-mm layer of transparent foil made from thermoformed plastic (eg, Essix, Dentsply Sirona).[19] Once the bracket adhesive has cured, the tray is removed, leaving the brackets bonded onto the teeth in the same manner as was determined using the working model.

Fig 11-3 Traditional IDB laboratory procedure.

Digital IDB in CAD Software

Digital IDB is essentially the same procedure as the traditional indirect technique described previously. This is true conceptually, but it is distinguished from the traditional technique in the following ways:

- The materials and the appliances that are used for taking impressions of the teeth (ie, impression tray material vs digital "impression" scan)
- The working environment of the entire procedure (ie, orthodontic laboratory vs software environment)
- The presentation of the brackets (ie, physical vs virtual)
- Transfer tray fabrication (ie, laboratory procedure with silicone vs 3D printing)

To perform digital IDB bonding, the dental arches must be digitized in order to import them into appropriate CAD software. Alternatively, this can be done directly using an intraoral scanner or by scanning the silicone impression or the stone cast using a desktop scanner. Any of these methods will result in the conversion of the physical state of the patient's dental arrangement to a digitized virtual equivalent 3D representation. Tomita et al reported that intraoral scanning might be more accurate compared to conventional impression/plaster cast methods.[41] In another study, Gül Amuk et al compared conventional plaster casts, digital models obtained by impression scanning, and plaster cast scanning and concluded that there was no significant difference between the three methods for dental measurements.[42]

The working environment of a digital IDB technique is obviously different than that of the traditional technique. It is contained within a computer screen without the need for any laboratory setting, plaster, dental models, separating mediums, pencil markers, light, or thermally cured resins. The brackets placed on the digital model are exact virtual copies of the brackets in their physical form. Finally, the way the transfer tray is fabricated is a result of complicated calculations within the CAD software, culminating with the exporting of an STL file to a 3D printer, which processes this data into its physical form.

Simply worded, the analog image of the dental arches is digitized using a scanner, then the equivalent of the entire laboratory procedure is performed in a digitized environment with a computer. This process results in the printing of a transfer tray by a 3D printer so as to be "undigitized" and become realized. Essentially this is a procedure of digitizing and undigitizing the dental arches (Fig 11-4). An early attempt at preparing trays for IDB using rapid prototyping was reported by Ciuffolo et al in 2006.[43] This relied on using a desktop optical scanner to digitize dental

Fig 11-4 Digitization of the dentition, tray design, and printing (ie, undigitization).

study models, which took as much as 90 minutes to do so under supervision.

Importing of the STL files into appropriate CAD software is the next step, after which the operator virtually bonds brackets that were previously imported into the computer's database. As bracket placement is being designed automatically, the same is occurring with the prototyping trays so that the software dictates coverage of the teeth together with the virtual brackets. In the final procedure, a high-end prototyping machine (a 3D printer) is used to print the trays, which are made of a rigid but elastic plastic-type material. The physical brackets are then manually inserted into the corresponding depression in the transfer tray. Delivery to the patient is performed as described above previously.

These principles have been adopted on a commercial level in such products as SureSmile (Dentsply Sirona) and OrthoCAD (Cadent). These offer a service resulting in patient-specific transfer trays for IDB.[44,45] Other companies have launched their own CAD software for in-house IDB, including 3Shape Orthoanalyzer, Onyx Ceph, Maestro Dental Studio, and DeltaFace.

In general, all in-house IDB CAD software packages share nearly identical fundamental methodologies of designing processes. It is not our purpose here to compare these but rather to present the contribution these make to the steps of the digital IDB procedure. Because Maestro Dental Studio is not overly complicated for orthodontists to use in performing the tasks required, the following sections use this CAD software to demonstrate the creation of indirect transfer trays through virtual bracket bonding.

Indirect Bonding Tray Digital Design

The digital IDB procedure can only take place if appropriate digital records are obtained. These include an intraoral scan, a full set of intraoral and extraoral clinical photographs, and panoramic and lateral cephalometric radiographs or a CBCT. The intraoral scan can be replaced with silicone impressions that are directly scanned in a desktop scanner or used to fabricate a stone cast, which is in turn scanned.

There are two ways to design a digital IDB workflow. The first is to virtually bond the brackets onto the virtual dental casts in their given original malocclusion, print the transfer tray, and deliver the brackets to the mouth in the determined arrangement. The second method is to perform a virtual setup of the corrected malocclusion, virtually place the brackets on the corrected teeth, and then digitally transfer the brackets in their exact position onto the initial malocclusion (see section titled "Patient Individualized Digital IDB" later in the chapter). Transfer trays are then fabricated in the 3D printer. In this way, virtual bonding design is retroengineered from the planned treatment outcome.

Workflow for Digital IDB Using the Initial Malocclusion Virtual Dental Casts

1. Importing of patient's personal information and surface and volume scanning

The first step of the procedure is importing the patient's personal data into the special chart of the software. The scanned dental arches are imported into the same computer window (Fig 11-5). There is also an option to import a previously done CBCT 3D scan. It must be noted that the CBCT scan cannot be imported as a DICOM file; it has to be converted to an STL file. The fusion of the intraoral

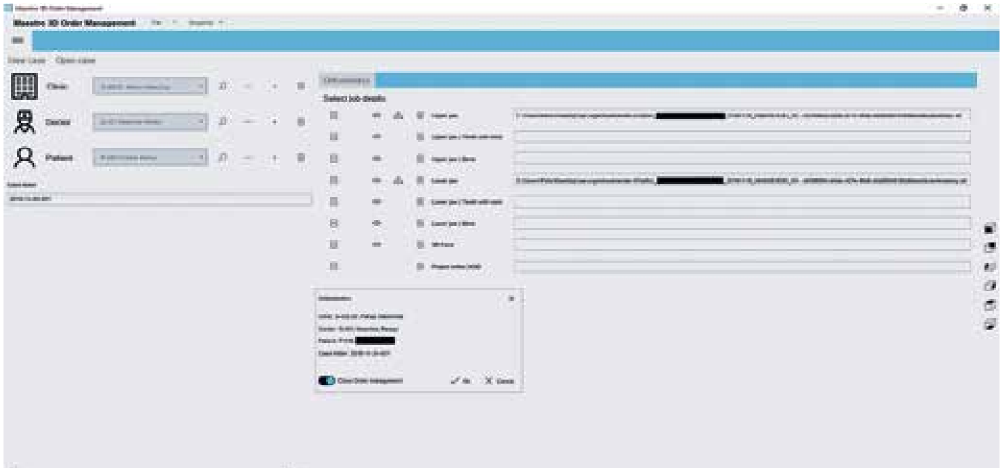


Fig 11-5 Importing of the patient's personal data and surface scan into the CAD software.

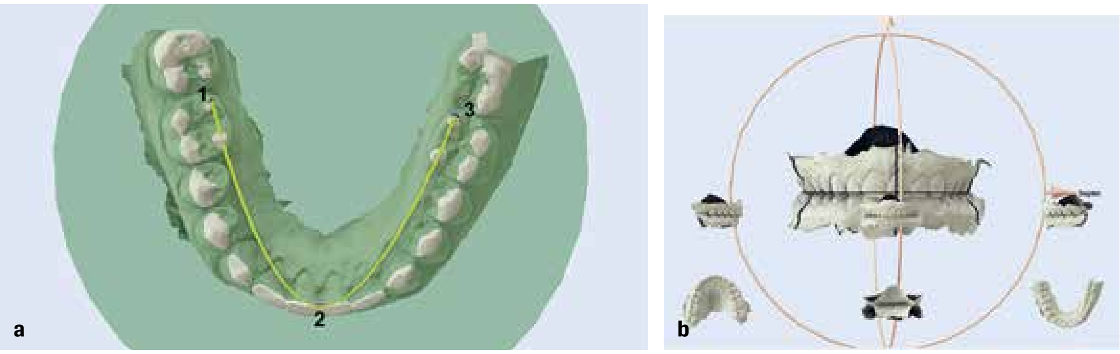


Fig 11-6 *(a)* Defining the "local irigo." *(b)* Defining the reference coordinate system of the dental arches.

scan with the CBCT scan will be performed in a function encountered later in the software.

2. Defining the reference coordinate system

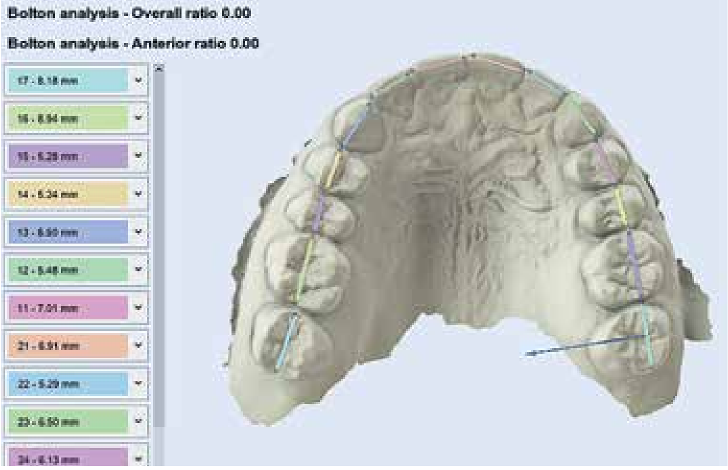
The second step is to define the reference coordinate system of the dental arches. First, a "local irigo" as it is called in the software must be defined by marking an arch from the distolingual cusp of the mandibular first molars to approximately the dental midline (Fig 11-6a). The next step is to define the coordinate system of the dental arches in occlusion (Fig 11-6b).

3. Measuring the mesiodistal width of the teeth

In this step, the mesiodistal widths of the teeth are measured. This indicates to the software the boundaries of each tooth so that they can be recognized by it as separate entities and distinguished from one another. This function also generates a Bolton analysis of the dental arches[46] (Fig 11-7).

4. Segmentation

Proper demarcation of the mesial and distal contact points of each tooth, as described in step 3, is essential also because this permits the software to automatically perform segmentation of the teeth (Fig 11-8). This is a key function in the process of designing digital IDB. This process entails the software separating each tooth from the adjacent teeth and the gingiva. The borders delineated by the software need to be inspected by the operator to ensure accurate segmentation. Deviations may occur due to distortions during scanning because of highly irregular tooth morphology, the presence of dental prostheses, or human error in defining the mesial and distal parts of the crown. When it has been determined that faulty segmentation has occurred,



Bolton analysis - Overall ratio 0.00

Bolton analysis - Anterior ratio 0.00

17 - 8.18 mm

16 - 8.94 mm

15 - 5.28 mm

14 - 5.24 mm

13 - 6.90 mm

12 - 5.48 mm

11 - 7.01 mm

21 - 6.91 mm

22 - 5.29 mm

23 - 6.50 mm

24 - 6.13 mm

Fig 11-7 Mesiodistal dimension measurement leading to a Bolton analysis.

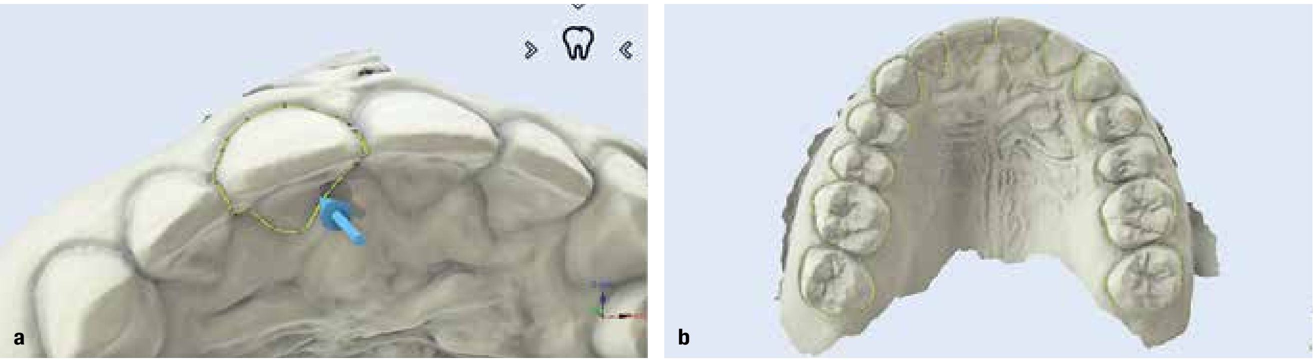


Fig 11-8 *(a)* Segmentation of a single tooth. *(b)* Complete teeth segmentation.

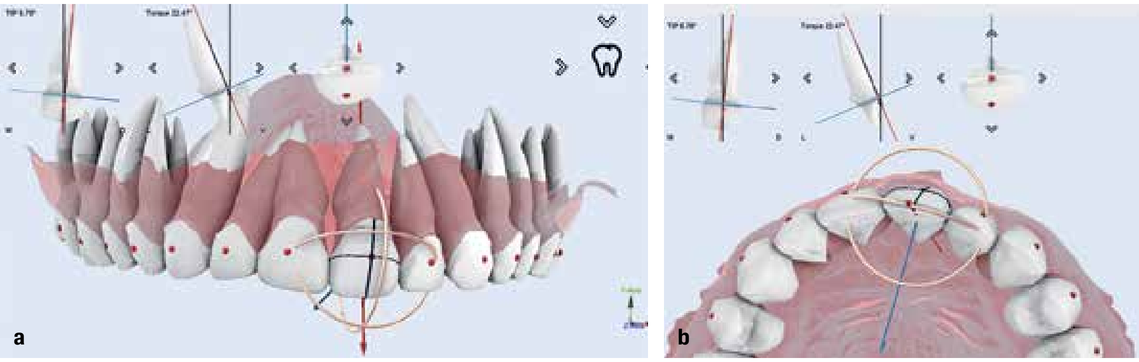
direct manual correction can be performed by dragging the misplaced line or point of demarcation as displayed on the computer screen to its proper position. Segmentation also provides the orthodontist with the ability to perform single tooth movements in the setup mode or to define the axes of the teeth at a later stage of digital designing.

5. Defining local axes of teeth

This stage is also crucial because it helps the orthodontist in accomplishing a correct virtual setup and it is one of the parameters that indicates to the software how to orient the brackets correctly when the brackets are to be virtually bonded to the dentition (Fig 11-9a). This automatic feature is a huge timesaver for the orthodontist because it precludes the need for the operator to manually perform this task, which would require an inordinate amount of time to verify bracket placement in each plane of space. By moving the three manipulator circles, the orthodontist can define the long axes of the teeth (Fig 11-9b). It is possible to zoom in and separate each tooth for fine axis correction (Fig 11-9c).

Once each local axis is quickly indicated for each tooth, the software calculates the approximate position of the root of each tooth in the space. This is an extrapolation, which is often inaccurate because it is not derived directly from any diagnostic record unless a CBCT scan including these structures is included. In a pair of studies comparing digital scans of patients where the positions of their roots were predicted and calculated by a software to CBCTs that included this information, Athanasiou and Halazonetis reported that software-driven prediction of individual root position was unreliable.[47,48]

For this reason, manual correction of the tooth axes must be done when appropriate. In this particular stage, a CBCT scan superimposed onto the surface scan would be most



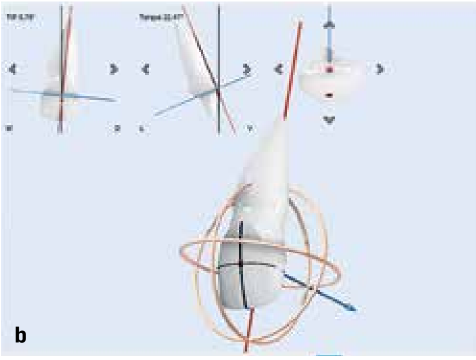


Fig 11-9 *(a)* Defining the local axes of the teeth. *(b)* Occlusal view of the dental arch. *(c)* A single tooth axis correction in higher magnification.

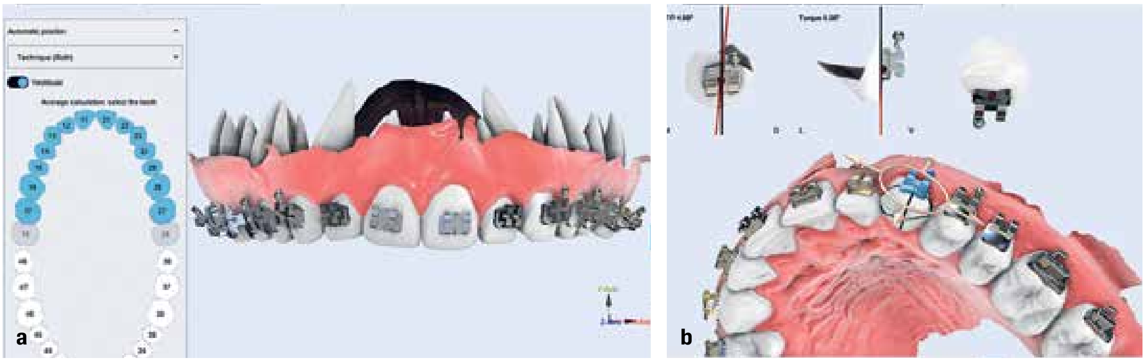


Fig 11-10 *(a)* Automatic positioning of the virtual brackets. *(b)* Manual correction of the bracket position in high magnification.

helpful to accurately define the tooth axes. Nevertheless, a CBCT scan should only be made in cases that justify the radiation exposure required to generate it.

6. Virtual bracket placement

Once segmentation and axis delineation have been accomplished, the next procedure is to virtually place the brackets onto the teeth. All orthodontic software packages contain an expansive library containing virtual copies of the most popular types of brackets. These are in specific files that cannot be exported and are protected by codes to avoid copying them by reverse engineering. Bracket choice is made first according to whether labial or lingual treatment is to be planned and then the specific brand of bracket to be placed. Having accomplished the procedures described previously now permits the software to instantly orient the bracket chosen for placement virtually onto each tooth according to the bracket height placement prescription that the operator indicates (ie, Roth, Andrews, MBT, etc; Fig 11-10a). A major advantage of digital IDB is the ability to observe in high magnification and in 3D the position of each bracket (Fig 11-10b).

Virtual bonding can also be done manually instead of relying on the automatic function. This procedure will obviously be more time-consuming than the alternative. There-

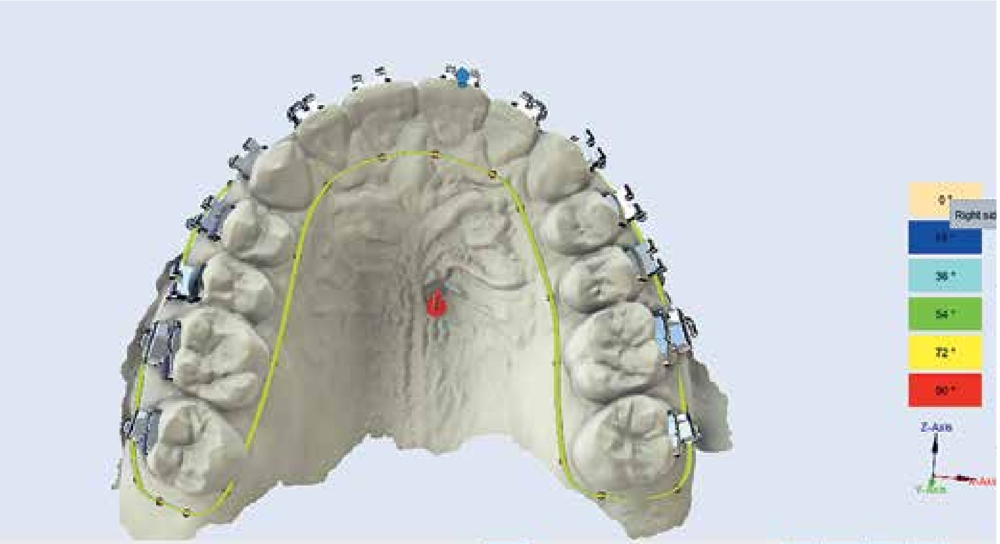


Fig 11-11 Design of the virtual transfer tray.

fore, it is preferable to place the brackets automatically and then manually perform any required adjustments. If there is a need for overcorrection, there is a function where the bracket can be rotated away from the tooth surface in the mesiodistal and/or occlusogingival direction (eg, for torquing). Particular caution must be taken to fill this created space with enough adhesive at the time of bonding.

7. Designing the transfer tray

Having virtually placed the brackets onto the digital model, the operator can now design the transfer tray that will be printed (Fig 11-11). The transfer trays can be designed in separate pieces or in one piece. In addition, the software gives the orthodontist three options regarding transfer tray design: a tray with the bracket impressions (Fig 11-12a), with windows (Fig 11-12b), or with jigs attached from the bracket to the printed tray acting as a docking device containing all the jigs together (Fig 11-12c).

Additionally, the thickness of the tray, its offset from the model as well as from the brackets, and the elimination of tray material extending into undercuts are also defined by the operator at this point. The latter task is significant because undercuts may prevent the tray from fitting properly or may cause difficulties in tray removal after bracket bonding (Fig 11-13). The software depicts areas with such undercuts by color-coding them for immediate identification.

8. Exporting and printing

The last step of the software procedure is to export the file of the transfer trays in an STL format to an appropriate digital printer. This process is referred to as “undigitization.” In reality, the virtual transfer tray is turning into a physical object through 3D printing. The files are positioned in the printer software on a virtual platform that corresponds to the actual printer platform (Fig 11-14). It is recommended that the trays be oriented with the external side facing the platform so that the accompanying supports that are created will not affect the internal aspect, where the details of the dental anatomy and positions of the bracket placement information are contained (Fig 11-15). Alternatively, the trays can be oriented in a vertical or diagonal manner, but this will prolong the printing time.

The materials for printing this kind of tray are specific. For instance, in the case presented herein, SprintRay IDB resin was used. SprintRay is a biocompatible IDB material that resists tearing and has ideal flexibility and accuracy. The time needed for transfer tray printing is under 40 minutes when using the MoonRay S 3D printer. This was done with the trays placed horizontally on the platform (see Fig 11-15).

After printing, the trays should be washed using 91% isopropyl alcohol for no longer than 5 minutes to clean and remove any uncured resin and then left to dry by evaporation. Once this has been accomplished, all the supports that were printed along with the tray to ensure its struc-

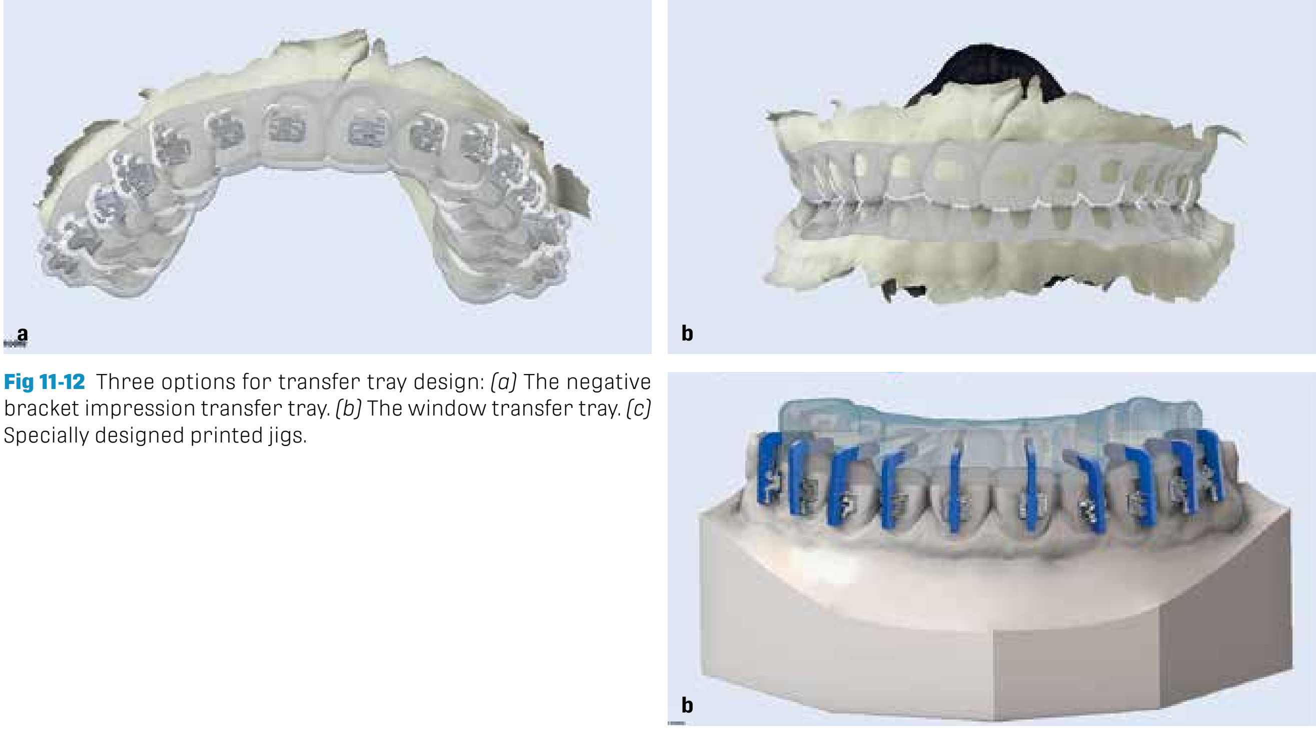


Fig 11-12 Three options for transfer tray design: *(a)* The negative bracket impression transfer tray. *(b)* The window transfer tray. *(c)* Specially designed printed jigs.

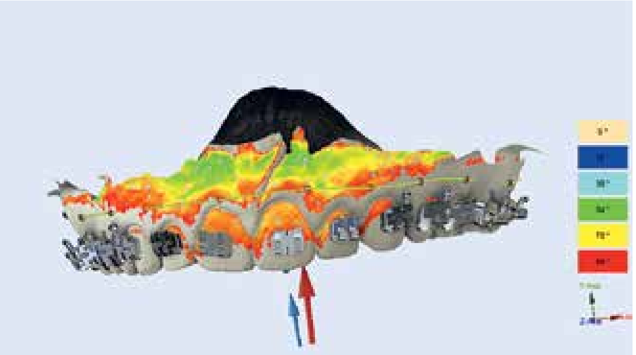


Fig 11-13 The undercuts highlighted in different colors.

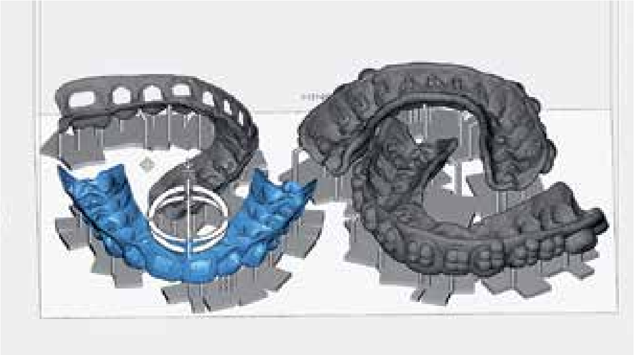


Fig 11-14 The virtual platform of the MoonRay S 3D printer.

tural integrity until completion are disconnected from the body of the tray. The trays are then postcured according to the manufacturer's specifications using a special UV light machine specifically for this purpose. This procedure ensures that any uncured resin within the body of the tray will undergo polymerization and gives the trays the desired characteristics.

9. IDB procedure

If the orthodontist chooses to use the transfer tray containing the bracket's impressions, then it is required that each

Fig 11-15 The indirect transfer trays printed on the 3D printer platform.

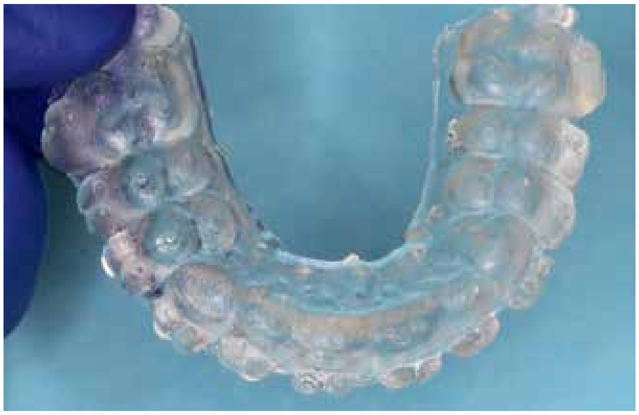


Fig 11-16 The negative bracket impression tray printed.

Fig 11-17 The window transfer tray printed.

bracket be manually placed into its negative impression within the tray. The patient can now be prepared for bracket bonding in the standard fashion. All the brackets loaded into the transfer tray(s) now have resin adhesive applied to their bonding bases. The tray is now ready for delivery to the patient's teeth (Fig 11-16).

If the window-type tray is going to be used (Fig 11-17), the patient is prepared for bonding in the standard fashion and then the tray is placed on the dental arch. This type of transfer tray acts as a guide for individual direct bonding of the brackets to the patient's teeth. At this point, adhesive is placed onto a bracket's bonding base, and the single bracket is fitted into the corresponding guide window in the tray. This procedure is repeated for each bracket requiring delivery/bonding. Strictly speaking, this technique is not a pure IDB procedure but rather a bracket bonding guiding procedure.

Light-cured composite resin adhesive is most commonly used to perform digital IDB. When this material is used to bond brackets in this manner, there is also the option of covering the softer, more flexible material of the transfer tray with a thin but more rigid clear plastic layer. This is composed of a sheet/foil of transparent thermoforming plastic, which adapts to the outside surface of the impression tray after it is heated and lowered onto the tray while a vacuum pulls it into position as it cools. A machine specifically manufactured to perform this function has been available for many years, and it results in a two-layer transfer tray.[19] In this instance, after bonding, the more rigid foil is removed first, and then the soft transfer tray is peeled from the now-attached brackets. It has to be noted that the soft printer transfer tray can be designed and printed in segments for easier removal after bonding.

IDB Case Presentation

A healthy 15-year-old adolescent boy presented to the author's clinic for orthodontic treatment. Clinical examination was performed followed by intraoral scanning of the maxillary and mandibular arches, and panoramic and lateral cephalometric radiographs were taken. A CBCT could also have been done in order to obtain more detailed information of the patient's root anatomy and positions when superimposed onto the teeth in the intraoral scan in the CAD software; however, the increased radiation exposure was not justified in this case. Intraoral and extraoral clinical photographs were also taken.

The surface scanning files were imported into the Maestro Dental Studio software to virtually bond the orthodontic brackets and design the bracket transfer tray. A panoramic radiograph was used for assessment of the position of the dental roots in relation to the crowns. Orthos Titanium brackets (Ormco) were selected for treating this patient, and these were available in the software library. For the sake of this presentation, both the transfer tray with the bracket impressions and the window transfer tray were designed and printed (see Figs 11-16 and 11-17).

The files were exported to the 3D printer for printing. The postprinting procedure of washing the trays with isopropyl alcohol 91%, drying, and postcuring in the UV postcuring unit were carried out. The mandibular arch was bonded using the tray with the windows, and the maxillary arch was bonded using the bracket impression tray.

The patient's dentition was isolated and prepared, and the teeth were cleaned using pumice followed by etching with 37% hydrophosphoric acid, which was removed with water spray and dried with oil-free air spray. The acid-

Fig 11-18 Indirect bracket bonding using the printed trays. The negative impression bonding tray is used in the maxillary arch, while the window bonding tray is used in the mandibular arch.

etched teeth then had a thin layer of light-cured bonding agent brushed onto them (Ortho Solo, Ormco) and light-cured adhesive applied to the bonding bases of the brackets (Enlight, Ormco). For the maxillary dentition, the tray containing the brackets with the applied adhesive was then placed into its proper position on these teeth, and the adhesive was cured with exposure to a handheld light-curing unit (Fig 11-18). The tray was then removed from the mouth, leaving the brackets bonded to the teeth.

For the mandibular dentition, with the use of the window version transfer tray, the same preparatory technique was followed as described above. Once the bonding agent was applied, the transfer tray was seated onto the teeth. At this point, individual brackets were loaded with the bracket adhesive and placed into the corresponding bracket window for each tooth (see Fig 11-18). Light-cured adhesive was used for bonding, and the transfer tray was removed. In reality, the window bonding tray does not fulfill the essential characteristics of an IDB tray. Instead, it is a bracket guiding bonding tray because it does not transfer the brackets to be bonded nor facilitate their "en masse" bonding.

Another alternative way to manufacture a bracket transfer tray is to export the dental models of the patient with the brackets attached, print the models in the 3D printer, and then manually take an impression of the printed dental casts with PVS or clear silicone like Memosil (Kulzer).

Patient Individualized Digital IDB: Riccardo Nucera's Technique

This section discusses the benefits of utilizing digital tools to produce the dental setup required for IDB and outlines the digital workflow.

Proper diagnosis is the cornerstone of every orthodontic treatment plan; however, its efficient administration depends on the accuracy of bracket bonding.[49] Every deviation from this principle detracts from the benefits of the straight-wire appliance.[50] Experimental reports have shown that 0.5 mm of vertical bracket placement discrepancy could cause up to an 8.3-degree difference of torque expression.[51] Furthermore, it has been demonstrated that IDB improves the accuracy of fixed appliance placement.[52]

However, bracket bonding accuracy is not the only aspect that affects the final occlusal outcome and the proper expression of the preadjusted straight-wire appliance. It has been reported that dental crown/root anatomical variations require adjustment of bracket bonding position. It has been shown that when brackets are bonded at the same distance from the incisal edges of teeth with varied crown vertical dimension, different torque values will be expressed.[49] In addition, there are several other categories of anatomical variation that have been demonstrated to influence orthodontic bracket prescription treatment outcomes. These include interarch Bolton discrepancy,[46,53–57] degree and variability of labial/buccal and lingual dental crown curvature,[58,59] interproximal contact anatomical variations,[60] root anatomy variability,[61] and crown and root dimensional variation (ie, vertical, mesiodistal, and labiolingual).[49,62]

In addition, the mesiodistal inclination of bracket bonding position can improve the interproximal contacts between anterior teeth, which influences the quality of the finished occlusion.

Consequently, bonding should be individualized according to tooth dimension and anatomical variations.

When dental anatomical variations are not considered during appliance placement, some of the benefits of the straight-wire appliance can be lost. This in turn reduces the predictability of the treatment outcomes and may require additional measures to overcome. These may be related to the level of experience of the clinician and will necessarily extend treatment duration. Whereas chairside evaluation and compensation for variations in dental anatomy is nearly impossible to provide, these are best determined from the evaluation of study models. In this way, this vari-

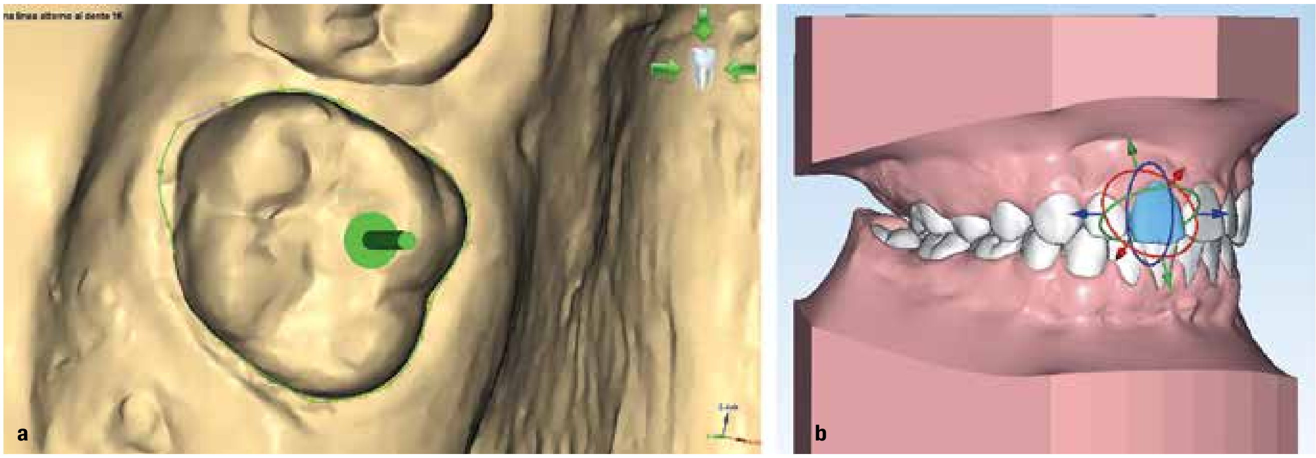


Fig 11-19 *(a and b)* Tooth segmentation and movement.

ability can be analyzed in the context of occlusion and realistic clinical results. Hence, a predictable path of tooth movement can be planned without regard to individual tooth variations.

Individual patient anatomical variability could be controlled for by performing a procedure called an orthodontic pretreatment setup. This is a procedure that involves manipulation of the teeth on a model in order to achieve resolution of the individual malocclusion. Traditionally, this has been a laboratory procedure requiring manual separation (cutting) of the teeth to be moved during treatment from the plaster cast representing the pretreatment condition and their replacement into the desired dental relationships. This is a labor-intensive and time-intensive procedure normally delegated to an external laboratory technician.

The digitization of this laboratory process has greatly simplified and shortened the time required to perform this procedure from hours to just 20–40 minutes per dental arch according to the expertise of the operator. It requires the following steps: *(1)* study model digitization (or intraoral scan acquisition), *(2)* virtual model preparation, *(3)* occlusal plane definition, *(4)* teeth segmentation (Fig 11-19), *(5)* defining of tooth axes (or adjustments if predefined by software), and *(6)* tooth movement according to an ideal occlusion.

The orthodontic virtual setup offers several benefits:

- It defines treatment objectives while compensating for individual patient dental variability.
- It allows an "a priori" 3D visualization of the expected clinical results and comparison with the pretreatment condition.
- It allows evaluation of dental interarch discrepancies (ie, Bolton Index proportionality).
- It allows evaluation of possible solutions (stripping and/or extraction, cusp remodeling).
- It allows the operator to place potential results within a facial soft tissue point of reference/context.
- It improves communication with orthodontic patients.

Orthodontic virtual setups are performed routinely for cases treated with clear aligners. In these instances, the setup execution is an essential step to design the prototyped models and fabricate clear aligners. This is not a prerequisite for cases treated with conventional fixed appliances because their use predates the digital revolution, and the described laboratory setup has not become popular due to its added time and expense. However, the availability of digital tools to perform these procedures should make this option more acceptable for the modern practitioner.

In order to elucidate these benefits, this section describes the benefits of IDB to improve the accuracy of bracket positioning, together with the benefits of an orthodontic digital setup to perform a procedure that takes into account the anatomical variability of patient dental anatomy with the aim of obtaining an improved finished occlusion. This entire procedure can be called "patient individualized digital indirect bonding" (PIDIDB). This procedure is shown using actual clinical parameters of a 13-year-old girl with full dentition and good skeletal proportion who underwent comprehensive orthodontic treatment with a preadjusted setup (Fig 11-20).

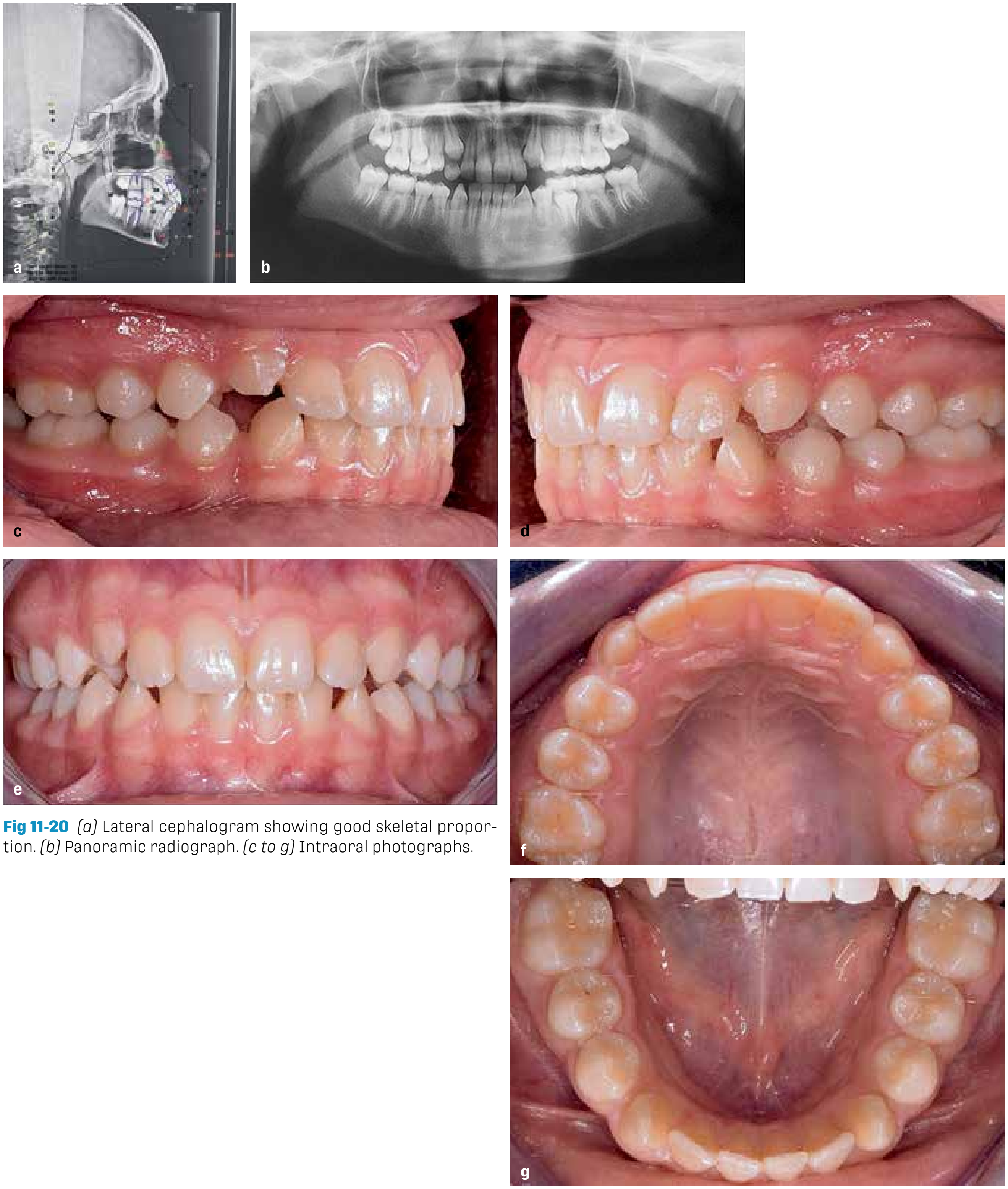


Fig 11-20 *(a)* Lateral cephalogram showing good skeletal proportion. *(b)* Panoramic radiograph. *(c to g)* Intraoral photographs.

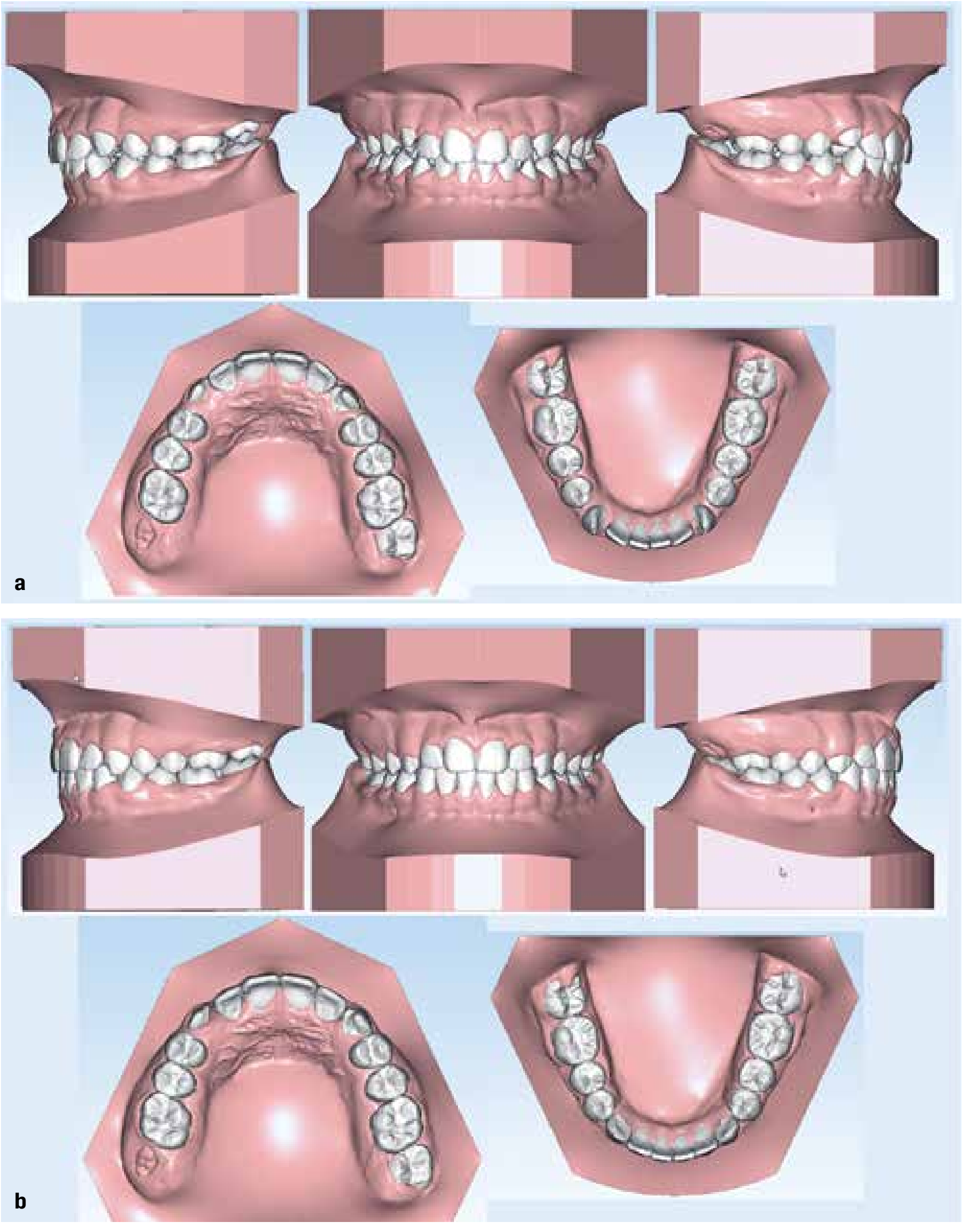


Fig 11-21 *(a)* Digital models with segmented teeth before setup. *(b)* Digital models at the end of setup, showing the teeth in their desired positions.

To perform the PIDIDB procedure, the dental casts of this patient were scanned using the Maestro MDS500 3D scanner with Maestro 3D Easy Dental Scan Software. These were set to medium-quality model and two-axis scanning acquisition protocols. Following the acquisition of digital dental models, each tooth was delineated or segmented (Fig 11-21a), indicating to the software the boundaries of each tooth. Having accomplished this, Dental Ortho Studio Software version 4.0 (Maestro 3D) was used to virtually move the teeth into the desired positions (Fig 11-21b). Figure 11-22 presents the superimposed initial malocclusion and setup teeth positions.

Once the teeth have been virtually straightened, the orthodontic brackets of choice are virtually placed onto the dentition so that they assume positions along an aligned dental arch incorporating an archwire devoid of any detail bends, ie, a “straight wire” (Fig 11-23). Currently, a digital representation of nearly every known type of orthodontic bracket has been included in software “libraries” from which they can be chosen for the purpose described above. In this clinical case, Forestadent Mini Sprint straight-wire appliances were used with the McLaughlin Bennett 5.0 bracket prescription.

Fig 11-22 Superimposition of initial malocclusion and final setup.

Fig 11-23 *(a and b)* STL digital replica of brackets used for IDB.

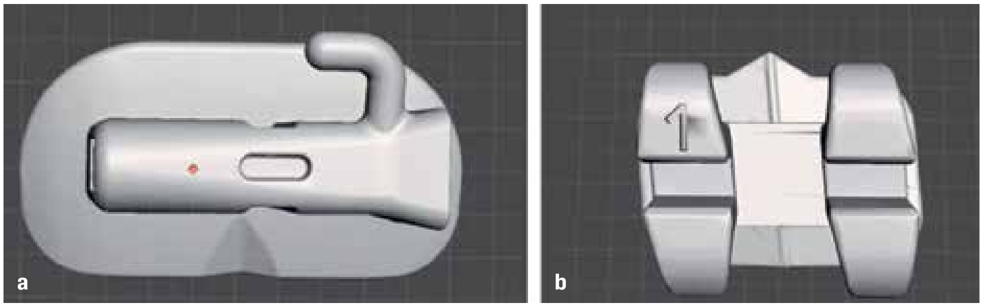


Fig 11-24 Models with virtual bracket positioning according to the straight-wire approach.

The "straight wire" concept means that the virtual brackets are positioned according to an unbent reference archwire that virtually fully engages/fills their slots (Fig 11-24). At this point, the software performs the key step of this procedure. It transfers the individual bracket-tooth position from the setup model to the pretreatment model (Fig 11-25). The final tooth positions and the locations of the brackets virtually placed onto these teeth having been determined, they are now retrofitted onto the teeth in their pretreatment positions to facilitate their movement to the digitally determined end-of-treatment dental positions.

Once the locations of the brackets on the teeth in their maloccluded positions have been determined, it becomes necessary to physically transfer this information to the

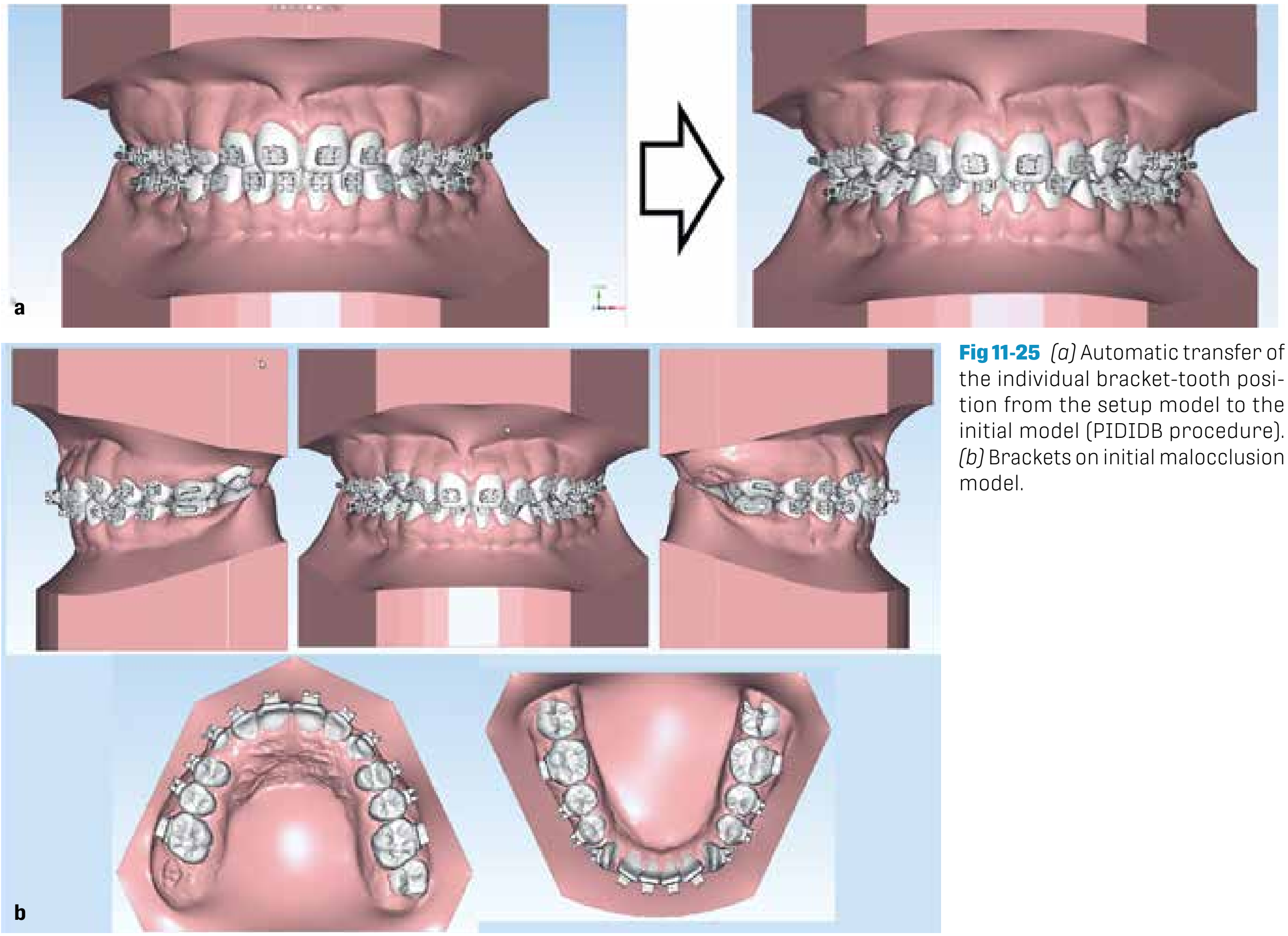


Fig 11-25 *(a)* Automatic transfer of the individual bracket-tooth position from the setup model to the initial model (PIDIDB procedure). *(b)* Brackets on initial malocclusion model.

actual patient. At this point, a transfer tray is designed virtually to perform this task. As such, the boundaries of an IDB tray are defined within the software to determine how it will cover the teeth. This is performed by designing a line with control dots on the considered dental arch that will demarcate the edges of the bonding tray (Fig 11-26). In this stage, it is also possible to decide the thickness of the tray, its distance from the model, and the amount of offset for auxiliary parts.

The software provides three options for IDB tray design. The first is the design of a bracket-positioning guide only. This entails the design of a covering of the teeth and provides for a "window" on each corresponding to the exact dimensions of the base of the chosen bracket type. This enables clinicians to perform an assisted bracket bonding procedure (Fig 11-27). The second option is to design an IDB tray that covers only half of the occlusogingival height of each bracket in order to easily remove the IDB tray once the brackets have been bonded (Fig 11-28).

The third available option is the printing of a model with the teeth in their pretreatment positions together with the brackets in their determined ideal positions, referred to as *bracket keys*. The bracket keys are defined by the software without any undercuts so that the ensuing vacuum-formed thermoplastic or silicone-based dental impression material can be used to create a mold of the dentition containing the location of the properly positioned orthodontic brackets. Into the keys created in either of these types of molds, the clinician manually inserts the corresponding actual orthodontic bracket for transfer to the patient's teeth (Fig 11-29).

In the clinical example presented here, the first option was used because it is the simplest solution available with the Maestro Ortho Studio 3D software for the IDB procedure. The bracket bonding guide appliances were designed and subsequently printed with stereolithography 3D printing technology. The STL file was sent to the printer software and printed with adequate supports (Fig 11-30). These

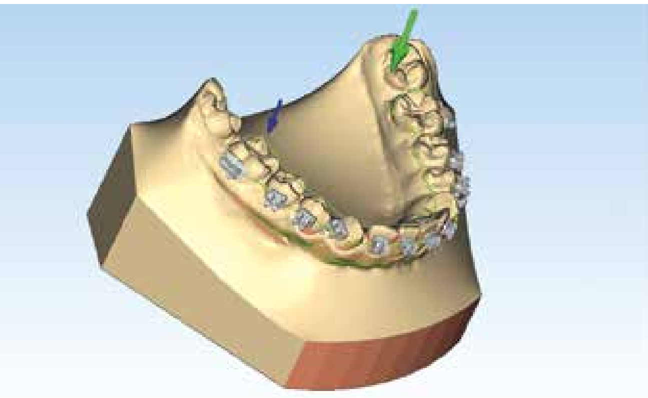


Fig 11-26 Defining the IDB tray.

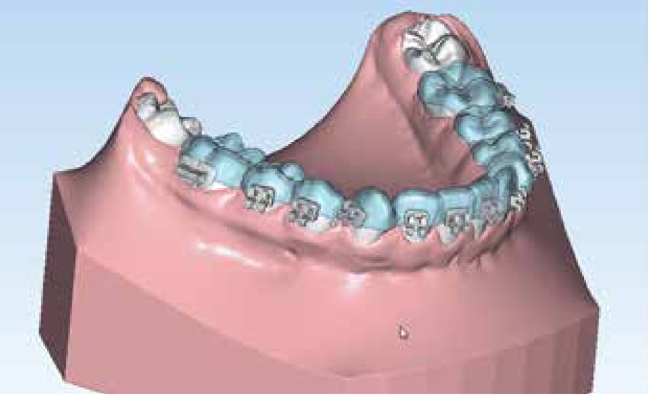


Fig 11-27 Window bonding guide for assisted bracket placement.

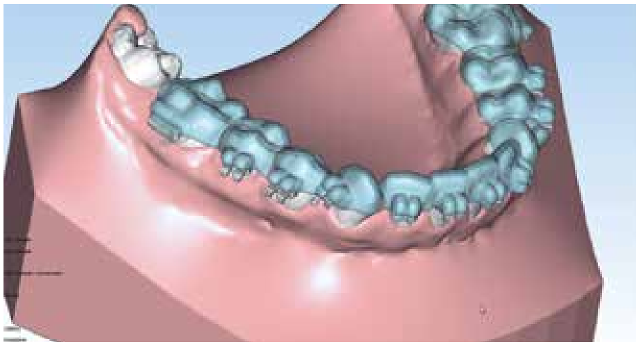
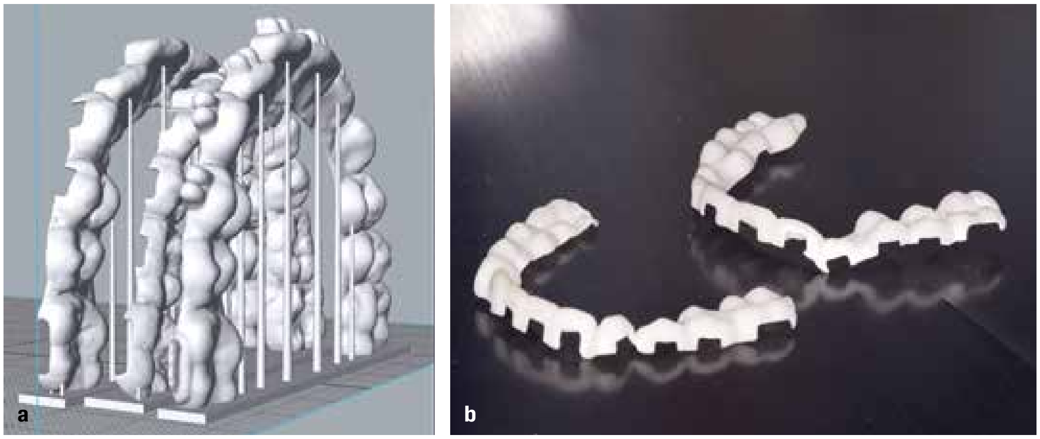


Fig 11-28 IDB tray partially covering the digital bracket for easy removal during bonding.

Fig 11-29 Designed model with bracket keys (virtual brackets without undercuts). This model can be 3D-printed and used to make conventional thermoplastic or silicon bonding trays.

Fig 11-30 *(a and b)* Window bonding trays printed in an SLA 3D printer.



bracket guide appliances were preliminarily attempted on stone casts (Fig 11-31). Subsequently, 3D-printed bracket guide appliances were fabricated to perform assisted IDB bonding (Fig 11-32). At the end of the bonding procedure, it is possible to compare the planned bracket position with the final clinical bracket position via intraoral photographs (Fig 11-33).

Another possible approach to perform PIDIDB includes the use of specific jigs for IDB (Fig 11-34). The jig (shown in blue) is an element that can be intimately coupled with the

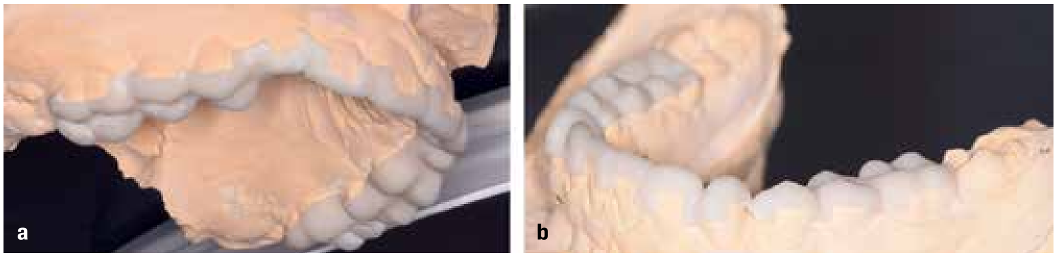


Fig 11-31 *(a and b)* Window bonding trays fitted on stone casts.

Fig 11-32 *(a and b)* Maxillary and mandibular arch bonding using 3D-printed window bonding trays.

Fig 11-33 Final clinical bracket position *(a)* compared with planned bracket position *(b)*.

bracket slot using two arms: The first is firmly connected with the bracket slot in a way that the bracket can be held by the jig with a specific orientation, and the second has a rectangular section and is fitted into a special occlusal wafer through correspondingly designed holes (Fig 11-35). The wafer provides positive seating onto the occlusal surfaces of teeth, with the jig acting as an intermediate element to hold the bracket in the planned position. The use of jigs offers several advantages, such as providing access to remove exuded excess composite bracket adhesive with a probe before it is cured. Also, IDB jigs permit the planned bracket inclination to be maintained during the bonding procedure; any shift of

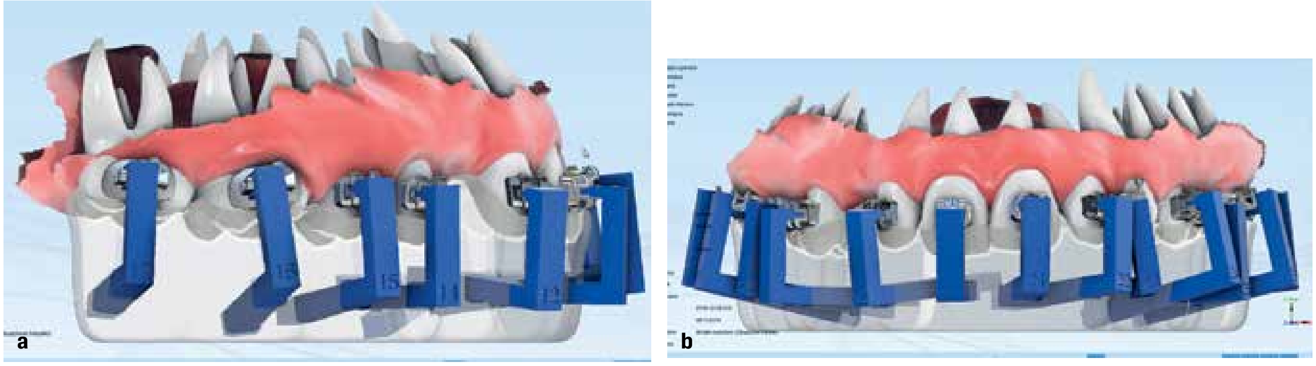


Fig 11-34 *(a and b)* Digital design and positioning of jigs with the wafer used for IDB.

Fig 11-35 3D-printed wafer in place over the teeth.

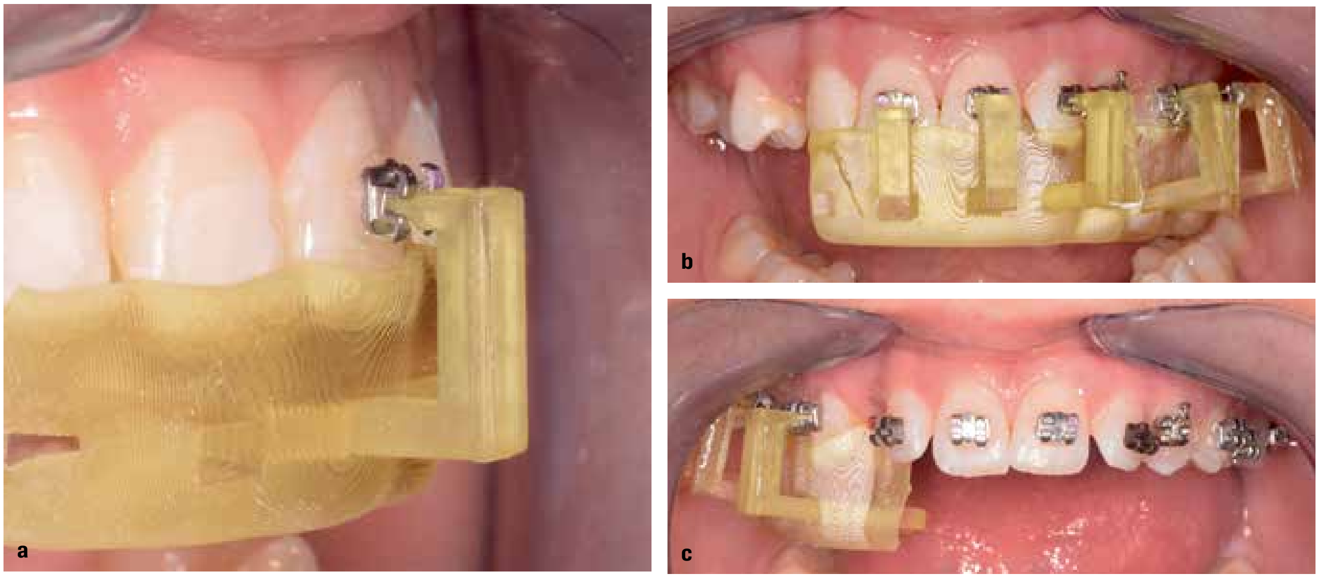


Fig 11-36 *(a to c)* Specially designed IDB jigs maintain the brackets' planned inclination.

bracket position caused by the shape of the dental crown can thus be avoided using this method (Fig 11-36).

The use of jigs also presents some limitations that make this IDB technique challenging to execute. For example, this procedure requires the use of a specific jig for every single bracket. The jigs are usually not provided by the bracket manufacturing companies but can be designed with CAD software (Fig 11-37); however, this requires informatic skills

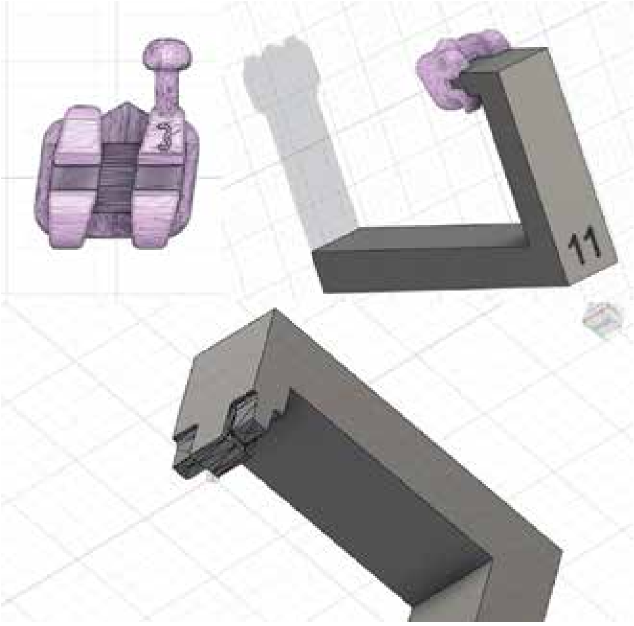


Fig 11-37 Digital design of specific IDB jigs in CAD software.

that are not the usual strong suit of clinicians or orthodontic technicians. Predesigned jigs can be imported into the Maestro 3D software and then 3D-printed along with the occlusal wafer to clinically perform IDB (see Fig 11-36).

PIDIDB seems to offer several advantages. The most important advantage is that this procedure allows the clinician to individualize bracket bonding according to individual patient dental morphology and dimension. This approach should reduce if not eliminate the need for any bracket repositioning during advanced stages of treatment, which potentially increases treatment efficiency and hence reduces treatment duration. Moreover, it could increase tooth movement predictability and improve the efficiency of a given fixed appliance.

Prior to the availability of digital tools to do so, this procedure was performed in analogic methods, especially when lingual orthodontic appliances were chosen.[63–65] The advent of digital technology has improved this IDB procedure and made it easier, faster, more accurate, more accessible, and potentially viable as an in-office procedure. While PIDIDB requires laboratory time and additional materials, which imply an added cost to the patient, chair time is reduced, and a potential exists to reduce the duration of overall treatment with better clinical outcome. Studies should be undertaken to scientifically validate this methodology and to prove that PIDIDB has a positive impact on the whole of treatment efficiency and efficacy.

Conclusion

It is evident that digital IDB is a procedure that can be entirely performed within the orthodontic office. There is no need for a dental technician or a dental laboratory. The so-called "virtual patient" is constructed within the environment of a computer, and a 3D printer is used to fabricate the transfer tray. This configuration of digitally driven software and hardware now places every aspect of appliance choice and patient-specific design within the hands of the clinician without the need for auxiliary functionaries. The fact that the doctor has a more accurate tool to administer treatment more efficiently is justification enough for every modern orthodontist to avail themselves to these tools for the benefit of their patients and the profession.

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12

In-House Orthognathic Surgical Splints

Federico Hernández Alfaro
Adaia Valls Ontañón

Orthognathic surgery (OS) involves the surgical manipulation of the elements of the facial skeleton to restore the proper anatomical and functional relationship in patients with dentofacial skeletal anomalies.[1] An established diagnostic tool to plan these procedures has been the field of cephalometrics. Multiple cephalometric reference planes have been described to determine the ideal dentoskeletal harmony; choosing the appropriate reference is dependent on cultural and individual surgeon's esthetic preferences.[2–5] Regardless of the selected reference plane, surgical planning is essential to establish the final position of jawbones and the required movements of osteotomized segments. Consequently, it is fundamental to accurately transfer such planning to the surgical setting.

The current gold standard is to transfer the determined surgical plan outcome to the actual procedure through the use of surgical splints. These are individualized and fitted plastic appliances that serve to orient one or both jaws once they have been mobilized. In maxillomandibular surgeries, an intermediate splint is used first to guide the movement of one jaw relative to the other that has yet to be mobilized (Fig 12-1a). Then a final splint guides the movement of the other jaw and secures the final occlusion (Fig 12-1b). Regardless of which bone is moved first, precise repositioning is imperative, because once stabilized, it becomes the reference for repositioning the other bone. Needless to mention, in single-jaw surgeries only the latter splint guiding the final occlusion is required.

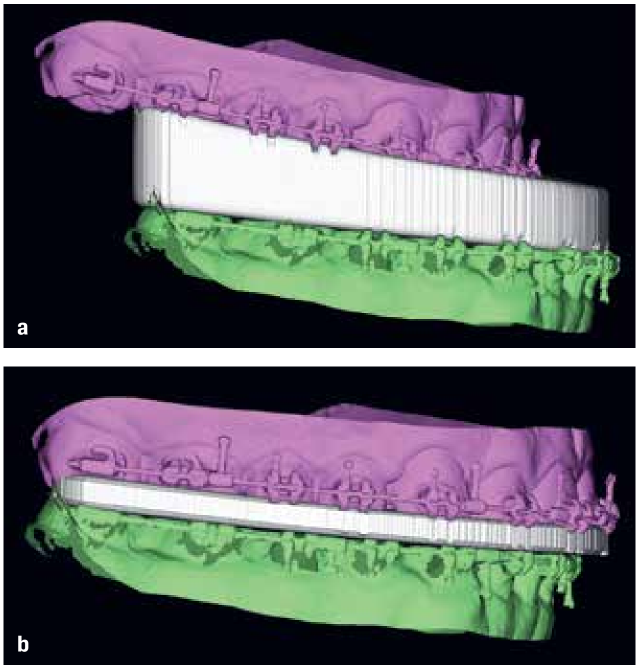


Fig 12-1 *(a)* Virtual intermediate splint. *(b)* Virtual final splint.

Surgical planning in OS has seen remarkable advancement in recent decades. The most significant progress in this aspect has been the evolution from a 2D lateral or anteroposterior cephalometric facial analysis performed manually on acetate paper to 3D computer-aided planning. Similarly, occlusal analysis has progressed from articulator-mounted dental casts to virtual digital dental models. Now CAD/CAM surgical planning has replaced the previous methods to be recognized as the diagnostic, treatment planning, and splint designing/fabricating gold standard.[6,7]

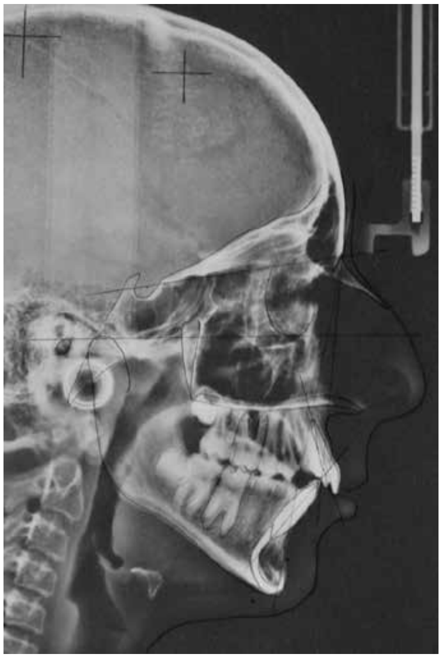


Fig 12-2 2D manual cephalometric tracing.

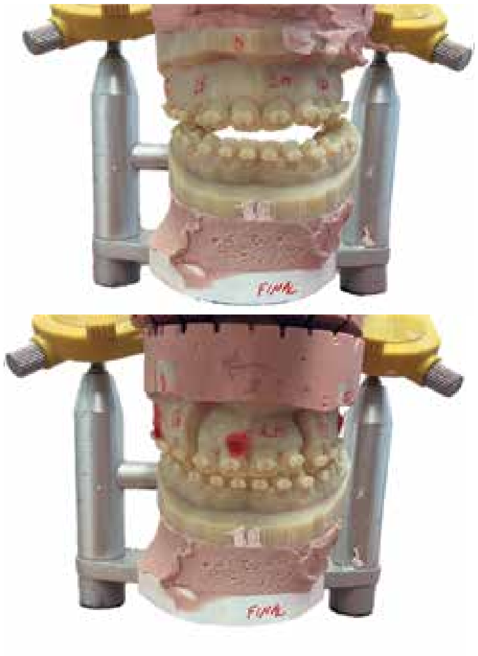


Fig 12-3 Model surgery integrating the treatment plan to the casts mounted on an articulator.

This chapter compares and contrasts the methods described earlier in order to illuminate their differences. It must be stated that the aforementioned digital technologies entail significantly higher initial costs. Thus, in-house workflows using planning software and home 3D printers are stressed in an effort to improve the cost-effectiveness of these procedures.

Conventional Orthognathic Surgery Planning

The conventional OS planning has historically been based on 2D facial analysis (photographs, radiographs) and occlusal determinants based on facebow-oriented and articulator-mounted poured stone dental casts. In this method, the use of an anatomical articulator with a facebow transfer is fundamental in order to achieve the proper position of the maxillomandibular complex in space and its relationship to the optimum functional centric occlusion.[8]

A thorough cephalometric study is the basis for determining the amount of surgical movement required for each component of the maxillomandibular complex (maxilla, mandible, and chin). This is performed according to accepted angular and linear determinants comprising a specific cephalometric protocol, keeping in mind that these are influenced by individual surgeon bias regarding criteria of facial harmony and beauty.[9,10] Figure 12-2 presents a traditional manual cephalometric tracing.

Having predicted the amounts and directions of surgical skeletal alterations to be performed, the resultant dental occlusion is determined by carrying out these manipulations on a pair of plaster casts. This so-called "model surgery" is performed in order to integrate the treatment plan to the casts mounted on the articulator (Fig 12-3). This step is essential because it directly determines the anticipated final occlusion resulting from the planned surgery. The result of the cast surgery is transferred to the laboratory technician as a record of the state to be maintained and as a template to be used in the fabrication of the required surgical splint. In this way, the jaws are held in their planned locations until fixation can be accomplished. The splint, as it is described here, is fabricated from acrylic resin directly onto the provided dental casts.

Each stage of this procedure has been traditionally accomplished manually. This entails measuring standardized 2D craniofacial records (cephalometric and photographic) by hand with a protractor and ruler (see Fig 12-2), taking dental impressions, pouring dental casts, and then sectioning those casts to facilitate the simulated manipulations of the surgery. These procedures culminate in producing a maxillomandibular orientation to which the needed surgical splints are formed in a laboratory setting.

Virtual Planning in Orthognathic Surgery

Conventional surgical planning has seen some utilization of digital capabilities. For example, computer software has been developed that analyzes 2D cephalometric records and simulated jaw movements in these planes (Fig 12-4). However, advances in 3D imaging technology such as computed tomography (CT) and, more recently, CBCT have remarkably improved craniomaxillofacial diagnosis, especially when facial asymmetries exist. Furthermore, these 3D images can be used to virtually simulate OS and predict the postoperative outcome.

Paralleling advances in imaging technologies has been the emergence of the medical application of DICOM-processing software, permitting 3D virtual surgical planning. In addition, this capability has enabled the 3D printing of surgical splints using CAD/CAM. Together, these have revolutionized the essential measures needed to maximize the preparation for OS.[11]

In essence, digitization of this process has improved OS planning and enabled the following: *(1)* user-friendly data management, storage, and sharing; *(2)* communication between colleagues as well as with patients; *(3)* drawing of specific osteotomy lines; *(4)* fabrication of patient-specific splints and guides; and *(5)* a more predictable and accurate overall final surgical outcome.[12]

The incorporation of these 3D computerized tools has the potential to improve surgical accuracy, shorten its duration, and reduce patient morbidity. In addition to these benefits, these capabilities vastly improve the efficiency of presurgical preparatory measures, making the utilization of these virtual tools more time- and cost-effective than conventional planning.[13] However, it is important to note that computer-simulated surgical planning cannot replace the need for constant intraoperative monitoring of jaw movements and real-time comparisons between the planned and actual outcomes.

Orthognathic Surgery Digital In-House Workflow

There are currently several software programs for OS virtual planning available. Most of these must be purchased; however, reliable free software also exists.[14] Regardless of the chosen software, OS virtual planning is meant to be carried out in-house. The equipment necessary to do so includes the following:

- Intraoral scanner
- OS virtual planning and designing software
- 3D printer

A CBCT machine is also helpful, but due to its high cost, it is not always feasible to be maintained in a maxillofacial surgery office. However, it may be possible to refer the patient to a centralized imaging center that could export the necessary 3D files/images.

The following sections sequentially describe the workflow for in-house OS virtual planning.

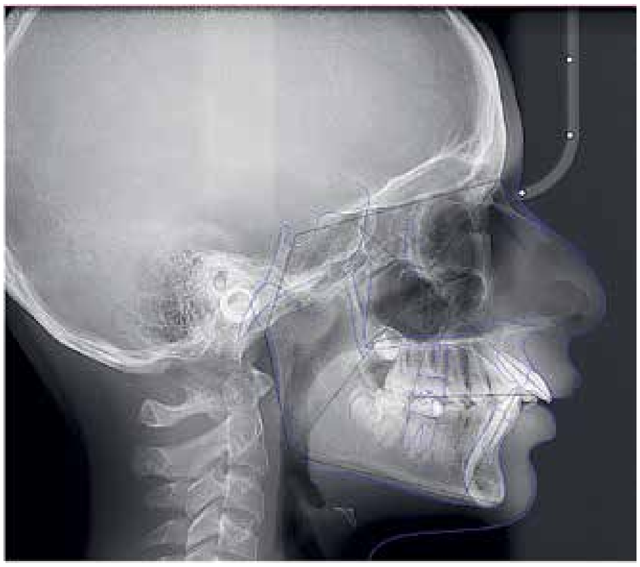


Fig 12-4 2D digital cephalometric tracing. (Courtesy of Dr Núria Clusellas Barrionuevo.)

1. 3D image acquisition

A single CBCT scan of the head of the patient is taken with the patient breathing quietly without swallowing, sitting upright in natural head position (NHP), the tongue in a relaxed position, and the mandible in centric relation with a 2-mm wax bite in place in order to avoid direct contact between teeth. (Note: Patients need to be instructed by trained personnel to maintain this position.) CBCT images are exported in DICOM format and coupled with a specific software (eg, Dolphin 3D Surgery). The "raw" file

Fig 12-5 Intraoral 3D surface scanning.

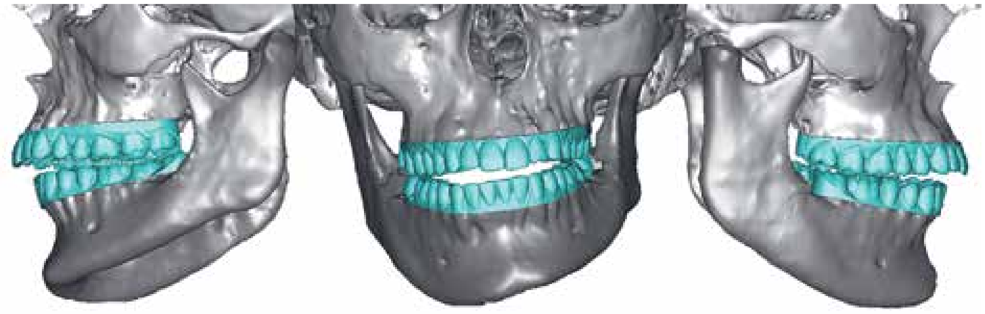


Fig 12-6 Process of CBCT cleaning and fusion with intraoral surface scan data.

is processed to a "clean" 3D virtual image of the head of the patient, which is stored as an STL file.

A CBCT provides an inaccurate visualization of the teeth and the dental interocclusal relationship. For this reason, an intraoral surface scan of each dental arch and a virtual bite record is also required. This is stored as a second STL file for subsequent fusion of the two data sets[7] (Fig 12-5). The result of these procedures is an accurate representation of the skull and dental arches of the patient precisely as they are anatomically and ready for use in the software program (Fig 12-6).

2. 3D virtual planning

Having 3D images not only allows for accurate (anatomical) diagnosis but also facilitates computer-assisted simulated surgery using specific software programs like Dolphin 3D Surgery. Orienting the virtual patient's head to NHP, cephalometric analysis can be carried out by plotting the landmarks required. It is important to highlight that the same anatomical points selected by the surgeon are used for this purpose in both classic 2D and modern 3D diagnostics (Fig 12-7).

After a definitive diagnosis has been determined, the clinician needs to mark selected landmarks in order to design the maxillary and mandibular osteotomies. Based on these boundaries, the repositioning of osteotomized bony structures is virtually simulated following an operator-specific cephalometric protocol (Figs 12-8a and 12-8b). For example, the authors have adopted the upper incisor to soft tissue plane (UI-STP) protocol, as described by Hernandez-Alfaro[9] (Fig 12-8c).

Completion of virtual surgical simulation then requires operator verification of anatomical and surgical alterations to ensure that the intended outcome has merit. For example, the resultant dental occlusion needs to be scrutinized in order to establish that correct intercuspation can be anticipated without any interfering occlusal contacts and that a symmetric interarch relationship is achieved, including condylar seating. In addition, this permits confirmation that no interferences are created between the osteotomized bony structures as well as the validation of final outcomes[15] (Fig 12-9).

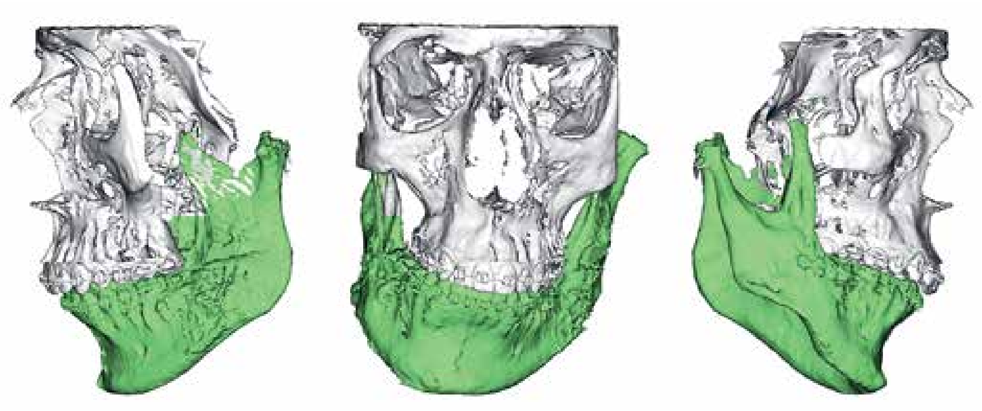


Fig 12-7 Virtual patient's head in NHP for cephalometric analysis.

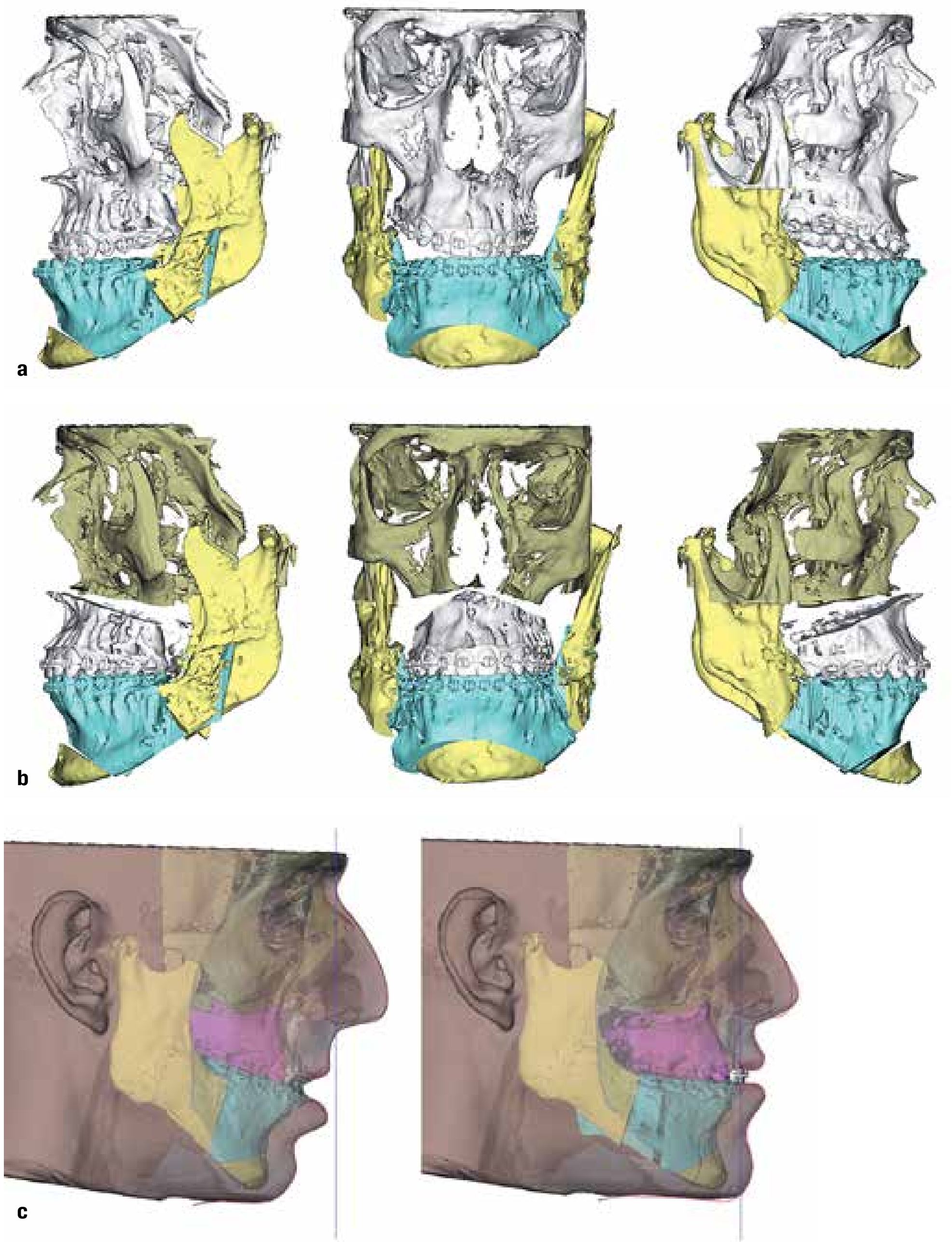


Fig 12-8 Virtual 3D planning in an orthognathic case. *(a)* The mandible is repositioned. *(b)* The maxilla is repositioned. *(c)* Surrounding soft tissue.

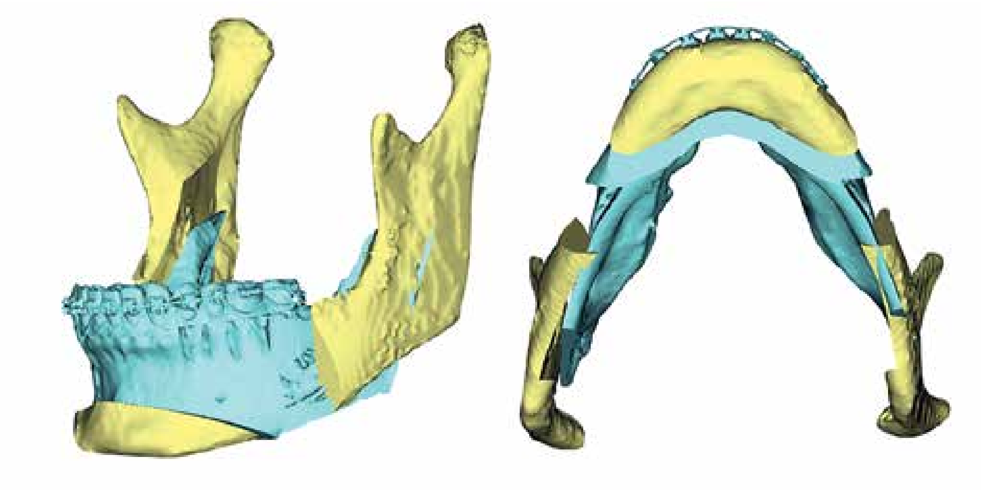


Fig 12-9 Checking interferences between proximal and distal mandibular segments.

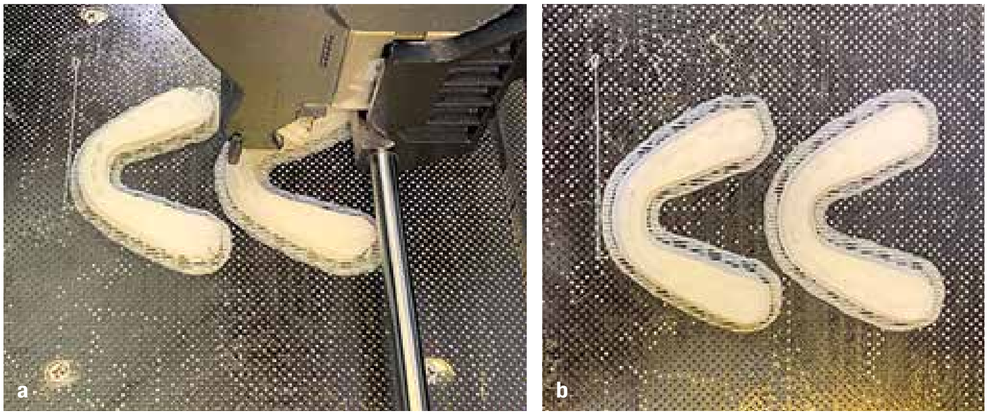


Fig 12-10 *(a and b)* Surgical splint printing using an in-house FDM printer.

3. CAD/CAM surgical splints

The same software is used to design the surgical splints (see Fig 12-1). Firstly, correct intercuspation needs to be checked. If premature/interfering occlusal contacts are detected, then these must be eliminated. Then the amount of dental surface covered by the splints, as well as their appropriate thickness, is selected.

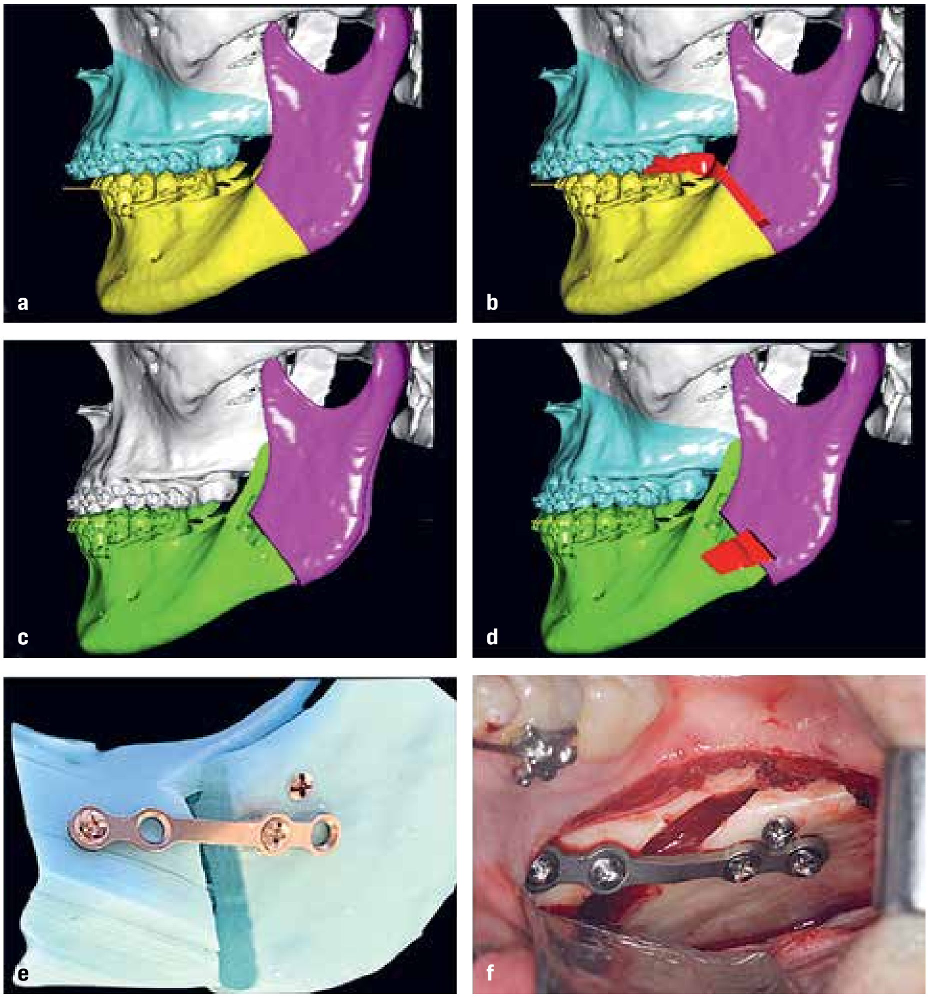
Finally, for splint manufacturing, the data comprising the virtual planning can be exported to a laboratory or facility with medical-grade 3D printing capabilities. The incorporation of this equipment within the confines of a clinical practice permits a complete digital in-house workflow with an in-house 3D fused deposition modeling (FDM) printer (eg, UP Box3D, Tiertime) using a filament made by thermoplastic material such as polylactic acid (PLA; Fig 12-10).

Skull Printing: Cutting Guides and Preshaped Miniplates

The ability of the practitioner to obtain one-to-one 3D imaging diagnostic information has also provided an opportunity to maximize other aspects of presurgical preparation. For example, the manufacturing of cutting guides and preshaped miniplates has meant increased accuracy of surgical procedures and elimination of time-consuming formation of fixation plates during the surgery. Moreover, miniplates will not be damaged due to the need to manually bend them to adapt to the individual anatomy of the patient, which introduces stresses to commonly available universal shaped fixation plates that decrease their reliability in providing rigid fixation.

The ability to enter into a surgery with essentially stencil-like cutting guides allows for better accuracy in surgical

Fig 12-11 *(a to f)* Design of mandibular cutting guides and miniplates with CAD/CAM technology. (Courtesy of Dr Jonathas Daniel Paggi Claus.)



performance. The availability and use of these guides *(1)* increases the likelihood that the osteotomies will be performed exactly the same as planned; *(2)* simplifies the process of achieving the level of desired symmetry; and *(3)* greatly reduces the risk of injury to structures such as the infraorbital and inferior alveolar nerves, the palatine pedicle, and the dental roots, etc. Therefore, the use of such tools should decrease morbidity and increase surgical accuracy associated with these procedures.

The above being said, it needs to be understood that at present, the benefits provided by surgical guide splints also entail two main inconveniences. First, they are bulky and require more soft tissue detachment in order to accommodate their placement. Second, they only provide a method of locating the place where an osteotomy cut should be placed on the surface of the bone without any reference to the depth or directional orientation it is to be done. Hence, their use has not eliminated certain aspects of procedural inaccuracies because, while they are useful for marking the osteotomy superficially, the cutting direction is not totally transferred to the basal-most area of the mandible and the backward-most area of the maxilla.

The manufacturing of these supplemental tools requires three additional steps to the virtual planning process using the specific software. First, after marking osteotomy lines, future fixation drill markings are identified in areas of the bone with appropriate thickness and quality, while avoiding relevant adjacent anatomical structures (ie, nerves, vessels, and dental roots). Second, after virtual simulation of the surgery, miniplates are designed with CAD/CAM technology and machined from titanium. Third, a set of bone-supported guides that are perfectly adapted to the specific patient's bony surface are designed to ensure correct intraoperative drilling of the holes and positioning of the miniplates (Figs 12-11 to 12-13). The mandibular sagittal split osteotomy guide usually requires that it be

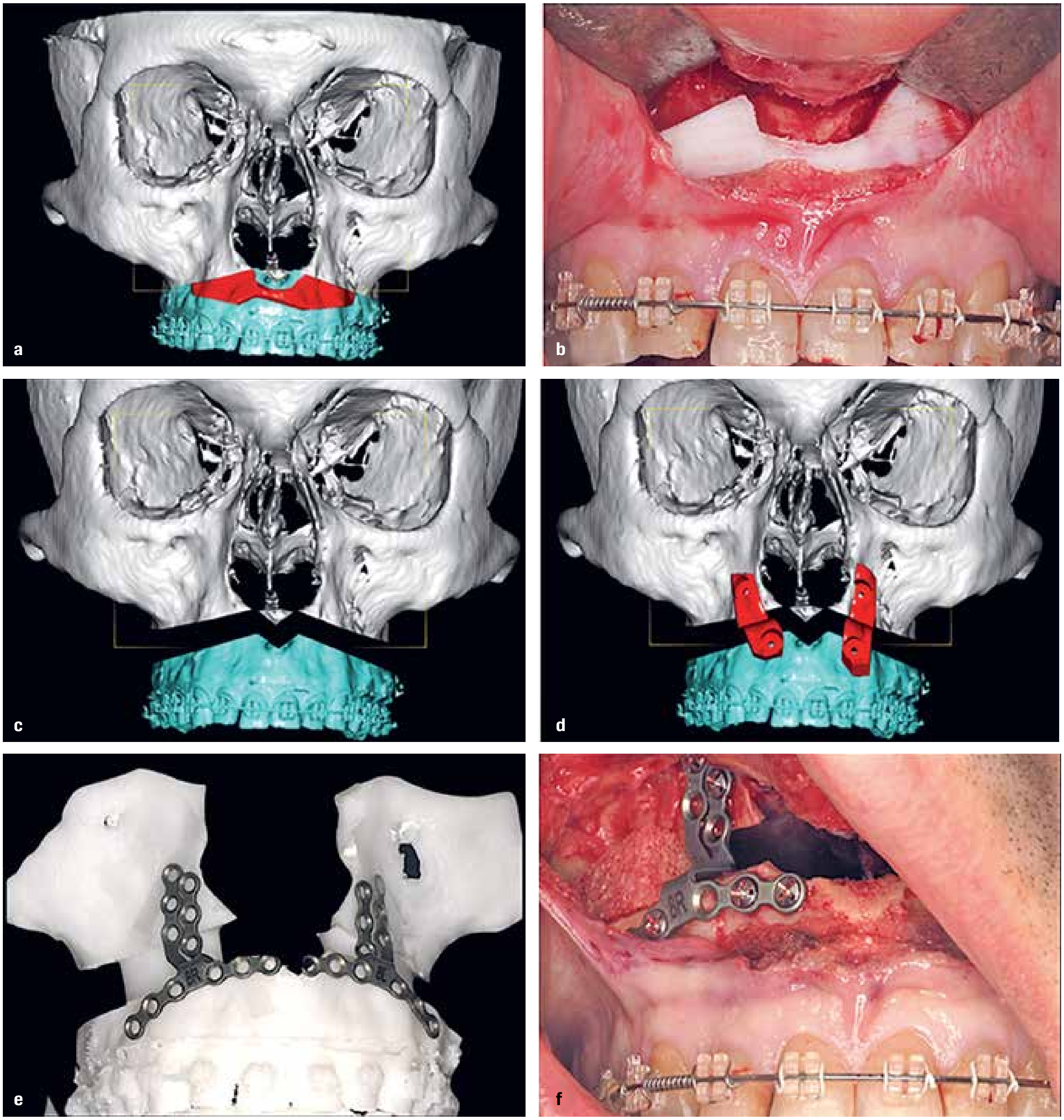


Fig 12-12 *(a to f)* Design of maxillary cutting guides and miniplates with CAD/CAM technology. (Courtesy of Dr Jonathas Daniel Paggi Claus.)

connected to an occlusal splint in order to ensure stable positioning. The stability and accuracy of cutting guides and preshaped miniplates as described herein have not been thoroughly tested in order to obviate the use of the intermediate and final splints.[14–17] Box 12-1 outlines the advantages and disadvantages of in-house design and printing of surgical splints.

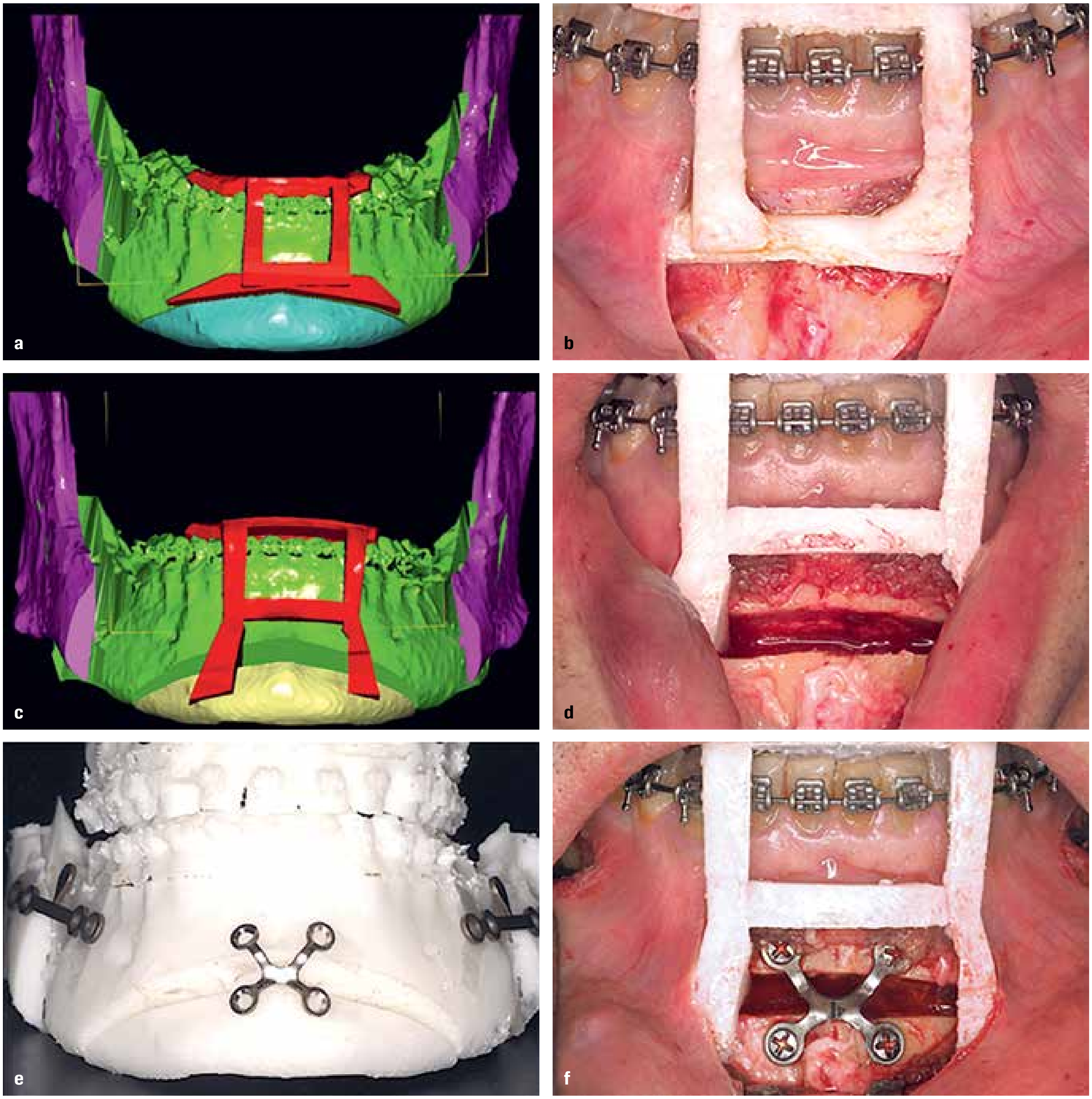


Fig 12-13 *(a to f)* Design of chin cutting guides and miniplates with CAD/CAM technology. (Courtesy of Dr Jonathas Daniel Paggi Claus.)

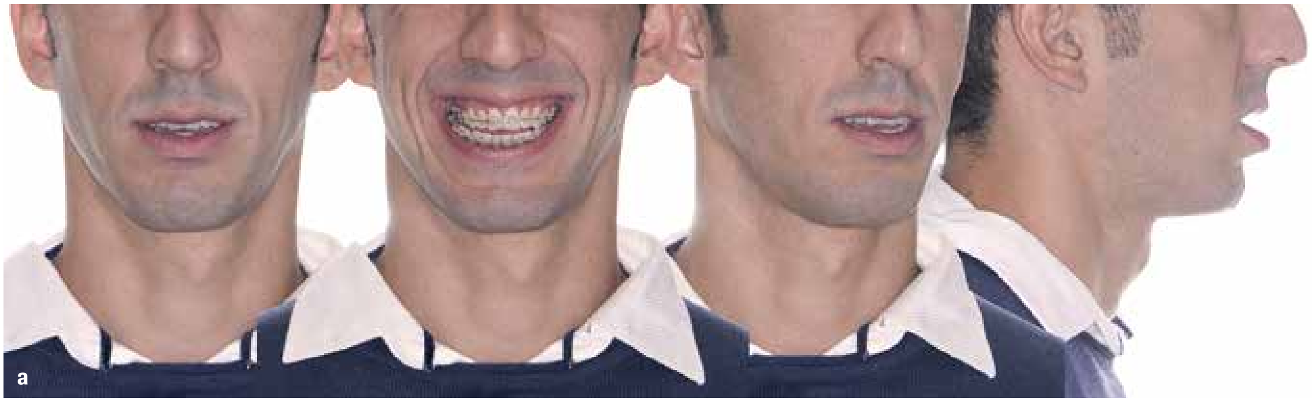
Box 12-1 Advantages and disadvantages of in-house design and printing of surgical splints

Advantages

- Data management
- Self-tailored design of osteotomies, miniplates, and guides
- Improved surgical accuracy
- Outcome prediction
- Cost- and time-effectiveness

Disadvantages

- Soft tissue prediction is not reliable
- Clinician training is required



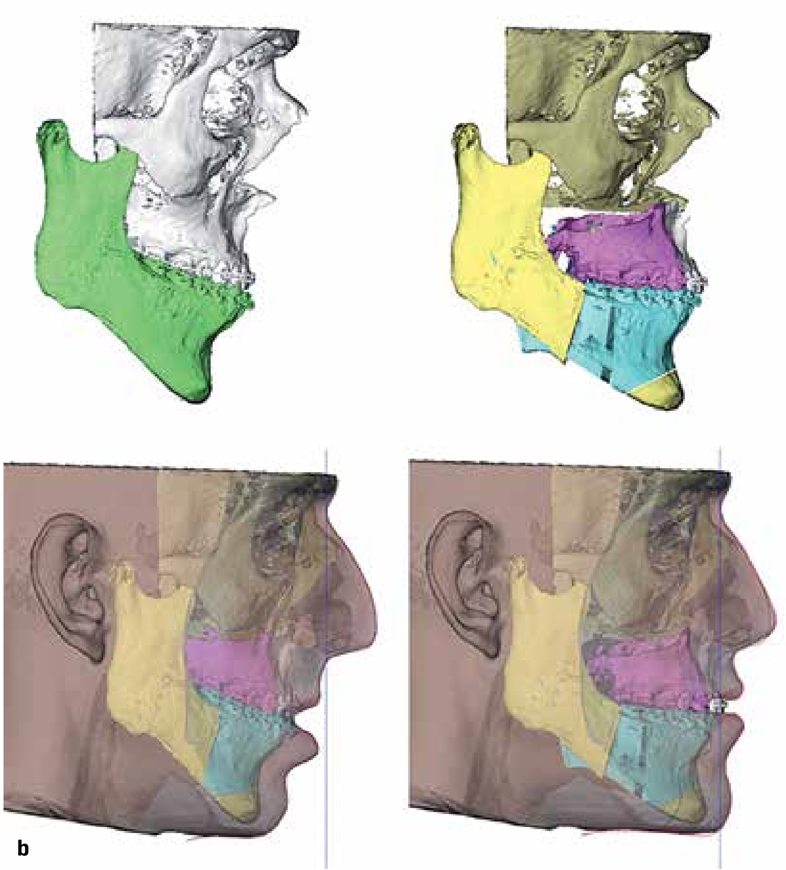


Fig 12-14 **Case 1.** *(a)* Pretreatment photographs of a patient treated with a conventional protocol (orthodontics followed by surgery). *(b)* Virtually designed maxillary, mandibular, and chin osteotomies together with soft tissue prediction.

Case Presentations

Case 1

A 34-year-old man without relevant medical history seeking settlement of his malocclusion presented with a Class III anterior open bite dentoskeletal relationship with a biretrusive profile (Fig 12-14a). A conventionally staged treatment timing protocol was followed: ie, orthodontics-surgery-orthodontics. Surgery was planned virtually, including skeletal movements and resultant soft tissue prediction (Fig 12-14b). Surgical splints were designed and printed following our in-house protocol using PLA filament (Fig 12-14c). One-year follow-up photographs show functional and esthetic improvement (Figs 12-14d to 12-14f).

Fig 12-14 *(cont)* *(c)* Intraoperative photographs showing in-house 3D-printed surgical splints using an FDM printer. *(d)* Posttreatment final occlusion. *(e)* Comparison of frontal facial photographs before and after surgery. *(f)* Comparison of lateral and oblique facial photographs before and after surgery.

Case 2

A 26-year-old man without relevant medical history, whose main complaint was malocclusion, presented with a Class III malocclusion and biretrusive profile (Fig 12-15a). A surgery-first protocol (surgery-orthodontics) was followed, with braces being placed immediately prior to surgery to have them available as purchase points during the surgery (Fig 12-15b). Surgery was virtually planned for bone repositioning, and surgical splints were designed and printed following our in-house protocol (Figs 12-15c to 12-15f). One-year follow-up photographs show functional, esthetic, and neck soft tissue support improvement (Figs 12-15g to 12-15i).

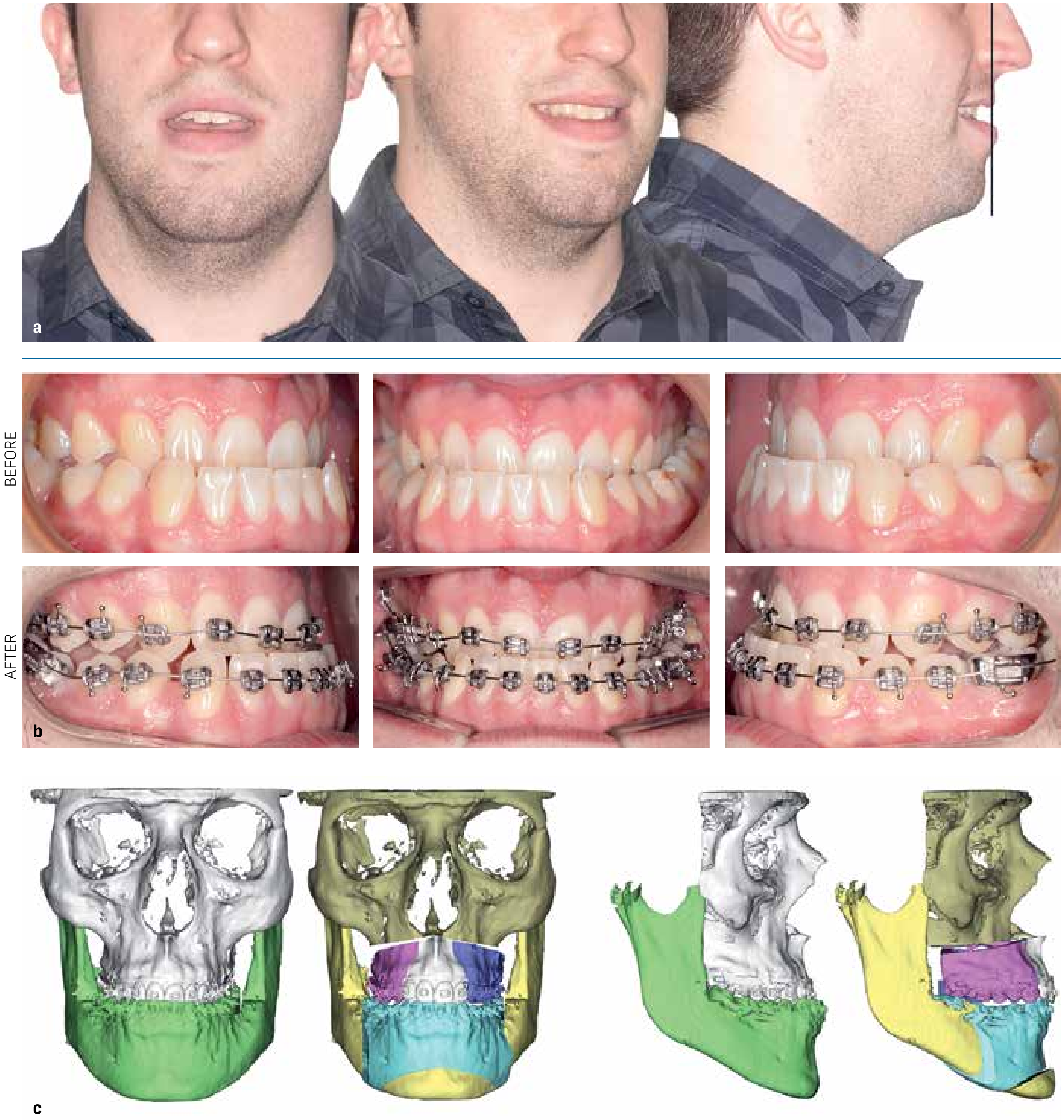
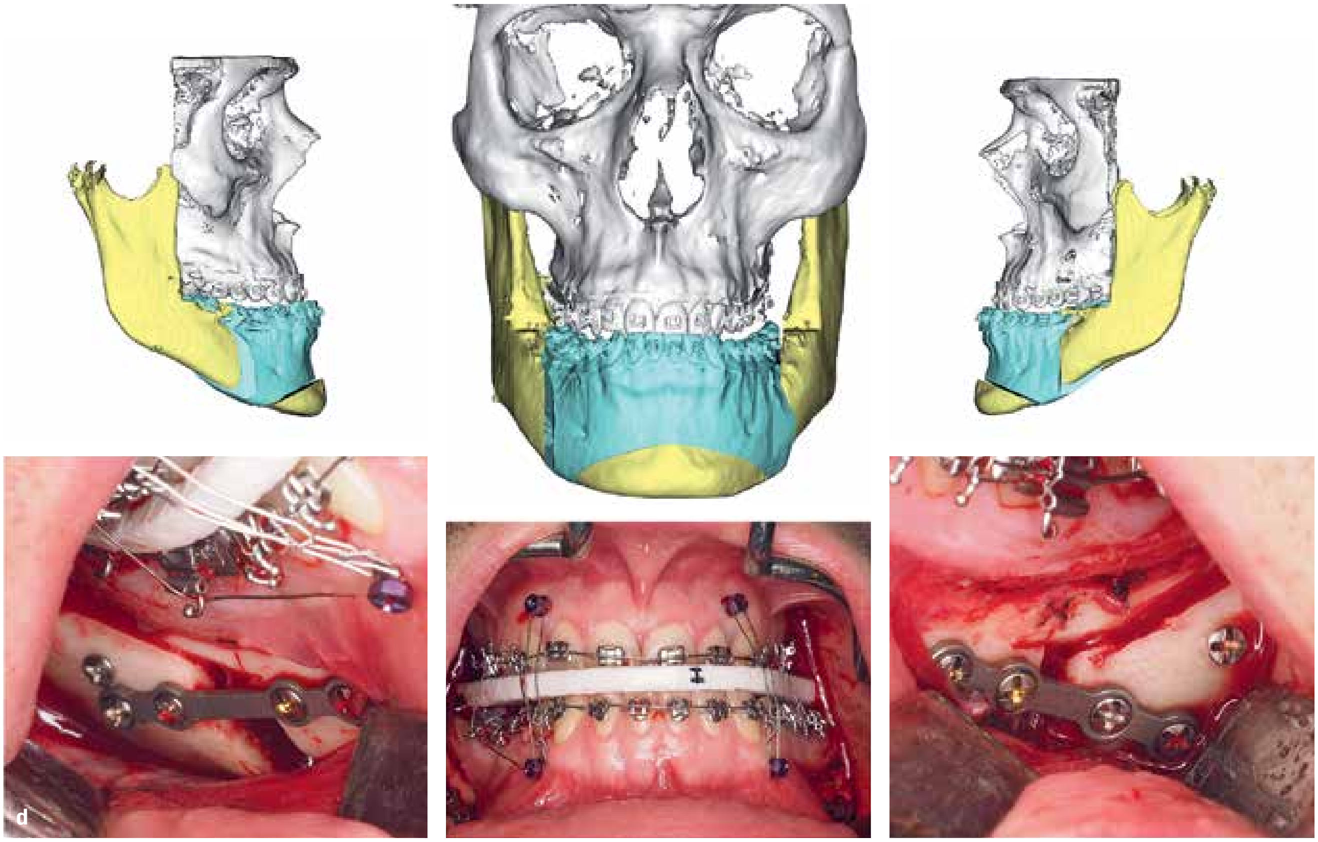


Fig 12-15 **Case 2:** Surgery-first case. *(a)* Pretreatment photographs of the patient. *(b)* Intraoral photographs before and after orthodontic bracket bonding immediately prior to surgery. *(c)* Virtual surgical planning.



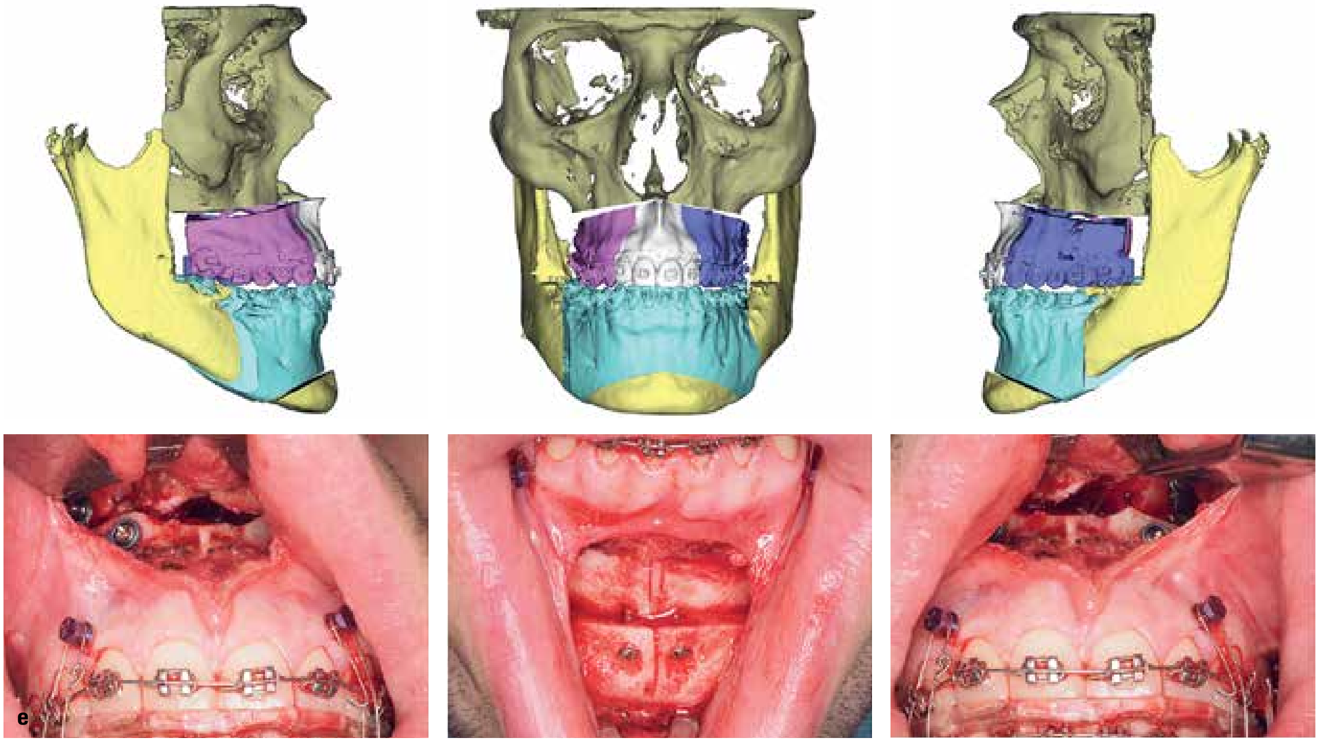


Fig 12-15 ***(cont)*** *(d)* Virtual mandibular surgery and mandibular operation. The in-house printed surgical splint is visible. *(e)* Virtual maxillary and chin surgery. The in-house printed surgical splint is visible.

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Fig 12-15 *(cont)* *(f)* Intraoral prebonding, presurgical, and postsurgical photographs. *(g)* Intraoral pretreatment and posttreatment photographs. Total treatment time was 7 months.

Fig 12-15 *(cont)* *(h)* Comparison of lateral photographs before and after surgery. *(i)* Comparison of frontal and oblique facial photographs before and after surgery.

Conclusion

Computer-aided planning in OS has become an essential tool for proper diagnosis, treatment planning, and outcome prediction. Additionally, when the surgeon is capable of directly using this tool, its benefits can be optimal. Moreover, in-house surgical design and printing maximize this potential and provide several advantages, not least of which is decreased dependence on external laboratory manufacturing. However, presently these capabilities involve high costs, and proficiency in their use requires time-consuming training proportional to the periodicity of its use. Ongoing developments both in the digital components and in construction materials serve in reducing the monetary cost incurred in the designing and printing of surgical splints and fixation plates. The advantages they produce together with their increased accessibility should increase their inclusion into the in-house armamentarium of more maxillofacial surgery clinic digital workflows.

Acknowledgments

The authors would like to thank Dr Jonathas Daniel Paggi Claus and Dr Matheus Spinella Almeida for their contributions regarding the in-house hybrid technique for customization of guides and miniplates.

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13

In-House Orthodontic Archwire-Bending Robots

Alfredo Gilbert

Robotics has been used for decades in the orthodontic industry. Nevertheless, it wasn't until the late 1990s that innovations brought forth by the SureSmile system (Dentsply Sirona) advanced this to the forefront of orthodontics. Now it is impossible to separate robotics/engineering from orthodontics, because digitalization has served to standardize, facilitate, and perfect laboratory, clinical, and presurgical processes.[1]

Lingual Archwire Bending

The emergence of lingual orthodontic techniques has significantly benefited from the application of advanced engineering. In addition to the technical difficulties incurred due to poor access to the lingual aspect of the dentition, the wide range of anatomical variation and confounding biomechanical variables created with the use of this technique present even experienced clinicians with routinely difficult challenges. For example, the forming of lingual orthodontic archwires is an extremely complicated procedure due to the aforementioned inherent aspects. These combine to amplify any mistake in wire bending into confounding iatrogenic effects. Although precisely made archwires are crucial to the success of lingual orthodontics, the irregular lingual dental anatomy and small interbracket distances make manual wire bending difficult, especially in cases involving anterior crowding.[2]

Lingual archwires require numerous first- and second-order offsets due to the relationships that exist between adjacent teeth in the normal dentition. Minor errors in proportion and symmetry of these in archwire design will produce undesirable clinical consequences.[3] For example, distal bends of an overlong lingual archwire may act as a kind of "trigger point," moving the anterior segment forward and opening the bite, or an inadequate offset in the premolar region can displace the entire relevant buccal segment (Fig 13-1).

Fig 13-1 *(a and b)* Maxillary left first premolar incorrectly positioned due to a wire bending error.

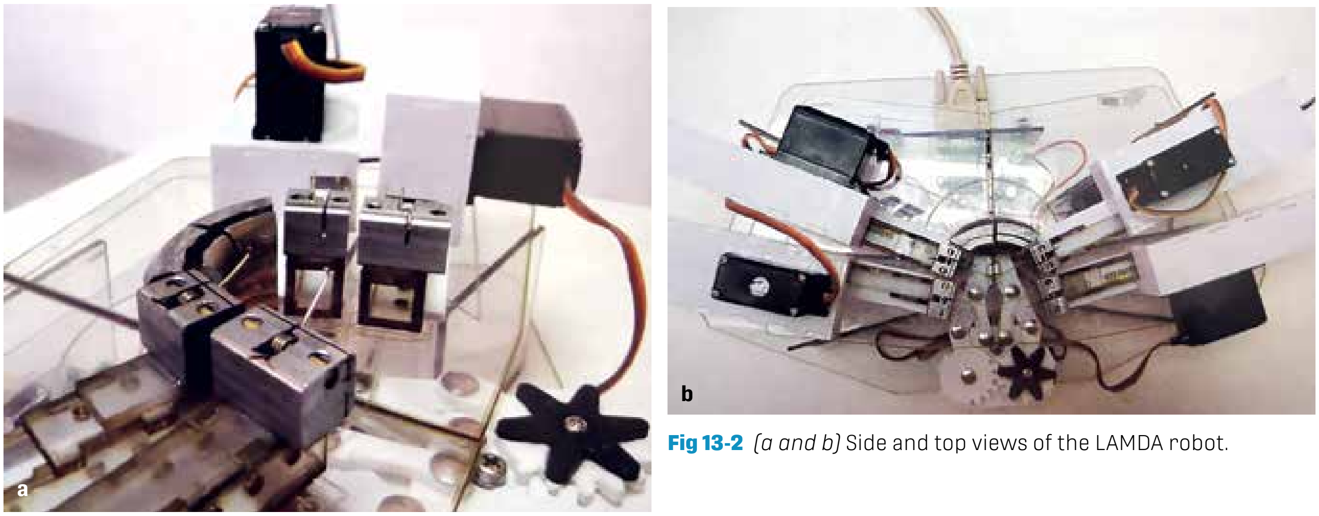


Fig 13-2 *(a and b)* Side and top views of the LAMDA robot.

Biomechanically, there are important differences between the labial and lingual techniques. Clinicians need to take into account that lingual appliances are often bonded vertically closer to but behind the center of resistance of a given tooth or segment of teeth. This is of major significance due to rotational effects expressed by teeth as they are retracted along the archwire. It must be noted that these effects differ from those incurred during similar phases of treatment with labial appliances. Therefore, these characteristics tend to produce a situation that can complicate the interincisal angulations.[4] It cannot be understated that these biomechanical difficulties are increased further when third-order movements are attempted.

LAMDA System

To prevent these complications, we designed our first in-house robot for bending lingual orthodontic wires in 2011, the LAMDA (lingual archwire manufacturing and design aid) robot (Fig 13-2). It was designed to be used in-office either before or after brackets were bonded, thus eliminating the need to have these produced by an external laboratory with the accompanying delay and added fees. This robot made only first-order bends; the other two dimensions were accomplished using the Hiro system.[5]

To design an archwire for a patient with no brackets in place, a digital occlusal photograph of the dental casts must be taken and exported, in either .JPG or .BMP format, into the dedicated LAMDA software on a computer. Using the occlusal photograph as a patient-specific template, the location on the archwire design where its distal ends are located is first selected. Then each sequential location for intra-arch in-out bends is also selected. If this is done before lingual bracket placement, it is mandatory to allow sufficient space for the desired bracket depth. In the example shown in Fig 13-3, the widths of the canine and premolar differ by about 2 mm in each arch, requiring accurate offsets in the lingual archwire to avoid lingual or labial movement of neighboring teeth. The position of any point is easily modified by right-clicking on the point and dragging it to the desired position.

The LAMDA software assigns x and y coordinates to each point, using pixels as the unit of measurement.[6] To convert the distances to centimeters for the wire-bending robot, the program must be calibrated by carefully marking two points 1 cm apart next to the cast and including these two points in the digital occlusal photograph. As the cursor is moved over various line segments and connecting points on the digital archwire, the program displays the distances between any two points and shows angles as positive (bends to the left) or negative (bends to the right). A similar protocol is followed in a patient with brackets already bonded, but a single occlusal photograph is used instead of a photograph of the plaster cast.

Calibration from pixels to centimeters is accomplished by marking a 1 cm space on the occlusal mirror before taking the photograph (Fig 13-4). A passive archwire can be designed by tracing the exact positions of the brackets. Alternatively, an active archwire can be made with appro-

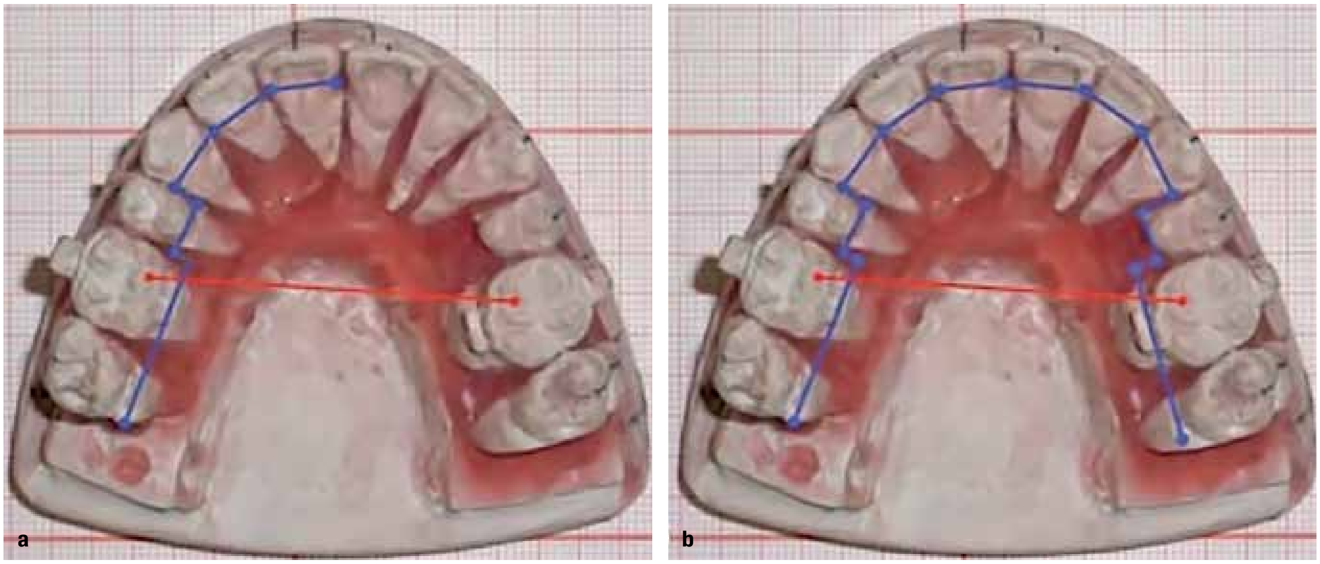
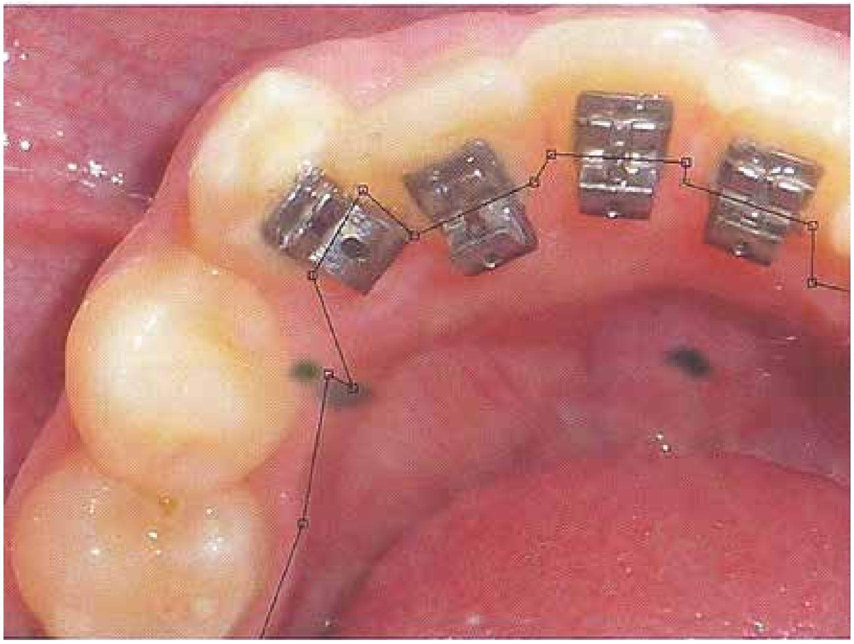


Fig 13-3 *(a and b)* Width difference between canine and premolar. Program tools can be used to make interdental measurements (intermolar width in these images).

Fig 13-4 Archwire designed for bonded brackets, with two green marks made on an occlusal mirror for calibration.



priate adjustments. LAMDA can also be used to accurately measure intercanine and intermolar widths during treatment from either the cast or occlusal photographs (see Fig 13-4). Although interdental distances are more accurately measured from the study casts with a digital caliper, the LAMDA program can be used to monitor changes during treatment and to confirm that an archwire is not too wide or too narrow without taking new impressions at every archwire change.

Data files in the LAMDA system are in .DAT format and contain references to the working photographs and information concerning the calibration distances and the coordinates of the points used to define the archwire shapes. The program can export text files listing all the lengths and angles used to design the archwire, and the user can print out an image of the finished design with the “Print Screen” option. Occlusal photographs should be taken at each appointment so that LAMDA can be used to deter-

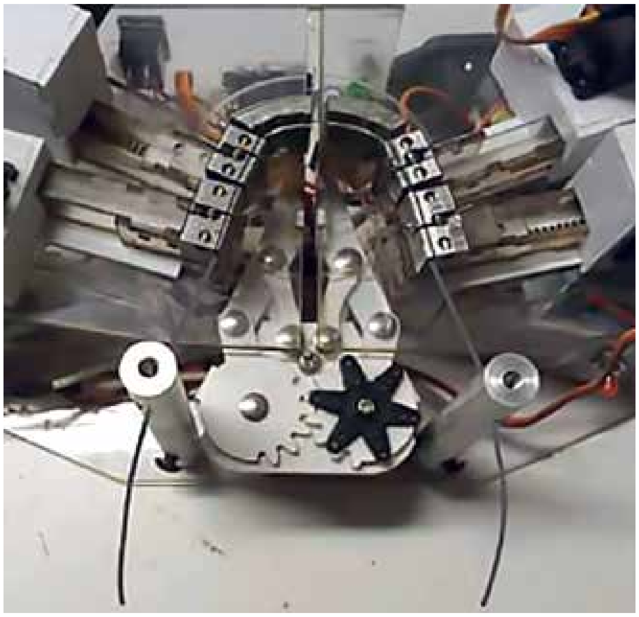


Fig 13-5 Heat-tempering of Ni-Ti archwire.

mine the caliber and design of the next archwire. As a general rule, if the line drawn on the screen does not adapt perfectly to the virtual bracket slots, an increase in wire size is not warranted; more flexible archwire alloy compositions such as titanium-molybdenum alloy (TMA) or memory wires may be advisable instead of stiffer stainless steel archwires.

Gantry robots, like the one used in the LAMDA system, have the ability to move an end effector (the device or tool at the end of a robotic arm) in multiple planes of space with great precision but with limited degrees of freedom. These are also known as "Cartesian coordinate robots" because their axes of control are linear and at right angles to each other. They are often used to span relatively extended workspaces and act on objects with vertical planes of symmetry. Because the LAMDA robot works only on the x and y axes, it is relatively simple, compact, and inexpensive to manufacture.[7,8]

The LAMDA robot has incorporated a heating element that can raise the temperature of a nickel-titanium (Ni-Ti) archwire to 600°F, making it possible to bend the wire without losing its capacity to transform reversibly between the austenitic and martensitic phases[9] (Fig 13-5). The robot manufactures stainless steel archwires in about 5 minutes and Ni-TI archwires in about 6 minutes.

Figure 13-6 shows the use of a lingual appliance in the orthodontic treatment of a female patient who presented with four missing maxillary premolars. The difference in buccolingual thickness between the canines and first molars makes wire bending especially difficult in this kind of case. Using the LAMDA system, this problem is completely eliminated. The task of designing and fabricating appropriate sequential archwires in order to treat the patient efficiently becomes simplified. The treatment duration of this case was 7 months.[10]

To test the fit of lingual archwires produced with the LAMDA system, 15 orthodontic specialists proficient in the lingual orthodontic technique were presented with a single patient's pretreatment plaster cast and occlusal photograph. They were asked to bend one archwire manually and one using the LAMDA system. The participants had no prior training or experience with the LAMDA software or robot. A 16th orthodontist performed a blind evaluation of the 30 archwires, assigning a score between 0 and 10 to each wire based on how well it adapted to the cast. The mean score for the 15 manually bent archwires was 6.9; the mean score for the 15 archwires designed and manufactured with the LAMDA system was 9.0 (Table 13-1).[10]

Successful orthodontic treatment demands careful control of laboratory procedures and attention to patient-specific details, more so when treatment is undertaken with lingual appliances. Designing the archwire over a digital image reduces the possibility of errors caused by mirror angles and off-axis viewing of the arches from within the mouth. The choice of a bracket positioning and transfer system is also particularly important.

In 2017, an advanced version of the LAMDA system was made available, the Lamdabot 2 (Fig 13-7). This version included an increase in the number of motors from 4 to 12. This advancement permits a new configuration of wires, because now all the teeth of the arch can be reached in order to work with the multibend system (Fig 13-8). However, this added capability still had limitations with regard to the placement of vertical or sagittal bends and in instances where anterior tooth torque control during space closure is required.

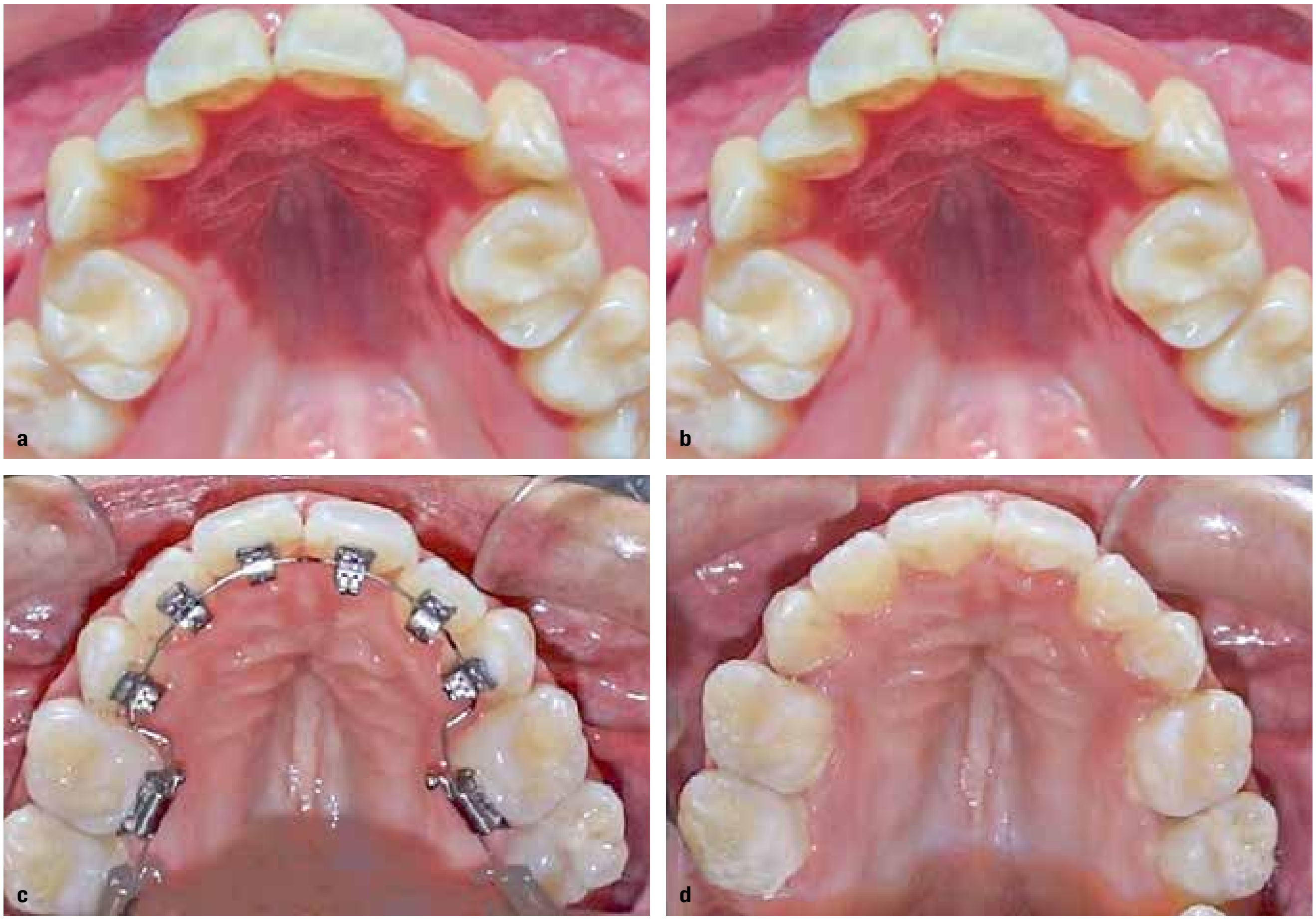


Fig 13-6 *(a)* Patient with four missing maxillary premolars before treatment. *(b)* Design of the lingual archwire. *(c)* Stainless steel wire (0.016 × 0.022 inch) used for finishing. *(d)* Results after 7 months of treatment.

Table 13-1 **Archwire adaptation scores between manually bent and robot-bent archwires**

Orthodontist no.	Manually bent	Robot-bent
1	6	8
2	7	10
3	5	9
4	7	10
5	6	8
6	8	9
7	5	9
8	8	9
9	7	9
10	8	9
11	6	9
12	6	9
13	8	9
14	8	9
15	8	9
Mean	**6.9**	**9.0**

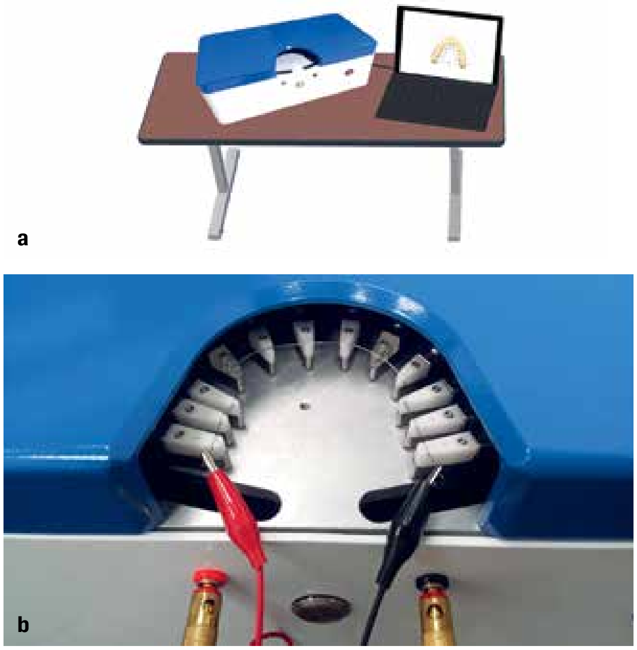


Fig 13-7 *(a)* Lamdabot 2. *(b)* The second-generation LAMDA increased the number of motors from 4 to 12.

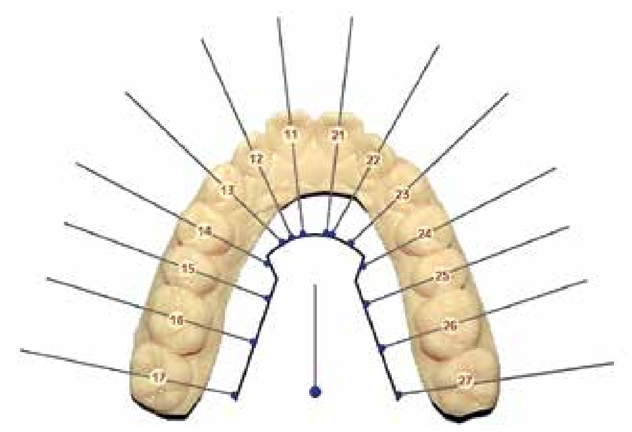


Fig 13-8 Multibend system.

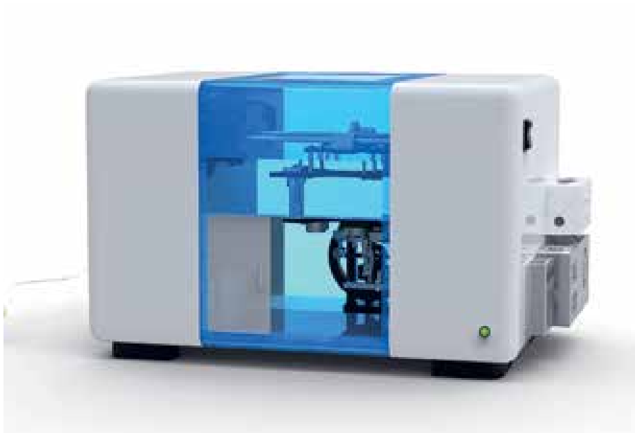


Fig 13-9 Verdopplerbot system.

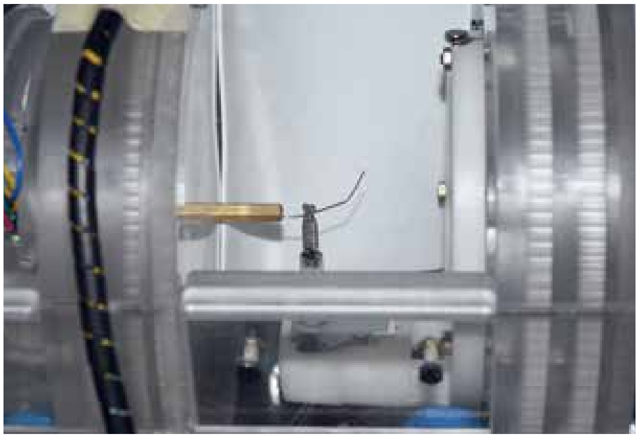


Fig 13-10 Verdopplerbot system wire fixation device.

Verdopplerbot System and Mechanical Movements

To resolve these limitations, in late 2017, the Verdopplerbot system was created (Fig 13-9). This consisted of a lingual orthodontic robot capable of bending arches in all three planes of space. The system consists of a CNC device with movements in the *x*, *y*, and *z* planes. In this way, the appliance can make horizontal and vertical offsets as well as give torque to the archwire (Fig 13-10). This version provides seven degrees of freedom:

- X: Movement on the horizontal axis
- Y: Vertical axis movement
- Z: Movement on the sagittal axis
- E: Wire extrusion movement (helps move wire back and forth)
- D: Compensation thresholds in small spaces
- S: Fixing the cable at the time of bending
- T: Cable twist (torque)

There are three cable attachment points:

1. *Initial position:* Controls the correct extrusion of the wire and has a clamping point when it is necessary to maneuver between the curves and the twisting of the wire.
2. *Torque fixing point*: Concentrated so that the wire can be made mainly when this attachment point is close to the fixed attachment point.
3. *Fixed:* The torque is handled with a maximum of 90 degrees.

With these fixing points as well as the degrees of freedom, we have a wide variety of possibilities to be able to perform the required handling of the wire.

Obtaining Cartesian coordinates increases arch stiffness and allows for individual movements, which are much better controlled. The segments that make up the *x*, *y*, and *z* axes promote near-absolute control of vertical, horizontal, and sagittal movements. These features allow the robot to bend horizontally, vertically, or in any other angle; the torque is applied to the wire through the sliding of two opposing round devices located in the center of the machine. The other round device can rotate from vertical to horizontal and can stop in any intermediate position, thus providing the clinician latitude to make many desired compensations, either vertical, horizontal, or angulated to the wires (Fig 13-11).

The wire must be held fixed during the forming procedures. This is done by a pair of holding screws with the fixation obtained from the motor shaft. The rotation motor allows arch rotation. The third motor functions as a vector at the moment of bending. Figure 13-12 shows a completed wire.

Robot Software

The software controlling the wire-bending robot has a friendly interface and facilitates all robot manipulations. The system allows the handling of three axes (horizontal, vertical, and sagittal), enabling the robot to bend the wires in any of the three dimensions of space.

Force vectorization was calculated for three different alloys: stainless steel, Ni-Ti, and TMA and in five different calibers. With stainless steel, 360-degree bends can be created, although it is not recommended to exceed 180 degrees in order to avoid fracturing the wire. Ni-Ti alloys can be bent horizontally and vertically up to 90 degrees of angulation given that a cycle of heat treatment with the included thermotransformer be applied. For TMA, arch bending up to 360 degrees is available in order to produce closing loops as part of archwire fabrication.

In addition to its use in the design and control of bending information to the robot, the software program includes an agenda to download the data of the patient to the computer. From there, the orthodontist can choose the photographs and start drawing the archwire (Fig 13-13).

Hardware: The Joystick

The hardware includes a joystick for use in accurately making small adjustments to the wire (Fig 13-14). The joystick is activated in a step-by-step format, allowing the orthodontist to perform any type of arch overcorrection. Torque placement is performed using two wireless joysticks that control the coordinated actions of two clamps that simultaneously "hold" and twist the rectangular wire. This information is transmitted to the robot for processing. The joystick utility is for precision handling, especially where detailing is needed, and allows the operator to accurately access all aspects of the periphery of the wire. In this way, the lingual arch can be manufactured in such a way to

Fig 13-11 The round elements bending the wire in the horizontal, vertical, and sagittal dimensions.

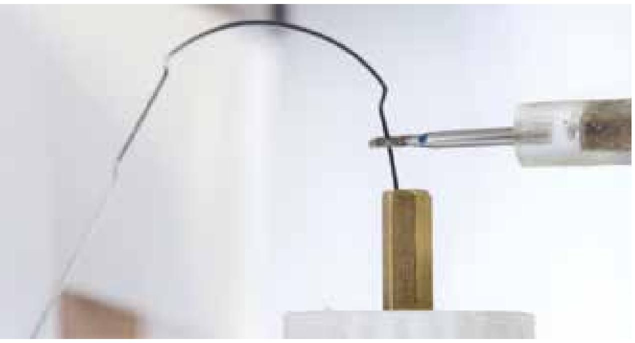


Fig 13-12 Final wire.

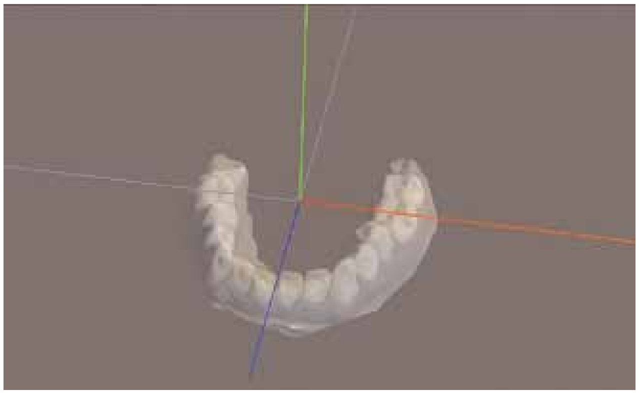


Fig 13-13 Verdopplerbot Driver software.

Fig 13-14 Joystick.

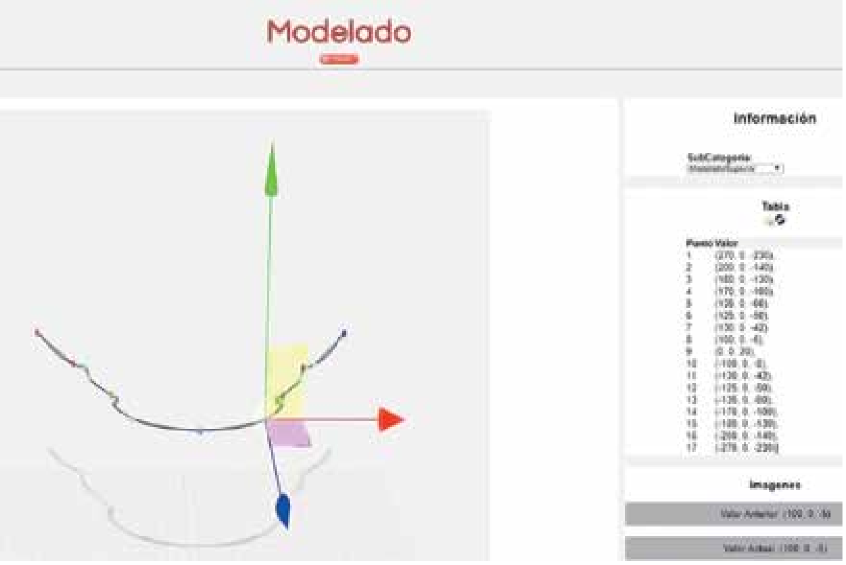


Fig 13-15 Operating system for designing archwires.

Fig 13-16 Smartphone app.

ensure accuracy during planned tooth movement. The use of the joystick also increases the speed of the bending step. When the archwire is completely virtually designed (before being bent), the operator can use the joystick to make some small details in order to reach the more forward points of the dental arc. After doing this, the robot can manufacture the wire.

All aspects of the archwire design are preserved in the program's memory and can be used to design ensuing and sequential archwires. In this way, an artificial intelligence system is implemented within the treatment of each patient.

Application in Clinical Practice

The implementation of new in-house robotic devices in wire manipulation has application in both lingual and labial orthodontic techniques. This is especially true if a patient-specific treatment modality is desired or where manually producing archwires becomes highly inaccurate. Where the clinician directly designs these archwires (Fig 13-15), the time spent waiting for outsourced production, as well as the fees required for these services, are avoided. The time required to make a rectangular arch with offsets and torque is 6 minutes; the margin of error is negligible, and the waste of material is almost nonexistent. In round wires, when there is no need to add torque, the processing time is reduced to 3.5 minutes.

The use of the functional prototype of the Verdopplerbot system has been proven to accomplish its functions in a highly accurate manner, as based on an investigation that has been submitted for publication. It was reported that archwires designed and formed in this manner for patients undergoing extraction-based orthodontic treatment modalities were produced in a time-efficient manner with less material waste and highly accurate first-, second-, and third-order detail bending. The system has proven to be efficient, fast, and accurate, with the versatility making it capable of being able to make the arches immediately even from a smartphone platform (Fig 13-16). The precision that the entire digital protocol gives to the manufacturing of the archwires represents an improvement over previous working conditions.

Conclusion

It is evident that 3D technology, engineering, orthodontics, and artificial intelligence can be integrated to improve patient care in both lingual and labial techniques in order to effect a more accurate treatment outcome. This is especially true in the lingual technique, where accurate wire bending is difficult to perform manually. The availability of an in-house wire-bending robot is an invaluable adjunct to efficiently form the archwires designed by the clinician to more predictably move the teeth into their proper positions. Digital technology will continue to have an undeniable and irretractable place in all aspects of medical treatment, including orthodontics. It will advance the orthodontic profession and continue to provide better tools to diagnose and provide treatment with increasing predictability and accuracy to benefit our patients.

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14

Artificial Intelligence and Machine Learning in Orthodontics

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Cristina Grippaudo
Silvia Allegrini
Ambrosina Michelotti

Artificial intelligence (AI) is the ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings. The term is frequently applied to types of systems endowed with the intellectual processes characteristic of humans, such as the ability to reason, have a visual perception, discover meaning, generalize, or learn from past experience. Thus, AI itself is a general term that describes computers mimicking human intelligence and computer systems able to perform tasks normally requiring human intelligence.

Machine Learning

"Machine learning" (ML) is a subset of AI (see Fig 14-1) and was originally described as a program that learns to perform a task or makes a decision automatically from data rather than having the behavior explicitly programmed. ML is characterized by mathematical and statistical techniques enabling machines to improve their abilities by experience. ML methods are categorized on the basis of algorithms and models used.[1] The types of ML algorithms differ in their approach, the type of data utilized, their input and output, and the type of task or problem that they are intended to solve. Methodologic approaches to learning include supervised, unsupervised, semisupervised, reinforcement, and self-learning. Based on the task to be learned, machine algorithms may be concerned with problems such as classification, prediction, feature learning, sparse dictionary learning, anomaly detection, and association rule learning.

Performing ML involves creating a model, which is based on associated training data, that can then process additional data to make predictions. Various types of models have been used and researched for machine learning systems, including artificial neural networks (ANNs), decision trees, support vector machines (SVMs), regression analysis, Bayesian networks, and genetic algorithms (GAs). However, the two main types of ML methods that are currently used in health care are supervised and unsupervised learning.

In supervised learning, the machine is trained using data for which ground truth is available and it is well "labeled." It means that some data is already tagged with the correct answer. Supervised learning is typically used in the context of classification. Unsupervised learning, on the other hand, does not make use of label outputs; it is an ML technique where a model does not need to be supervised. Instead, the model is allowed to work on its own to discover information by detecting inherent structure or regularities in the data. It deals with unlabeled data, and it is commonly used for tasks such as clustering or categorization.

Diagnosis and outcome prediction are two areas that may particularly benefit from the application of ML techniques in the fields of medicine.[1] This includes a possibility for the identification of high-risk medical emergencies such as relapse or transition into another disease state. ML algorithms have recently been successfully employed to classify skin cancer using images with comparable accuracy to a trained dermatologist and to predict the progression from

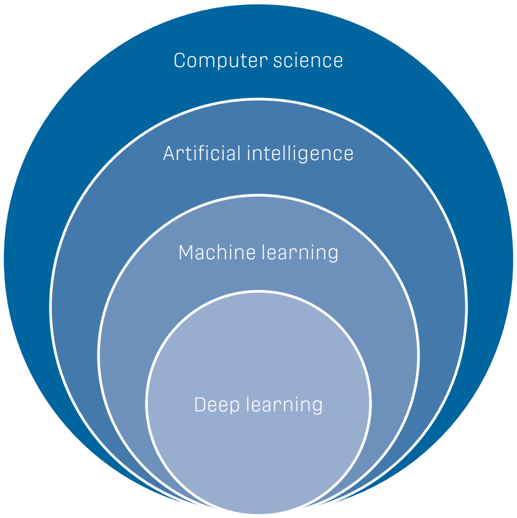

Fig 14-1 AI and its subsets.

prediabetes to type 2 diabetes using routinely collected electronic health record data.[1]

Deep learning is a subcategory of ML, even though *artificial intelligence*, *machine learning*, and *deep learning* are three terms often used interchangeably to describe software that behaves intelligently. However, it is useful to understand the key distinctions among them. You can think of deep learning, ML, and AI as a set of Russian dolls nested within each other, beginning with the smallest and working outward. Deep learning is a subset of ML, and ML is a subset of AI, which is an umbrella term for any computer program that does something smart (Fig 14-1).

ML and deep learning are both responsible for the recent breakthroughs in computer vision technology. This is one of the most powerful and compelling types of AI that everyone has almost surely experienced in any number of ways without even realizing it. Computer vision focuses on replicating parts of the complex human visual system and enabling computers to identify and process objects as images and videos. Typical computer vision tasks include image classification, segmentation of areas of interest, and object detection and recognition. Until recently, computer vision only functioned with a limited capacity. Thanks to advances in AI and especially innovations in deep learning that have reshaped the architectures of classical ANNs, the field has been able to take great leaps in recent years and has been able to surpass humans in some tasks related to detecting and labeling objects. One of the factors behind the growth of computer vision is the amount of data that can be generated that is then used to train and make computer vision better, allowing models to use thousands of predictor variables.[2] Expert system (ES) is another important branch of the field of AI. ES is a computer program system that simulates the judgment and behavior of a human or an organization that has expert knowledge and experience in a particular field. It imitates the decision-making and working processes of experts and solves actual problems in the field of a single specialty.[3] Traditionally, ESs have adopted methods for explicitly representing knowledge, for example, by means of a set of rules or by formal ontologies. An advantage of ESs is that the reasoning behind a decision can be explained, whereas decisions made by ANNs cannot be easily explained. This difference has led to an emerging field of research concerned to interpret this divergence, but the power and flexibility of ANNs has put them at the core of both computer vision and recent ES applications. In an ANN, a variety of artificial neurons are connected to each other, forming a net, which is organized in layers. Between the first (input) and the last (output) layer, there are a certain number of (at least one) so-called "hidden layers" that are responsible for decision-making of the AI.[4,5] The ANN is a computational or mathematical model whose purpose is to mirror the biologic signal processing of the cerebrum with its mesh of interconnected neurons. An understanding of biologic neural networks allows for the construction of an ANN that can help construct models of complex relationships or establish patterns within a group of data points. The ANN can process nonlinear relationships and can exhibit learning ability. ANN ESs may be trained with clinical data only and therefore can be used in cases where "rule-based" decision-making is not possible. This is the case in many clinical situations. ANNs therefore may become important decision-making tools within dentistry.[3]

The four areas that may benefit from the application of AI and ML techniques in medical fields are diagnosis and treatment planning, personalized treatment, clinical trial research, and smart electronic health records. The aim of this chapter is to provide a breakdown of several of the pioneering applications of AI in orthodontics for continued innovation.

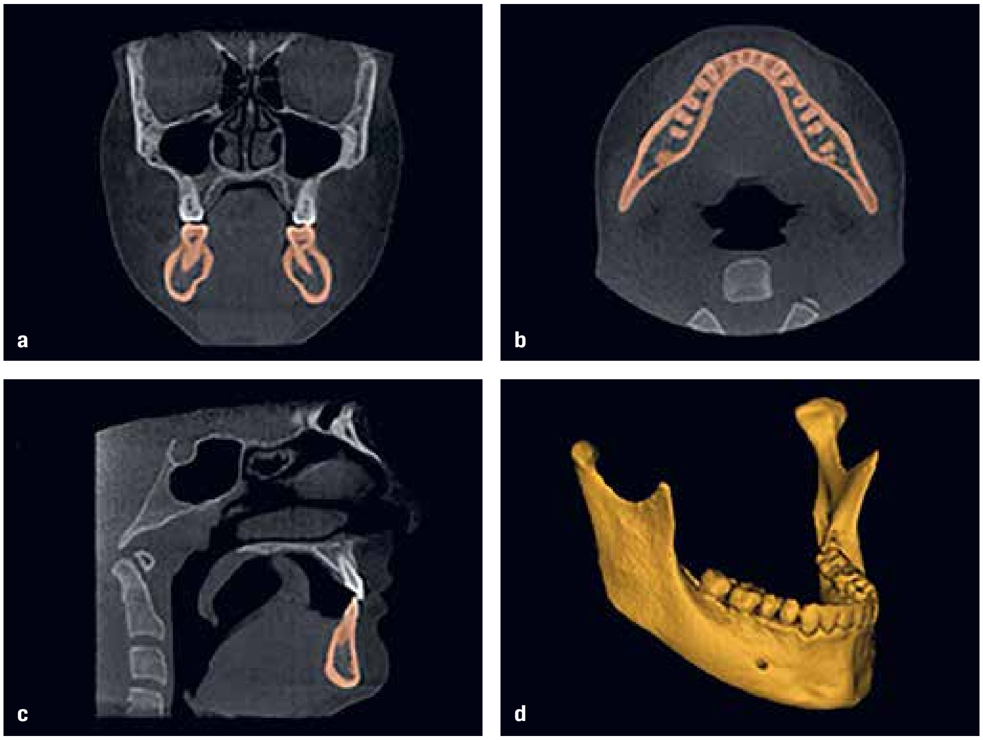

Fig 14-2 *(a to d)* Manual segmentation of the mandible and 3D rendering.

Diagnosis and Treatment Planning

The most important part of any orthodontic treatment is to determine the proper treatment plan.[6] AI in health care can automate the manual work and speed up the process of diagnosis, treatment planning treatment outcomes, and predicting the growth pattern.[7] In this respect, AI is particularly helpful in areas where the diagnostic information a doctor examines is already digitized.

Advances and increased affordability regarding digital data have catalyzed an increased demand within the orthodontic profession to automate procedures such as cephalometric analysis and several diagnostic tasks that were once carried out manually by the clinician, including segmentation of automatic structure from CBCT images and decision-making regarding premolar extraction. Several attempts to automate the process of cephalometric analysis have been carried out.[8] These have been developed using both 2D images (lateral cephalometric radiograph) and 3D images (CBCT). The practical aims of automating these measures are to reduce the time required to obtain such an analysis, improve the accuracy of landmark identification, and reduce any error due to clinician subjectivity.[9–11] For the past two decades, automatic identification of landmarks has been developing using multiple methods that involve computer vision, AI, and deep learning techniques. This evolving capability has also produced an increasing reliability and accuracy of landmark identification, which has been a point of contention from the outset of the manually performed cephalometric analysis. Presently, trained AI algorithms are capable of analyzing new cephalometric radiographs in a fraction of a second with comparable precision to experienced human examiners, the latter still deemed as the gold standard.

Recently, ML and deep learning techniques have been applied also for fully automatic segmentation of maxillary and mandibular bones and upper airway from CBCT images and for skeletal bone age assessment.[12] In 3D medical imaging, *segmentation* is defined as the construction of 3D virtual surface models to match the volumetric data.[13] In other words, this is describing a method of separating out a specific element (eg, the maxilla, the mandible, and the upper airway) in such a way as to “remove” other structures not of interest for better visualization and analysis. This allows the evaluation of the size, shape, and volume of the anatomical structure already segmented (Fig 14-2).

Manual segmentation currently seems to be the method with the greatest accuracy. This procedure entails that the segmentation be performed slice by slice by the user,

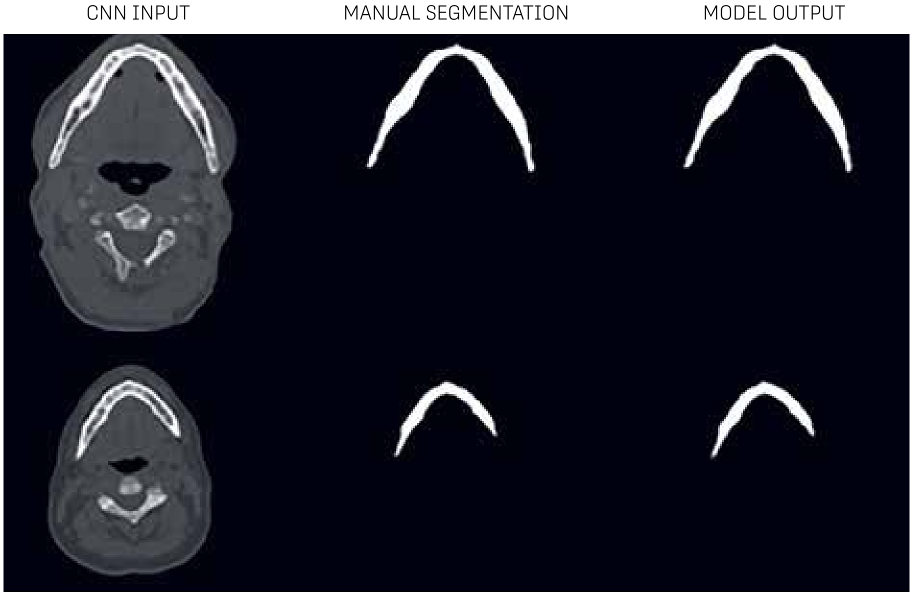

Fig 14-3 Manual segmentation of the mandible versus fully automatic segmentation. The two models perfectly overlap.

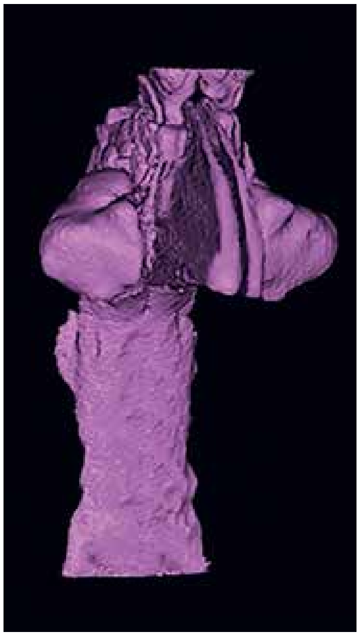

Fig 14-4 Fully automatic segmentation of the sinonasal cavity and pharyngeal airway based on CNNs.

after which the software then combines all slices to form a 3D volume.[13] Given that multiple slices are included in every scan, it should be understood that this method is very time-consuming; therefore, the obvious utility for fully automated systems to segment any structure from CBCT images would have immediate practical application. Currently, AI deep learning has shown very promising results in performing this task. Specifically, convolutional neural networks (CNNs) learning task-specific features directly from data have led to a series of breakthroughs in CBCT segmentation, which have been shown to be superior to previous methods employing general handcrafted features.[14,15] Practically, with automatic segmentation, the clinician does not need to select boundaries or threshold values or trace any anatomical structures because these steps are carried out automatically by the software; the clinician needs only to upload the DICOM file. Figures 14-3 and 14-4 show two examples of automatic segmentation of the sinonasal cavity/pharyngeal airway and mandible based on CNNs.

Specifically, for orthodontic treatment planning, decision-making ESs, based on ANNs, have been designed. These ESs not only can assist less-experienced orthodontists and students in learning but also can help patients to obtain a clearer understanding of their treatment plan. ESs have already been applied to aid in determining whether extractions are necessary as part of orthodontic treatment.[3,6] The operator-agreement rates obtained by these ESs have been found to range from 80% to 93% for the diagnosis of extraction vs nonextraction.[6]

As far as treatment outcomes are concerned, AI has also been applied in the prediction of soft tissue treatment outcomes. For example, ANNs have been used to forecast the change in lip curvature after orthodontic treatment with or without extractions and treatment outcomes of Class II and Class III malocclusions. Using ANNs, predictive models were developed to predict the posttreatment peer assessment rating (PAR) index in Class II patients based on their pretreatment PAR index.[16] In addition, AI has been applied to the classification of growth patterns with a reported agreement rate of 64% in classifying favorable or unfavorable growers based on changes of their sagittal relationships.[17]

Personalized Treatment and Big Data

Medicine is undergoing a revolution that will transform the practice of health care in virtually every way. This revolution is emerging from the convergence of systems biology—a holistic approach to biology (and medicine)—and the digital revolution with its ability to generate and analyze "big data" sets.[18] The convergence of the digital revolution and systems approaches to wellness and disease has redirected the path of modern medicine from a reactive disease care model to a path that elucidates each individual's unique health and disease status at the molecular, cellular, and organ levels. This information can potentially make disease care more cost-effective by personalizing care to each person's unique biology and by treating the causes rather than the symptoms of disease in a proactive manner referred to as P4 (predictive, preventive, personalized, and participatory) medicine.[18] P4 medicine will be more effective treatment because it is based on individual health data paired with predictive analytics and is closely related to better disease assessment through a process of tailoring medical treatment to the individual characteristics of a given patient.[19]

P4 medicine differs strikingly from current evidence-based medicine in several regards.[20] Namely, P4 medicine provides medical recommendations before a patient becomes sick (presymptomatic markers), as opposed to evidence-based medicine, which responds only after a patient has become symptomatic or ill (symptom-based). In addition, P4 is based on massive amounts of data that are deeply integrated and can be mined for continued improvement of health care strategies, whereas evidence-based medicine relies only on a relatively small number of measurements that are not highly linked.

The need for a more personalized treatment applying a P4 approach has also been raised in orthodontics. This was stated in the proceedings of the Consortium for Orthodontic Advances in Science and Technology (COAST) symposia. This meeting provided a series of highly interactive workshops on the topic of Personalized and Precision Orthodontic Therapy.[21–23] A fundamental component of personalized treatment is the existence and use of *big data*, which has been popularly defined as data that is of a volume/size that challenges your current computational workflow, thus limiting your ability to perform analysis and/or interpret results.[19] Previously this term was described according to the four V's: volume (storage capacity needed to manage the data), velocity (the rate/speed at which data is received), variety, and veracity.[19] Volume is the primary challenge in amassing big data, and velocity entails the complementary nature required for measuring systems to submit recorded data to centralized storage. The concept of big data goes far beyond the data type and includes the aspects of data analysis, such as hypothesis-generating rather than hypothesis-testing.[24]

The potential value of medical big data has been demonstrated in *(1)* the delivery of personalized medicine; *(2)* the use of clinical decision support systems such as automated analysis of medical images and the mining of medical literature; and *(3)* the tailoring of diagnostic and treatment decisions and educational messages to support desired patient behaviors using mobile devices.[24] Regardless of its potential, it is essential to understand that data alone is useless. In order to extract any clinically significant information or treatment implications, data must be analyzed, interpreted, and acted on. It must also be understood that the complexity of doing so requires new architecture, techniques, algorithms, and analytics to manage harvested data and extract value and hidden knowledge from it.[24]

The field of data mining, sometimes called *knowledge discovery from databases*, advanced data analysis, and *machine learning* addresses the question of how best to use the massive amount of historical data in order to discover general regularities and improve the process of making decisions. Data mining has already produced practical applications in the area of analyzing medical outcomes. It has also led to a set of fascinating scientific questions about how computers might automatically support the process of scientific discovery.

Clinical Trial Research

AI and ML have several useful potential applications in helping shape and direct clinical trial research. Applying advanced predictive analytics in identifying candidates for clinical trials could draw on a much wider range of data

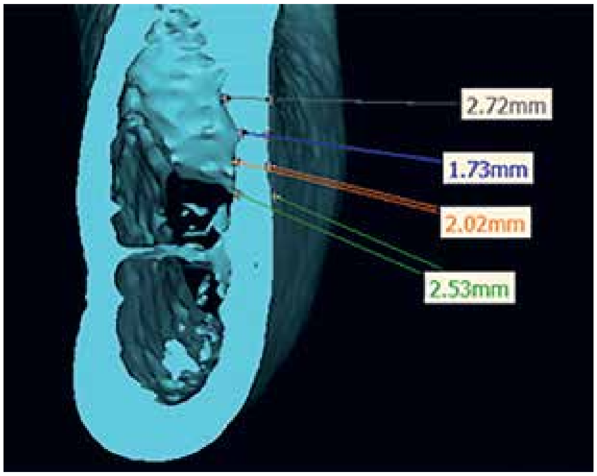

Fig 14-5 Evaluation of cortical bone thickness for miniscrew placement.

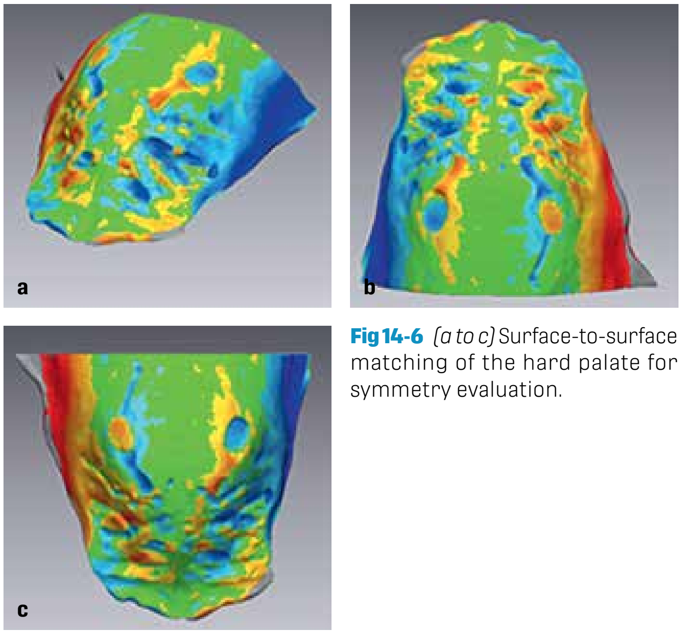

Fig 14-6 *(a to c)* Surface-to-surface matching of the hard palate for symmetry evaluation.

than at present. These could include social media and doctor visits as well as genetic information when looking to target specific populations. Inclusion of these data sources could result in smaller, quicker, and less expensive trials overall.

Digital Technology, Smart Electronic Health Records, and Teleorthodontics

There is no doubt that we are witnessing a digital transformation in orthodontics. The influence on our specialty by the inclusion of these technologic tools has been evident. Today, these allow us to easily obtain all the information necessary to diagnose, design, and perform even complex therapies in a simpler, more reproducible, and, in many cases, less expensive way. Perhaps the most perceptible influence these tools provide is that of the predictability of the treatment outcomes. This is an increasingly precise way for both the clinician and patient to visualize the expected result. For the former, this allows for pretreatment outcome assessment and a careful analysis of each therapeutic path. For the latter, it satisfies the question as to how the teeth will look after treatment, which facilitates improved communication between the doctor and patient. The combined effect of utilizing digital technologies in this manner allows a more simplified relationship with the patient, to whom the treatment plan and the results achievable through the different options can be clearly illustrated. Digital technology has dramatically and will continue to change the nature of clinical practice and orthodontic education.

Recent innovations in orthodontics include CBCT and 3D visualization, intraoral scanners, facial scanners, instant teeth modeling software capabilities, and new appliance developments using robotics and 3D printing. 3D printing is one of the fastest-growing digital technologies and allows orthodontists to develop and produce their own appliances (customized brackets, orthopedic appliances, and clear aligners) with nearly limitless potential applications. In addition, currently there are several software programs that can assist orthodontic clinical practice (Figs 14-5 and 14-6), and it is assured that more will be developed. It needs to be understood that presently almost none of these are AI-based—yet.

In addition to the above, there has been an increased use of microbiosensors and devices, as well as mobile apps with more sophisticated health-measurement and remote-monitoring capabilities. These types of technologies will undoubtedly provide a deluge of data that might influence diagnostic considerations and treatment efficacy. Sensor technology can also be integrated in monitoring patient compliance, which has always been a challenge in orthodontics, and a step forward in personalized medicine regarding optimizing tooth movements and bone remolding. Sensors can be integrated into brackets in fixed orthodontic appliances or into clear aligners. The development of next-generation intelligent electronic health records will most certainly incorporate built-in ML/AI to help with things like diagnostics, clinical decisions, and the fine-tuning of treatment to suit the individual patient.

Teleorthodontics is a broad term that encompasses the provision of orthodontic care, advice, or treatment through the medium of information technology remotely, rather than direct personal contact.[25] It is the automated (with AI) extension of teledentistry, which has been used in orthodontics since the 1990s. This capacity can be used for remote dental consultation, treatment planning and monitoring, appliance fabrication, or on-site job training. Recently, teleorthodontics including AI has been used for remote treatment monitoring of clear aligners. This system consists of three integrated platforms: a mobile app for the patient, a patented movement-tracking algorithm, and a web-based doctor dashboard where the orthodontist receives updates on the patient's progress. This system is able to detect nontracking aligners as opposed to fixed aligner changes. Accordingly, the patient receives weekly "GO" or "NO-GO" notification from the mobile phone app indicating whether they should move to the next aligner or continue to use the current one.

Conclusion

AI is already part of our everyday lives, and it is impacting our choices in one way or another. It is present whether we are using our smartphones, surfing the Internet, buying products online, using navigation, or listening to songs on our favorite music streaming service.

AI-driven software now regularly outperforms humans in key diagnostic tasks. For example, in medicine AI is beginning to simplify the lives of patients, doctors, and hospital administrators by performing tasks faster, with fewer errors, and at a fraction of the cost than those analogously performed by humans.

It can be anticipated that soon AI will allow clinicians to perform at higher levels than possible when unaided by synthesizing complex data that in the past might have required a multidisciplinary team.[26] Despite the recognized demand for clinical decision support systems (CDSS), the delay of their development and adoption might be due to the lack of formal evaluation of the systems, challenges in programming development, cost, and skepticism about the value and feasibility of CDSS.[27] On the other hand, it is important to note that these new algorithmic decision-making tools come with no guarantees of fairness, equitability, or even veracity. Whether an algorithm is high or low on the ML spectrum, best analytic practices must be used to ensure that the end result is robust and valid. This is especially true in health care because these algorithms have the potential to affect the lives of millions of patients.[28]

So what is to become of orthodontics in this time of AI? It is fair to state that the trajectory of our specialty is going to continue to change. The practice of orthodontics will never disappear, but our role in it as clinicians hinges on what we do next.[26] The individual clinician needs to be intimately aware and to adapt clinical education to the digital world.[26] It is not inconceivable that in the foreseeable future, at least for simple clinical cases, the clinical decision-making will no longer be driven by appliances but by AI. This scenario will require all fields of medicine to confront and resolve multiple problems such as licensure, liability, patient confidentiality, and unmonitored do-it-yourself orthodontic treatment platforms.

Furthermore, challenges such as methodologic issues, including legal and ethical issues, and clinical integration and utility issues must be overcome to realize the promise of AI and ML in orthodontics. In addition, like many advances within society that have occurred in the past, the development and reliance on evolving digital technologies is a double-edged sword: It will provide the trained practitioner practical tools to improve patient care, but it may also be accessed by patients to bypass the invaluable contribution made by an expert in order to enact a solely AI-derived treatment plan. Media outlets have already reported on the availability of straight-to-consumer treatments, including highlighting the not-infrequent severe damage these have caused multiple unwitting patients.[29] Thus, there is a case to be made that AI and ML should be governed by relevant experts, such as orthodontists, and avoid transfer of all decision-making to AI for the sake of our patients.

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ISBN 978-1-64724-051-6
90000>
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