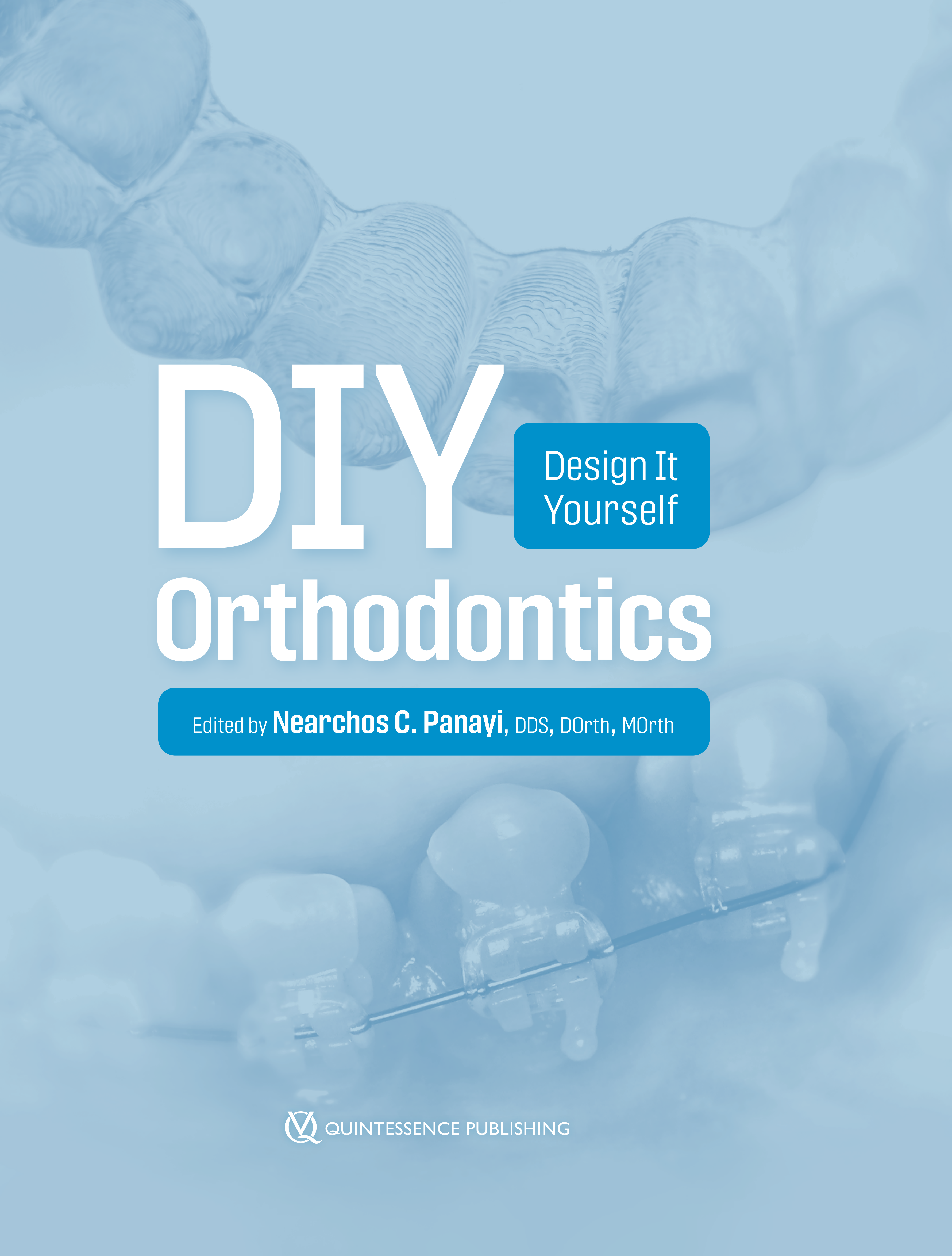

DIY Orthodontics

Design It Yourself

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

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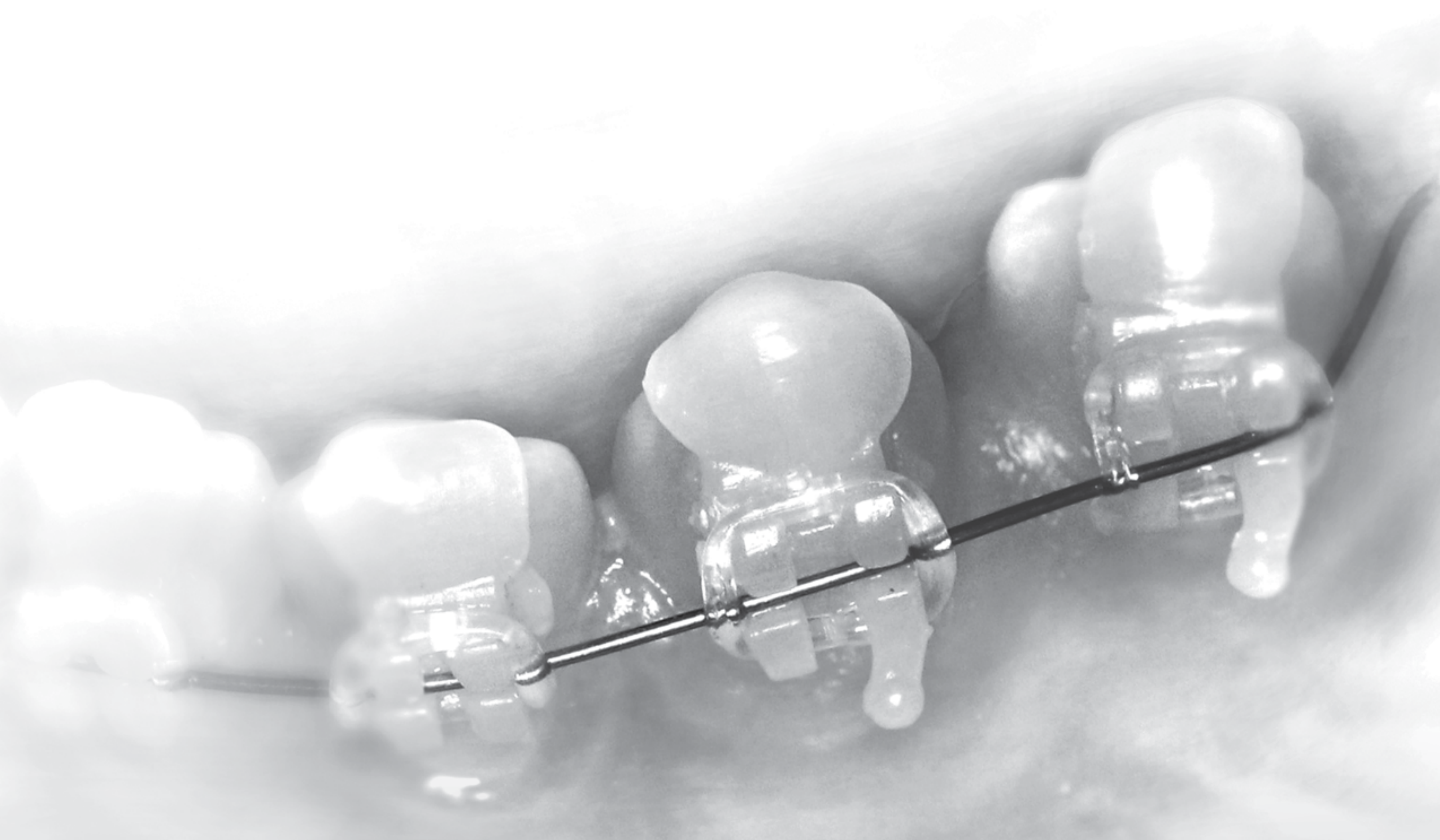
Beijing | Istanbul | Sao Paulo | Zagreb

Contents



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.

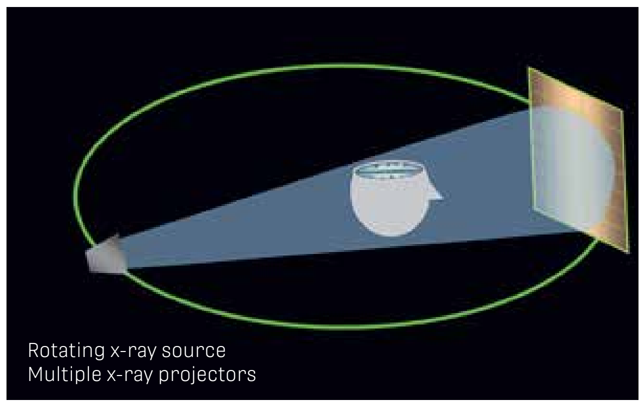

Fig 2-1 A rotating x-ray source, a flat panel detector, and a conical beam are the key components of the CBCT image acquisition process. The x-ray tube completes a full rotation around the patient's head, producing multiple exposures.

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

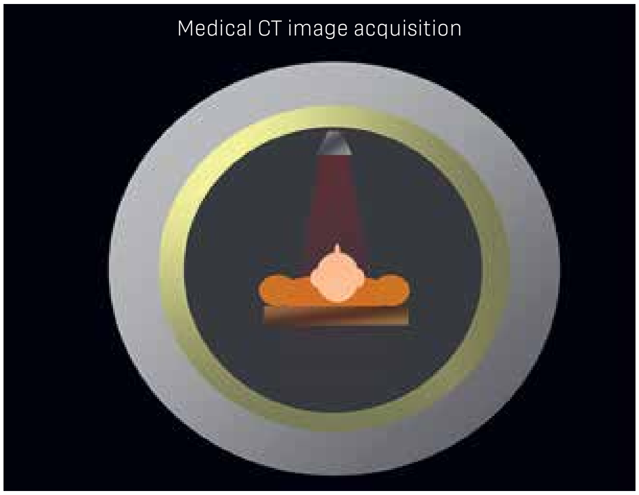

Fig 2-2 Medical CT image acquisition involves a thin fan-shaped rotating beam, a ringlike array of detectors *(yellow ring)*, and a supine patient. The x-ray source scans the area of interest with multiple rotations, collecting x-ray attenuation data.

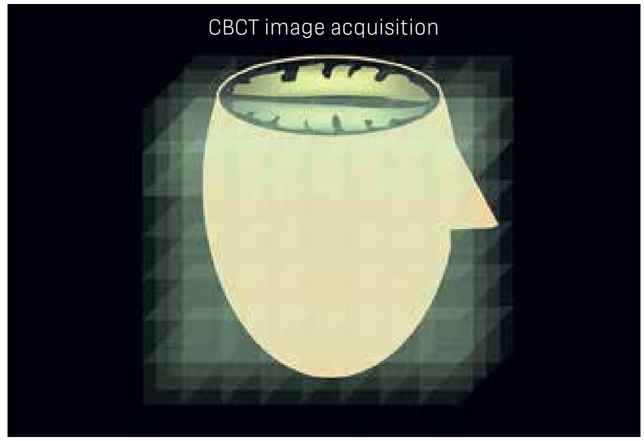

Fig 2-3 The moment a region of interest is determined, this area is "split" in numerous small fictional cubes from which the detector of the scanner will collect attenuation data; these cubes, known as *voxels*, are of a known spatial location and are assigned a shade of gray after the data are processed.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

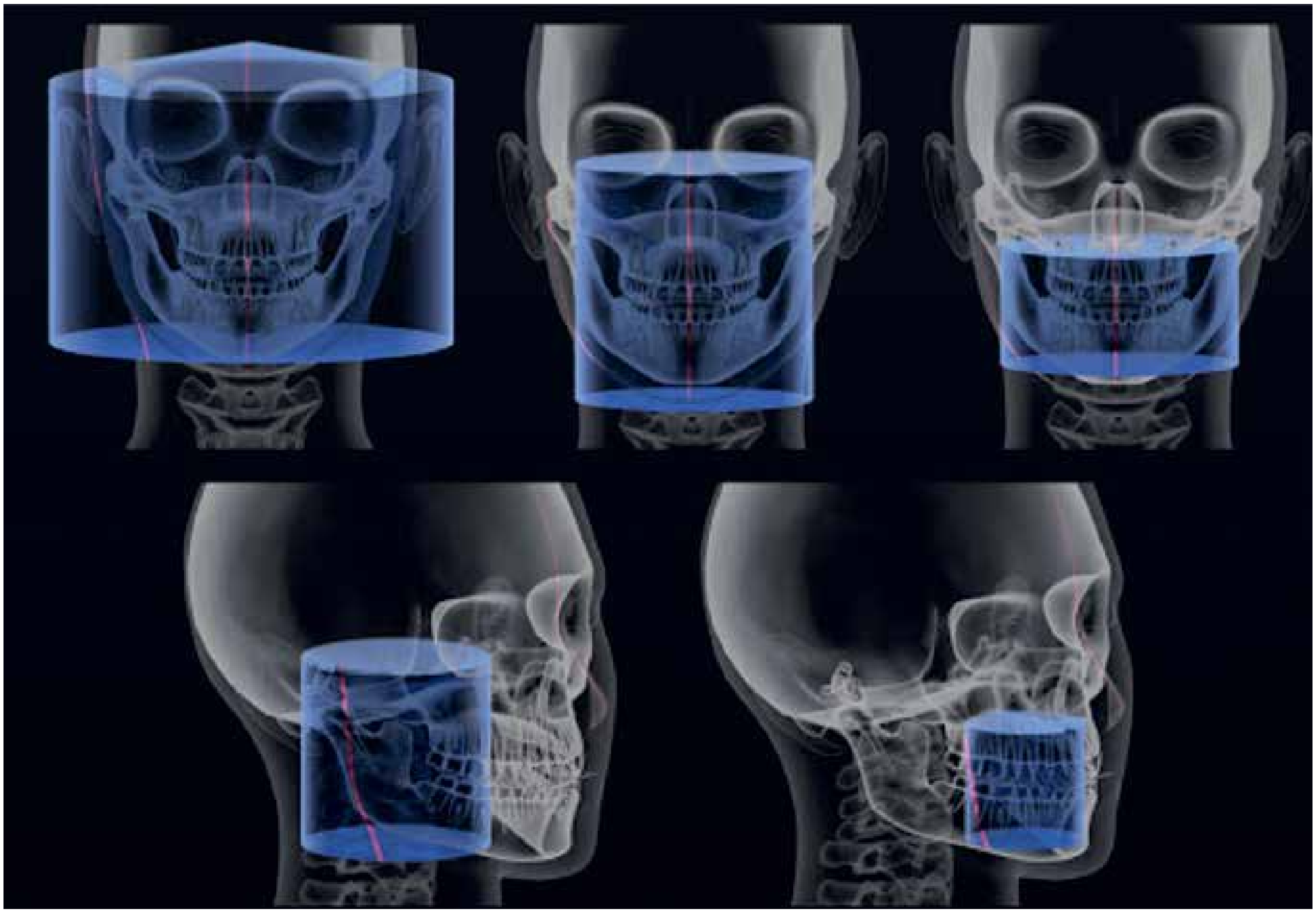

Fig 2-4 There are a variety of available FOVs in modern CBCT machines; these range from very small (40 × 40 mm) to very large to include almost the entire head of the patient (230 × 230 mm).

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.

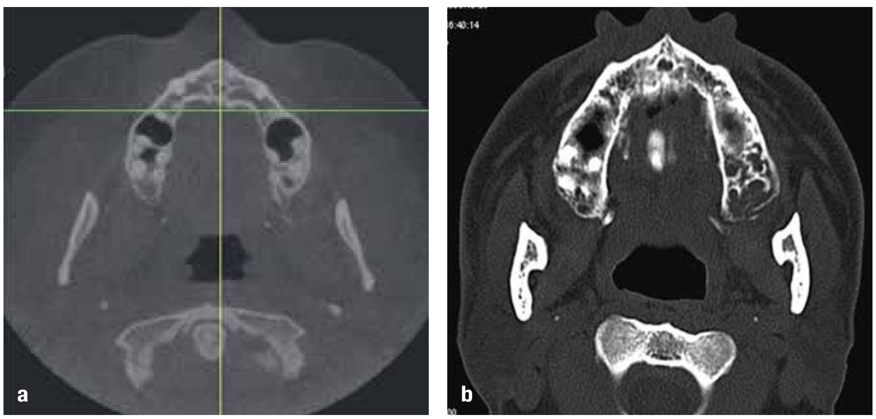

Fig 2-6 *(a)* A CBCT axial section at the level of the maxilla compared to *(b)* a medical CT axial section at the same level. Note the difference in the soft tissue contrast (much higher in the medical CT scan) because of the higher contrast resolution (many more shades of gray).

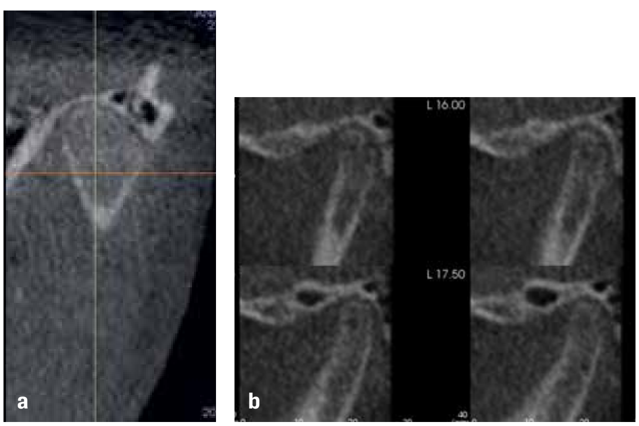

Fig 2-7 *(a)* Coronal CBCT section and *(b)* a series of sagittal CBCT sections of the left temporomandibular joint (TMJ) in a young patient. Note the diffuse "graininess" seen in all images; this is attributed to the noise in the scan (ie, the heterogeneous distribution of the x-rays onto the detector).

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

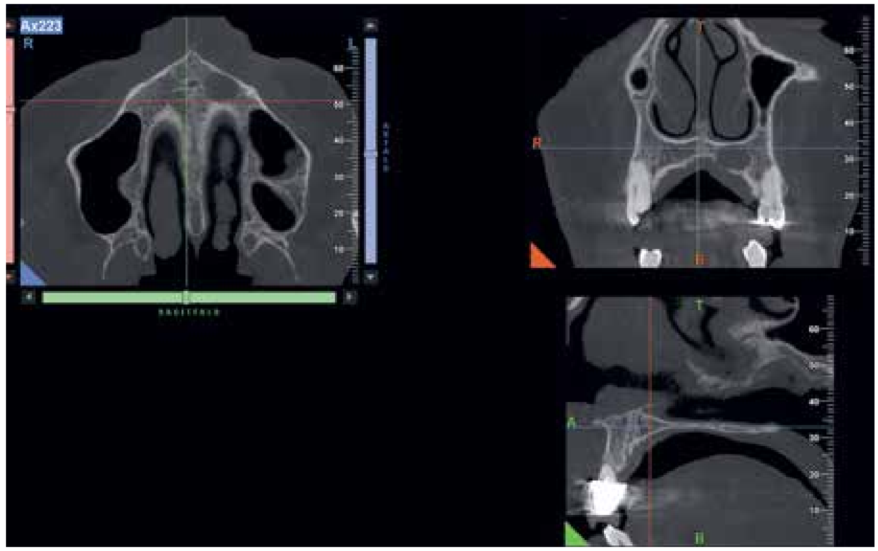

Fig 2-8 Standard multiplanar view of a CBCT volume of the maxilla with *(clockwise from left)* axial, coronal, and sagittal sections.

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.

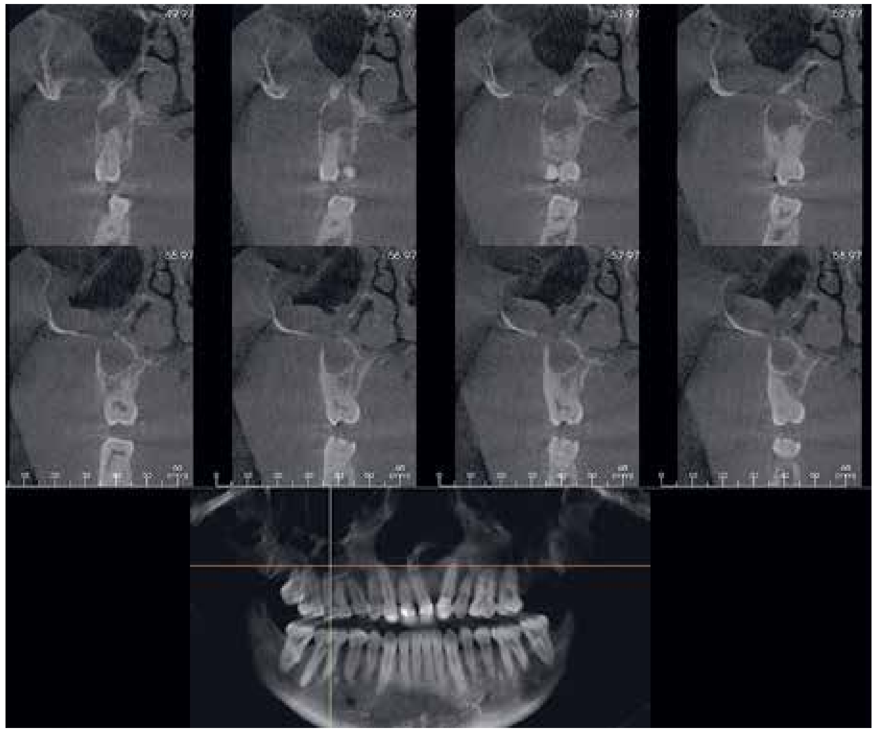

Fig 2-10 A CBCT panoramic reconstruction *(bottom)* and a series of cross-sectional images *(top)* of the maxilla for the assessment of postsurgical changes in the midface after orthognathic surgery (LeFort 1 osteotomy).

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).

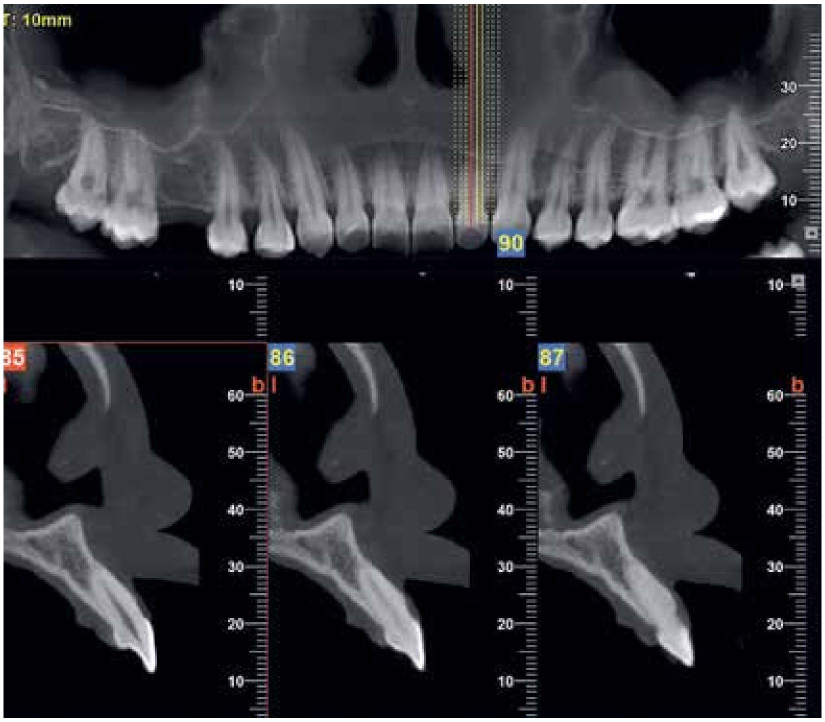

Fig 2-11 A CBCT panoramic reconstruction *(top)* and a series of cross-sectional images *(bottom)* of the anterior maxilla for the assessment of the integrity of the cortical plates and incisor root position inside the alveolar ridge.

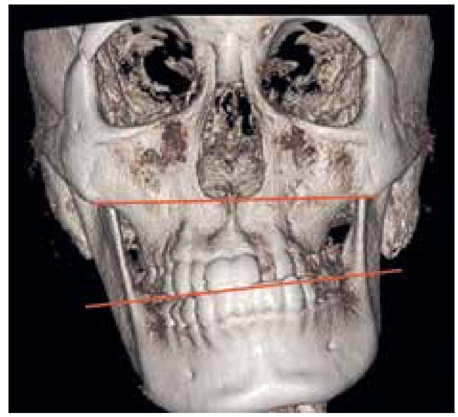

Fig 2-12 A CBCT 3D reconstruction illustrating a marked asymmetry between the right and left mandible due to hemimandibular hyperplasia (right side); note the deviated mandibular midline to the left.

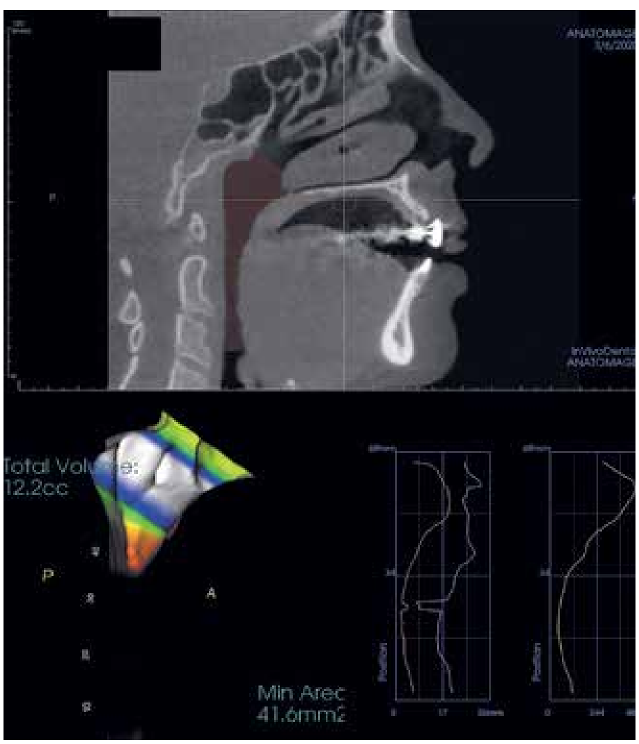

Fig 2-13 A CBCT midsagittal section with the airway highlighted *(red)*; this is a special software application that provides volumetric measurements of the airway *(bottom)*, a crucial tool in airway analysis.

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)

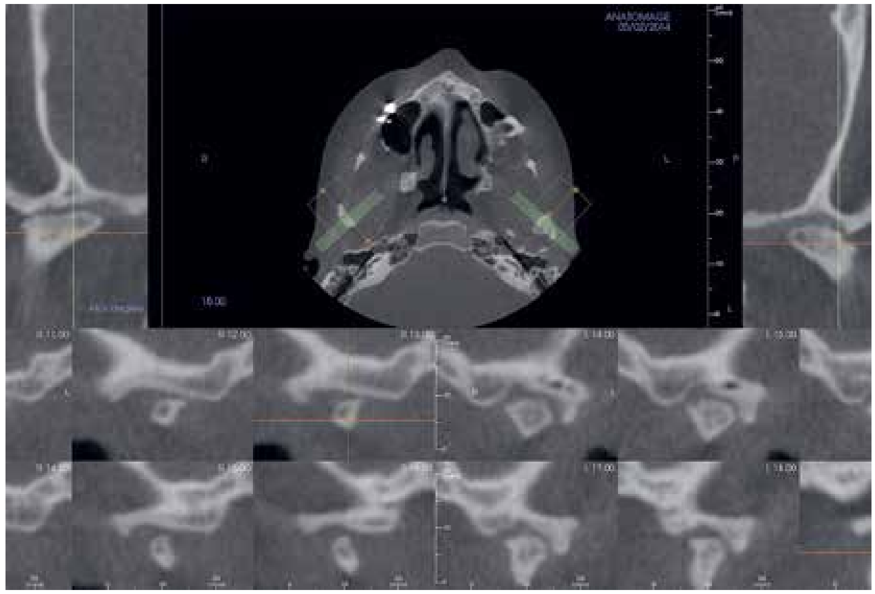

Fig 2-14 Coronal section *(top)* and a series of sagittal cross sections *(bottom)* of the right and left TMJs acquired for the periodic evaluation of the TMJ after extensive orthognathic surgery; note the marked degenerative changes in both TMJs.

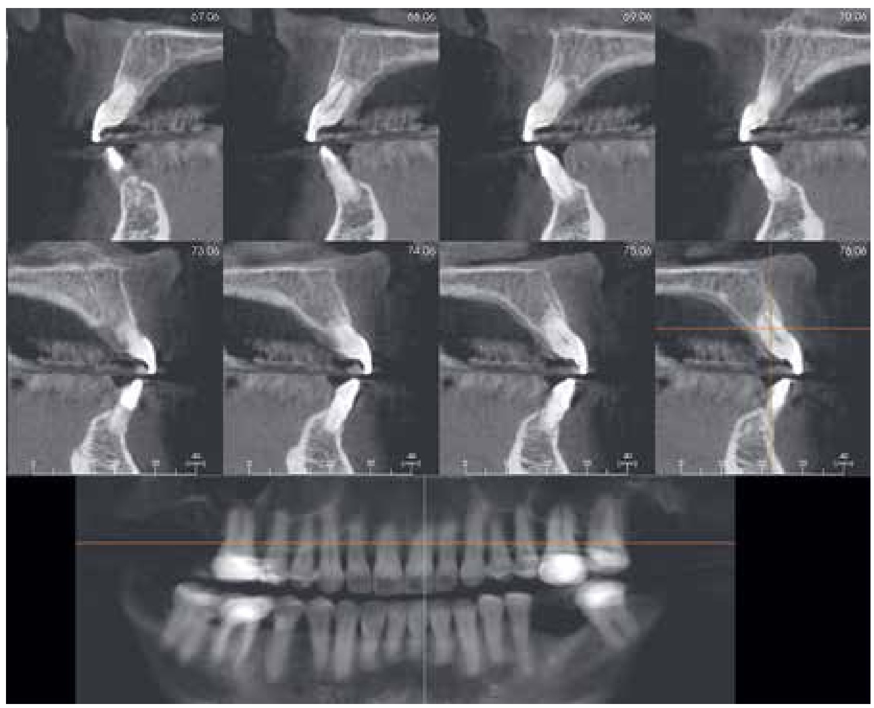

Fig 2-15 A CBCT panoramic reconstruction *(bottom)* and a series of cross-sectional images *(top)* of the maxilla and mandible showing extensive root resorption on the maxillary and mandibular incisors after orthodontic treatment.

- 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.

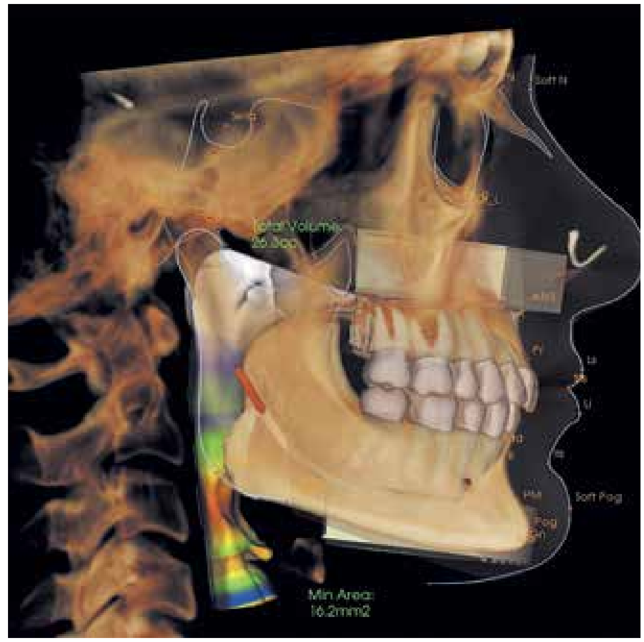

Fig 2-17 3D volume rendering of the skull, airway, and soft tissue outline with major anatomical landmarks identified; this is an application of contemporary software (courtesy of Anatomage Inc).

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.

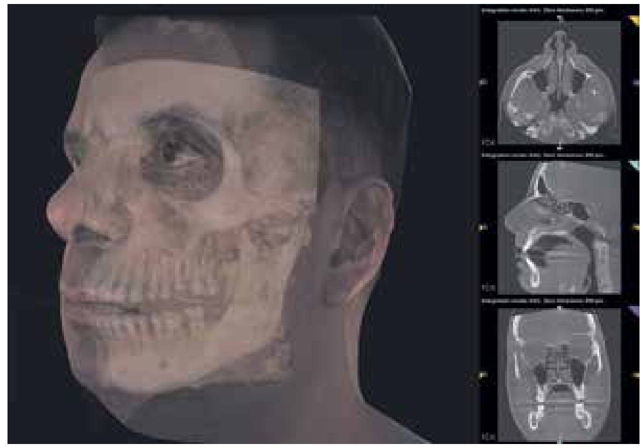

Fig 2-18 3D volume rendering of the skull with 3D photography.

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]

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).