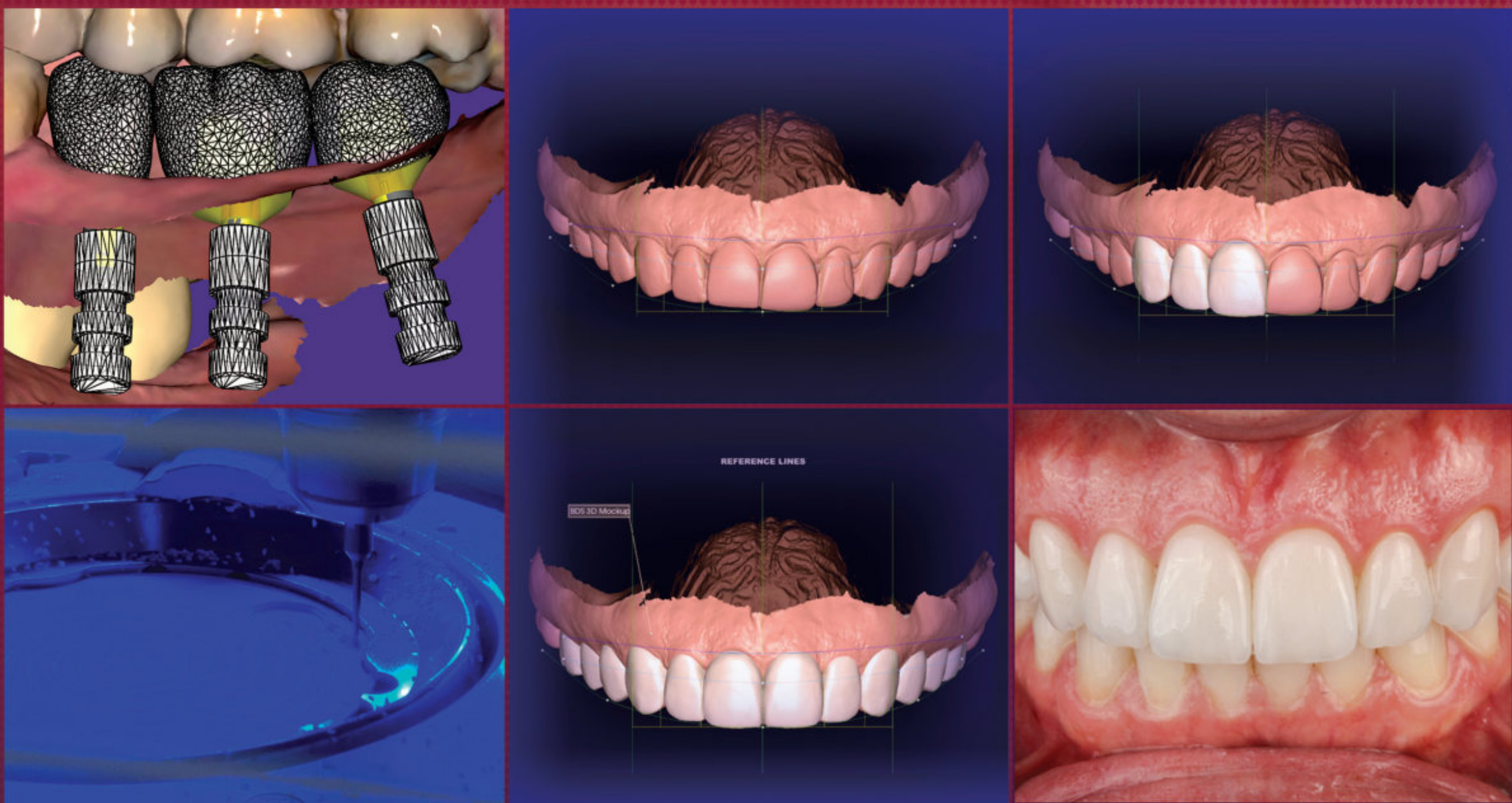
DIGITAL DENTISTRY

A STEP-BY-STEP GUIDE AND CASE ATLAS

EDITED BY
ARTHUR R.G. CORTES



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A Step-by-Step Guide and Case Atlas

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Foreword

Dentistry has been facing major changes, and along with this transformation come challenges. A catchphrase would be: evolution will always be accompanied by initial difficulties. Here we are today.

I understand, dear reader, the natural resistance that we have when looking at new directions and techniques, because as human beings, we love a place called the "comfort zone": a lovely place where nothing happens. My father, a retired dentist, had the same resistance that I see in a large number of colleagues today. In the past, we heard that, if you are used to a technique and material, you shouldn't change it because it would be working "right" for you. Nothing more wrong and misleading, otherwise, no major evolution would have taken place and we would be using candles instead of electricity because "it's been working so far." The future comes in huge waves of change, which initially obviously cause suffering.

The digitalization of dentistry has impacted processes and procedures, as well as workflows and time involved in clinical procedures. Make no mistake: it's not the future, it's the present.

I don't deny that there will always be room for individual talent, superb handicraft, and brilliant creativity in a unique case within our profession. But I believe that all art and creation will be accompanied by a less manually driven process and many digitalization tools, as we have already seen in plastic art and architecture.

This book fills a space in the high-level literature, related to the processes and techniques of digital dentistry. In a way, it can be a great relief for the difficulty that some professionals have faced in accepting new technologies, an analgesic with an extremely detailed package leaflet. Conceptual resistance can only be dealt with by consistent information. After a long period of COVID and its restrictions and doubts, we know more than ever that only science can overcome old concepts and preconceptions.

Like me, you the reader will be able to reduce doubts and opinions based on concepts that are often outdated, and face the new, with KNOWLEDGE.

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Preface

As dental professionals, we should always make sure that our knowledge and skills are up to date to improve our ability to care for our patients. In the current congresses and symposia, a number of exhibitors have been demonstrating technological products to be used in most areas of dentistry. On social media, it is also common to see professionals showing interesting clinical results after using these new products and related techniques. Even in dental research, we can see many new articles and even some new scientific journals focused on digital dentistry.

As a young professor who had just come back from Harvard University to Brazil in 2015, I was very excited to bring the new methodologies to the dental clinic of my family in São Paulo. My main research interest at that time, however, was magnetic resonance imaging in dentistry. Furthermore, as a clinician, I was dedicated almost solely to implant dentistry and was not fully convinced about the benefits of image-guided surgeries. Similarly, my father was already performing CAD-CAM crowns, but still using conventional impressions with the polyvinyl siloxane materials that he always loved to use.

Three years later, I met some of the opinion leaders of digital dentistry, who are now very good friends of mine. We were lucky that dentistry in Brazil has always been very well developed and respected. As a result, several congresses and conferences brought us opportunities to see new courses and exhibitors, always with the most novel and exciting technologies and techniques for digital workflow in dentistry. Several clinicians were doing an amazing job in applying the new technologies to enhance predictability in performing the principles of dentistry, which were actually the same. Despite everything seeming so promising, I realized that the train of digital dentistry was still at the station as regards research and evidence-based knowledge. At that point, I changed the main focus of my research to CAD-CAM and digital dentistry, and since then I have been in love with the topic.

After obtaining clinical and scientific knowledge on CAD-CAM, and talking to expert friends, I began to wonder: what if we had a book in the form of a step-by-step guide to provide evidence-based knowledge of the techniques that professionals might want to perform using these new tools to improve their practice? In addition, what if this could come along with an atlas of clinical cases, performed by me, my father, and the professionals that I have always admired in digital dentistry?

As a result of a huge team effort, this book aims to help colleagues who are dentists, dental technicians, and other members of the dental team to improve their skills to promote patient care. We did our best to try to help our community here. On the other hand, we know that several techniques and approaches are still being developed and investigated. So, this book shows what we know so far, and what we have been doing with the existing tools, techniques, and knowledge, rather than trying to define what is the best approach for every clinical situation. There are three initial chapters describing basic knowledge of CAD-CAM and eight other chapters covering all applications of digital dentistry. Since we also want the new methods to benefit all patients in a collective and inclusive way, there is also a chapter on the role of digital dentistry in preventive dentistry and public dental health. The final chapter is basically an atlas of clinical cases performed by the experts whom I have admired most in the field.

I really hope this book can be useful at some point in all our dental practices, and I thank all my co-authors and my team at the University of Malta for all the support that I have received.

Thank you very much,
Professor Arthur R.G. Cortes

Chapter 1

Introduction to Digital Dentistry

Renan L.B. da Silva, Jun Ho Kim, Roberto A. Markarian, Rui Falacho, Djalma N. Cortes, Alan J.M. Costa, and Arthur R.G. Cortes

SUMMARY

This chapter will discuss all the terms and definitions that the dental professional needs to know to understand the procedures discussed in the following chapters. Such definitions include abbreviations and general concepts of digital imaging and digital workflow. The chapter also presents a history of the use of CAD-CAM in dentistry in the last two decades, and the basic knowledge required plus ideas and alternatives to start with digital dentistry.

1.1 Definitions

Digital dentistry is the term used to describe the different modalities of dental treatment workflow that are mostly performed with the use of digital technologies. Several digital methods have been incorporated to dental practice to replace conventional methods and techniques in order to enhance treatment planning and predictability of execution. Nowadays, digital dentistry is considered a whole field of study within dentistry. As with any other field of study, digital dentistry involves a learning curve to be mastered and used in the clinical routine. Ultimately, the dental professional is responsible for using existing digital tools appropriately for patient treatment. In other words, the basic theories of dentistry are still the same and should be very well known by the professional, who will be able to use these new digital tools to enhance predictability in executing the treatment plan.

In order to become familiar with digital dentistry and take advantage of its benefits, it is required to learn a series of important concepts and abbreviations. The most important of these are discussed below.

1.1.1 Three-Dimensional Imaging

Conventional two-dimensional (2D) imaging modalities usually have several limitations such as image distortion, magnification, superimposition of anatomical structures, and lack of three-dimensional (3D) information for diagnosis and planning. In this context, 3D imaging modalities such as cone beam computed tomography (CBCT), intraoral and facial scanning systems provide 3D digital images for dentistry [1–3]. CBCT imaging allows for visualization and assessment of bone structures with high diagnostic accuracy and precision. For CBCT images, the professional needs to understand image acquisition parameters, since the quality of the image affects the quality of the work in digital dentistry. There are several CBCT acquisition parameters, such as field of view size (FOV), peak kilovoltage (kVp), milliamperage (mA), and voxel size. Each of these parameters has an influence on CBCT quality [2–5].

Intraoral and facial scanning can capture 3D patient images that can be used for digital treatment planning systems (Figure 1.1). The software will then develop a digital representation of the 3D object surfaces available, which will be automatically converted into 3D images composed by wireframe models.

Any 3D images can be rendered and edited in the 3D space, before being converted and saved in a specific file format [5]. As discussed in the next chapter, three file formats are commonly used in digital dentistry: OBJ, STL, and PLY. These files are based on the geometric reconstruction of objects by vectors, triangles or

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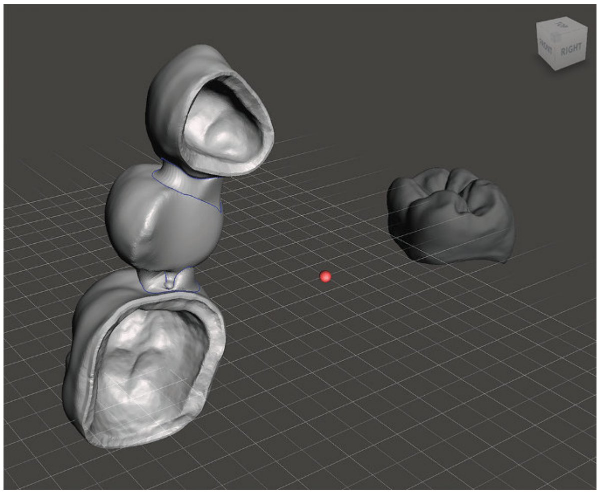

Figure 1.1 Three-dimensional objects imported in different coordinates of the 3D space (screen capture of MeshMixer software, Autodesk). Note that the fixed bridge is closer to the screen than the molar crown. The dynamic grid is used to orientate the spatial disposition of the 3D objects.

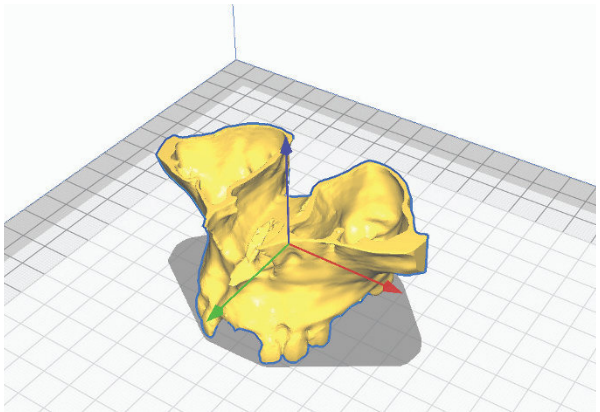

Figure 1.2 A 3D object (reconstructed model of a maxillary CBCT scan) is positioned in the 3D space of a software (Ultimaker Cura) to be 3D printed. Note the three axes depicted by the software in different colors (x-axis in red, y-axis in green, z-axis in blue).

polygons, considering their positioning in a 3D space. After all data is ready, it is possible to store the shape of a model and other details such as color or texture.

Three-dimensional images can be manipulated in various ways, depending on the characteristics of the software. For example, with DICOM and STL files, using the CAD software one can plan and perform digital surgery of dental implants and wax-up of future prostheses. After digital planning, the implant surgery guide, temporary crowns, and definitive crowns can be printed with additive manufacturing devices or milled by subtractive manufacturing devices [5, 6].

1.1.2 Coordinates and Planes

All 3D images are created or rendered in a virtual space of coordinates and planes. Any objects that are digitally designed within the 3D coordinates can be fully edited in the virtual space, before being manufactured. The coordinate system is a method of assigning numbers to points. In three dimensions, three numbers are required to specify a point. Plain 2D images have numbers related to only two coordinates (x and y). The coordinate that represents the third dimension is usually an axis called z. The z-axis is perpendicular to both the x-axis and the y-axis (Figure 1.2).

The coordinates and the respective planes provide references for the location, size, and volume of the 3D images. All 3D objects have their coordinates fixed in a virtual plane of the imaging software. It is important to make sure that multiple 3D objects to be manipulated or aligned are positioned in the same spatial coordinates, which can be used as spatial references. Therefore, 3D files from different imaging methods should be in the same 3D coordinates in order to be superimposed or combined with the aim of creating a virtual patient, as explained further in this chapter.

1.1.3 Computer-Aided Design and Computer-Aided Manufacturing (CAD-CAM)

The term *computer-aided/assisted design* is usually abbreviated as CAD. The methods used for image acquisition (CBCT, scanning imaging, photographs) and manipulation (software programs) can be included in CAD. On the other hand, *computer-aided/assisted manufacturing* (CAM) includes processes such as 3D printers (additive manufacturing) and milling devices (subtractive manufacturing). CAD-CAM technologies are currently used in biomedical engineering, clinical medicine, customized medical implants, tissue engineering, dentistry, artificial joint manufacture, and robotic surgery. Furthermore, the use of CAD-CAM technologies has been increasing in various fields of study of medicine and dentistry [5, 6]. Among the main devices that can be digitally designed and manufactured are different types of dental restorations and prostheses, surgical guides, occlusal splints, dental casts, and orthodontic aligners [5, 7]. Details of the main clinical applications of CAD-CAM in dentistry are further addressed in the next chapters.

1.1.4 Mesh

The term *mesh* is used to describe the surface of a 3D object composed of triangular or polygon faces. A mesh object does not have any actual curvature. Instead, the appearance of curvatures in a 3D image composed of meshes is obtained by increasing the number of surfaces. The most common file format of these 3D images is the STL file [5], which will be discussed in detail in the next chapter.

1.1.5 Image-Guided Treatment

Since 3D patient scans are taken prior to dental treatment, CAD-CAM technology can be used for the fabrication of surgical guides, preparation guides, and maxillofacial surgical templates. Most of these applications require 3D hard and soft tissue images generated by CBCT and optical scanning image modalities, respectively. Based on such images, CAD-CAM guides can be designed and manufactured to orientate directions of drilling procedures and incisions [5].

1.1.6 Image Superimposition/Alignment

Distinct 3D image files like DICOM and STL can be overlaid or aligned using CAD software. In the field of digital dentistry, aligning DICOM and STL is useful to plan implant placement. Details of image alignment will be addressed in the next chapter.

1.1.7 Resolution

In 2D images, the resolution depends on the number of pixels. A *pixel* is the smallest unit of a digital image that can be displayed and represented on a digital display device, also known as a picture element (pix = picture, el = element). A pixel is represented by a dot or square on a computer display screen. Pixels are the basic building blocks of a digital image or display and are created using geometric coordinates. Depending on the graphics card and display monitor, the quantity, color combination, and size of pixels vary and are measured in terms of the display resolution. A full high-definition (full HD) image is 1920 pixels in width and 1080 pixels in height, totaling 2.07 megapixels. Ultra HD (also known as 4K) resolution has 3840×2160 pixels, totaling 8.3 megapixels.

The 3D version of a pixel is called a *voxel*. In general, the smaller the voxel size is, the better quality a 3D reconstructed model will have.

The quality of radiographic images depends on contrast resolution and spatial resolution. Contrast resolution is proportional to the size of the contrast scale available to produce the image. As a result, the higher the contrast resolution of an image, the easier it will be to distinguish between multiple densities. In digital imaging, contrast resolution depends on the bit-depth of the imaging method, following a logarithmic scale. Therefore, a panoramic radiograph produced with an 8-bit system can show $2^8 = 256$ different gray-scale levels distributed from black to white. A CBCT device with a 12-bit system will offer $2^{12} = 4096$ gray-scale values. Spatial resolution is the ability of an imaging method to identify the actual limits and differentiate two adjacent structures [2–4].

Resolutions in 3D CAD files basically depends on the size and densities of the meshes. The quality of the respective manufactured device, however, is also dependent on factors related to CAM (e.g., resolution of 3D printers or milling devices). For 3D printers, there will be factors related to the resolution such as the number of layers and layer thicknesses. For milling machines, the resolution will be dependent on the number of axes and size of burs (see Chapter 3).

1.2 History of Digital Dentistry

Science and technology are the foundations of human development. From the rudimentary creation and improvement of stone tools, accompanied by the breakthrough in learning to control fire and the Neolithic revolution, which multiplied the sustenance availability, to the significant invention of the wheel which allowed humans to travel and produce machinery, or the overcoming of physical barriers with advancements in communications, technology is what sets humanity apart.

Alongside technology, a lexicon development has always been necessary to provide a common understanding of innovations in the meaning and usage of new or existing words. The technological lexicon expansion will often plainly exhibit a novel sense in use but also a rationalization as to why a fresh sense has surfaced. This derives from the need to name new inventions, and when these ascend to a well-known state, so does the correlated terminology. A widespread example of this lexicon expansion is the “digital” concept which, in the last century, underwent a huge increase in usage and meaning as an unswerving consequence of modern computing.

However, contrary to what is customary in technology, the term “digital” is by no means a new word. With its etymology in the Latin word *digitus*, meaning finger or toe, “digital” has come a long way since. In the fifteenth century, the word was used to identify Arabic numbers from 1 to 9 and 0 as digits. It was not until the twentieth century that the term became widespread and gained significance. In the 1930s and 1940s, the existing analogue computing devices which computed data with the normal decimal system were replaced by new machines which functioned with data represented as sequences of discrete digits.

In the late 1970s, electronics using the digital concept were no longer limited to research institutions and companies. As their cost dropped, the general public started to have access and myriad information sources and equipment were converted to the digital era. From a simple CD to a more complex digital sensor camera, radiovisiography or 3D scanner, the world was changed forever.

The construct of "digital" did not stop with machine development but acquired a broader meaning. It has evolved to encompass everything linked to digital or computer technology, as well as to describe any computer-mediated equivalent of an object or entity that exists in the palpable world. Daily uses of this concept are digital shopping carts and digital books, among others. Not only ordinary objects but also professions, expertise fields, and whole organizations acquire the digital connotation when they embrace technology (either hardware or software) for their activities. Examples of this are the many references to digital dentistry or the thriving European Academy of Digital Dentistry that quickly became one of the most respected and widespread scientific societies in the dental field.

Although the twentieth century was overflowing with the word "digital" as the most significant technological innovation in human history, it is predictable that the twenty-first century renders the word "digital," but not the concept, obsolete. As digital becomes the norm, the need to identify it as such becomes archaic. Fields like digital dentistry will overrun the previous model as all dentistry becomes digital, thus eliminating the need for an alias. Similar to the previously named "digital computers," so digital wax-ups, digital photography, and many more entities will lose the superfluous prefix.

Having discussed the past, present, and future general notions of digital, it is imperative to clarify the current concept of digital dentistry, as it may not comply with the ingrained notion promoted and labeled by the industry. Although more widely marketed in oral rehabilitation and surgery fields, digital dentistry has a vast predominance in endodontics, cariology, periodontics, orthodontics, and occlusion, among others. Nowadays, it is clear that digital dentistry encompasses all areas and not only the well-marketed misconception of "digital" as a synonym of CAD-CAM dentistry, a common buzzword in oral healthcare. CAD-CAM technology presents a vast sea of innovation opportunities and is undoubtedly one of the drivers of development in modern dentistry. Nonetheless, according to the concept regulated by the European Academy of Digital Dentistry, "Digital dentistry encompasses any and all scientific, clinical or laboratory techniques and/or procedures with the purpose of examining, diagnosing, treating, assisting directly or indirectly in the treatment, production of medical devices or any other techniques used by dentists and dental technicians to better pursue the goal of improving patient treatment, comfort and outcome, as well as the healthcare professional's work environment."

Taking the aforementioned concept, it is perceivable that dentistry areas such as endodontics present an even higher digitalization than other more well-known digital fields, as endodontists dwell in a fully digitalized workspace where all clinical procedures are performed with the aid of technology – diagnostics with 2D or 3D radiology, microscopes and cameras, apex finders, ultrasonic technology for accessing root canals, static and dynamic endodontic guides, instrumentation with highly advanced digital motors, irrigation activation techniques, and warm obturation methods.

The mandatory multidisciplinary approach in digital dentistry renders the task of defining a clear historical timeline impossible, as innumerable events, developments and clinical or laboratory fields are involved and intertwined in the modern concept.

However, focusing on oral rehabilitation and the developments in computer-aided design and manufacturing, the first CAD-CAM systems in dentistry date to 1971 when Dr François Duret introduced them in his DDS graduation thesis "Optical Impression," but the technology had been used since the 1960s in the automobile and aircraft industries.

In 1984, Dr Duret patented a CAD-CAM device, which was presented at the Chicago Dental Society Midwinter Meeting of 1989, where a dental crown was fabricated in a record time of 4 hours. In parallel, Dr Werner Mormann worked on the development of a digital scanning system to be used by the general dentist, which was branded CEREC 1 and launched in 1985. This innovative system was composed of a three-dimensional digital scanner and milling machine which, when combined, would allow dentists to produce chairside ceramic inlays and onlays in single appointments.

Since then, the technology has greatly improved and dentists and dental technicians experience a time when CAD-CAM can produce results that resemble pure magic, which is what happens when technology is advanced enough. The next two chapters of this book will cover CAD-CAM technology and available procedures in depth.

The advent of 3D printing is revolutionizing several dentistry fields, improving the quality and precision of surgical techniques, and gaining a massive preponderance in restorative dentistry. The term *3D printing* defines a manufacturing process in which additive techniques are used to build objects one layer at a time, in contrast to milling techniques that require a material block to be ground to the final desired shape.

Engineer Charles Hull introduced the first 3D printing technology in 1986 with his patented stereolithography (SLA) system and 4 years later, Scott Crump patented the fused deposition modeling (FDM) technique. Widely used in a multitude of manufacturing fields for the last 30 years, 3D printing with newly developed materials is on the verge of radically changing general medicine and dentistry. From the production of surgical guides, study casts, mock-ups, temporary indirect restorations, occlusal splints, and orthodontic aligners to the more recent production of long-term resin restorations, complete dentures and even titanium dental implants, this additive technology is thought to be the future of CAM, with some much anticipated innovations in materials and techniques that will soon allow ceramic restorations to be printed with higher customization possibilities and lower raw material waste.

With the advent of diagnosis, patient and case documentation, treatment planning, novel treatment techniques and more recently throughout the workflow in oral rehabilitation, digital dentistry is a reality with a promising future. However, much more is yet to come and other fields such as artificial intelligence (AI) will play a major and currently unimaginable role in overcoming all known boundaries. Already considered a rising field, AI technology in dentistry has been the focus of serious research. Software with deep learning capabilities is already helping to improve orthodontic treatment outcomes, caries diagnosis, diagnosis and prediction of periodontal diseases, risk assessment of oral cancer, treatment plan suggestions, patient data analysis, and smile design, among others.

Companies like Pearl, Smilecloud, and LM Instruments, among many others, lead the development of new tools and software capable of autonomously predicting pathology, suggesting treatment plans or providing solutions to improve clinical management and maximize cost-effective approaches, as well as patient safety.

Within its many limitations and shortcomings, digital dentistry is an unavoidable new reality. However, it should not be considered as a means of solving all problems and dentist/dental technician errors, but rather as a tool to maximize and improve processes already performed adequately.

Since the dawn of time, technology has brought forth what lies inside each of us in a sense that both mediocrity or greatness may emerge. Indubitably, a careful and knowledgeable dentist will see his/her work potentiated and productivity increased, but mediocre work will be emphasized by the technology. Hence, dentists and dental technicians should not look for refuge in technology or take it as a means of solving preexisting problems, but rather focus on acquiring knowledge and performing high-quality dentistry that respects all the basic principles and then potentiate it through a digital approach.

1.3 In-House and Outsourced Digital Workflow

1.3.1 The Digital Dental Clinic

For many years dental professionals have been delivering dental treatments based on analogue workflows and well-established principles of dental procedures. With the introduction of digital dentistry, many of the conventional steps in dental procedures are being changed for digital procedures, by means of computerized software, apps, hardware, equipment, materials and techniques.

Current and recent research projects have been addressing the actual benefits of the new digital methodologies arising in the field of dentistry. The need for such projects is also being investigated, considering that there would be no point in changing established workflows and implementing new technological methods without clear benefits for patients and professionals. Among the research findings that are further discussed in this book is the fact that digital workflows can increase quality and predictability, deliver faster results, standardize processes, and enhance communication among the dental team and the patient [8]. These findings mean that the adoption of digital workflows is becoming more popular in several countries. Nevertheless, only a small number of dental clinics and practices are actually adopting in-house CAD-CAM systems in their daily clinical routine.

1.3.2 Impact of Digital Technologies in Dental Clinics

The digital era is completely transforming the ways in which people interact, work, and live. In many areas, the number and types of jobs available are changing. At the same time, entire professions, markets, products, and services rise or disappear. The dental profession is also being impacted by the digital transformation. In a digital dental clinic, treatment workflows use computerized technology that can affect dental teamwork at all levels: administration, support personnel, receptionists, dentists, hygienists, and dental technicians.

Administration personnel and secretaries can quickly store and analyze large amounts of patient data, using dedicated management software, improving efficiency and diminishing the quantity of paper used. The dental hygienist will need to be able to understand and use high technology equipment such as dental scanners and digital x-rays, while support personnel should also be able to maintain biosafety measures in highly sensitive machinery. This means that, for instance, the hygienist could perform intraoral scans and be able to analyze and correct mistakes during the procedure if necessary, using specialized software under dentist supervision. Currently, dental hygienists and even dental technicians in most countries do not have digital dentistry training in school, making the selection of specialized personnel in the market more difficult. Therefore, with the adoption of digital trends, members of the dental team will need special education for the use of workflows, equipment, materials, and methodologies.

Another important aspect is that digital dentistry adds tools to aid in treatments that still follow the same principles of dentistry. The adoption of digital dentistry allows for enhancement of treatments and abilities obtained using conventional analogue techniques. For instance, oral surgeries can be more accurate and faster by using surgical guides to orientate drilling procedures (see Chapters 6 and 7). Digital imaging and new software tools are useful to enhance oral diagnosis. New materials such as zirconia and new ceramics improve esthetic outcomes. Machinery can work continuously with accuracy and speed that no human is able to achieve.

1.3.3 The Education of the Digital Dentist

The need for education in digital dentistry is also very clear for dentists, who might have a key position in the dental team. The role of the digital dentist is to plan, execute, and coordinate the dental staff while delivering digital treatments. Ideally, the digital dentist needs to make decisions, and thus has to fully understand both analogue and digital dental procedures. A growing number of studies are increasingly supporting satisfactory clinical outcomes with digital technologies. As a result, the reliability of CAD-CAM restorations is creating a growing demand from practitioners and students to learn about digitalization.

To support this trend, dental schools are increasingly improving their schedules with new information on digital technology for dentistry students. The student can be presented with concepts of digital dentistry applied in several areas of dentistry, but they are rarely allowed to conduct clinical cases, nor to receive more in-depth information.

Some academic discussions suggest that digital dentistry will advance to be a major field of study. One of the reasons for this is that the dentist needs to master new knowledge, skills, and training to conduct dental treatments [9]. This suggests that digital dentistry should be considered a separate specialty degree in the field of dentistry. On the other hand, others believe that digital concepts are merely a new way to resolve traditional problems, and therefore digital dentistry is to be considered a subfield derived from the main specialties (i.e., digital prosthodontics using the principles of conventional dental prosthodontics). Either way, digital dentistry represents a large field of study for young dental professionals and more experienced practitioners.

Most practices that decide to purchase their first digital equipment are generally given technical training that could last some days. However, this initial education is likely to be an introduction to the theoretical concepts, technical features, and capabilities of the equipment and/or software. At this initial point, further education on courses, books, and scientific publications helps to fill the gaps in training while the equipment is used in a dental clinical routine.

Typically, the initial production of digital dental work will focus on basic procedures but over time, as the digital dentist becomes more and more experienced, a mind change is likely to occur and a *digital way of thinking* emerges, providing new insights into planning and executing current dental procedures in novel ways. The dental clinic may thus be organized by digital dentists with expertise in digital technologies to organize and supervise the creation and outcomes of dental treatments.

1.3.4 Levels of Digitalization for the Dental Clinic

There is nowadays a paradox in the dental market as the most advanced treatments and materials are found in digital dentistry but only a minority of dental practices are digitalized. Factors which may be impairing a more widespread use of technology in dentistry include investment costs, technical education, and cultural resistance to change. There can be a misconception among dentists that in order to use digital technology, one must first invest large amounts of money and that the return on investment would be hard to obtain.

The reality is that virtually any dental practice can offer digital treatments, not necessarily initially producing their own work in house but outsourcing to third-party clinics or laboratories more advanced in digitalization. Other possibilities can start with mobile phones, by using dedicated apps that allow smile planning, for example. The complete digital clinic, in which every single procedure is conducted with digital equipment, delivering automated, standardized, cheaper, and reliable results, is beginning to be suggested as a feasible idea by some research findings [9, 10].

The actual digital clinic may be situated somewhere between the two extremes of lack of adoption and large investment for hard users. In a more realistic approach, the dental clinic and dental professionals can be digitalized in different levels. For instance, one orthodontic clinic may be digitalized for intraoral scans only, outsourcing the set-up, planning, and fabrication of aligners. Meanwhile another clinic is able to deliver same-day restorations produced with in-house equipment and personnel. The decision on the degree of digitalization for the practice will depend on the specialty of the dental clinic and the focus on their more specific needs.

1.3.5 Types of Dental Clinics and Business Models

The rise of digital technologies is also modifying the dental clinic business itself, bringing innovations that can enhance traditional niche clinics and create new business models. As the equipment used in digital dentistry is highly specialized, different business models may be required, depending on the specific field of study.

Some examples of equipment and set-ups that can be created for special purpose clinics are shown in Table 1.1. However, multidisciplinary practices may eventually influence the hardware and software needed.

- *Digital imaging diagnostic and radiology centers*: may invest in digital imaging equipment (panoramic radiographies, CT scanner). Depending on the services offered, some practices could provide intraoral scanning (or model scanners) and digital pictures for outsourced surgical planning. There is dedicated software available for imaging centers to provide better diagnostics and send back the requested information to the clinician.
- *Digital esthetics*: there will be a large demand for ceramic restorations (veneers, crowns). Practices could invest in smile design software, 3D printers, and single-unit ceramic milling machines.
- *Digital implantology*: a digital implantology center would probably need in-house imaging equipment and an intraoral scanner to correctly diagnose and create treatment plans. Additionally, guided surgery software would be needed to fabricate surgical stents, with a 3D printer. If digital restorations are to be executed, additional equipment similar to oral rehabilitation practices will be required.
- *Oral rehabilitation and prosthodontics*: oral rehabilitation is a complex area that encompasses many of the main specialty areas of dentistry. Therefore, a digital prosthodontics clinic could require equipment and software to create at least some items in house, while outsourcing more complex work. To do so, good additions would be an intraoral scanner, chairside software to design restorations, a small ceramic milling machine to produce single-unit same-day restorations, and a ceramic furnace. If more complex in-house prosthetic production is desired, a dedicated internal digital laboratory can be created.
- *In-house dental laboratory*: there is no limit to the work that can be created by an in-house dental laboratory when compared to commercial counterparts, since the same equipment and software can be acquired. However, a complete laboratory set-up would require a more robust financial investment in machinery, software, and materials. Additionally, a dedicated space is needed with special infrastructure planning to accommodate the hardware, and specialized personnel are needed to operate the machinery. The size, organization, and production rate of devices must be compatible with the desired workflow. Equipment for digital dental laboratory would include that required for a traditional lab plus a desktop scanner, a milling machine for 5-axis capability for large blanks and ceramic blocks, a ceramic furnace, a sintering furnace, CAD software to design prosthetics, and a resin 3D printer.
- *Orthodontics*: the digital orthodontist can enhance their practice with intraoral scanners. It is possible to acquire dedicated software and 3D printers to plan treatment outcomes, as well as in-house fabricated aligners.
- *General practitioner*: can invest in intraoral scanners in order to easily digitalize their orthodontic, restorative, and prosthetics patients. Digital sensors for radiographies are also widely used.
- *Surgery*: oral and maxillofacial surgeons can acquire dedicated software to plan orthognathic surgeries and

Table 1.1 Estimate of the amount of machinery, equipment, dedicated software, specialized personnel, and physical space dedicated structure to operate different types of digital dental business models.

	Intraoral scanner	Desktop scanner	Digital imaging	3D printer	Small milling machine	Large milling machine	Ceramic furnace	Sintering furnace	Physical space structure	Specialized personnel	Dedicated software
Orthodontics	X			x					x	x	x
General practitioner	X					X	X		x	x	x
Esthetic dentistry	X			X		X	X		x	x	x
Dental implantology	X		X	X		X	X	X	xx	xx	xx
Oral rehabilitation	X	X	X	X	X	X	X	X	xx	xx	xx
Surgery		X		X					x	x	x
Dental laboratory		X		X	X	X	X	X	xx	xxx	xxx
Imaging centers and diagnostics		X	X						x	x	xx
Planning center		X		X						x	xxx
Scan services	X	X									x
Milling centers					X	X		X	x	xx	x

would need at least desktop scanners to digitalize models, although an intraoral scanner would be preferable.

- *Planning centers*: a digital planning center is a new business model aiming to provide outsourced services to any dentist or practice, by means of dedicated software. The range of services provided can encompass orthodontics, implant surgery, smile design, oral surgery, prosthetic design, and so on. Software licenses can be expensive and require initial investment and often subscription updates charged yearly. Additionally, professionals are highly trained in software and can discuss the design with the dentist before delivery. The outcome of a digital treatment plan can be a physical item such as a surgical template or even digital files or pictures.
- *Scan services*: for those who do not possess an intraoral scanner but would like to use one, scan services bring the scanner to the customer's practice in order to register the digital impression. This novel business model can occur as a standalone company or be offered by digital dental laboratories.
- *Milling centers*: a digital milling center is a specialized dental laboratory focused on the production of milled structures or restorations. Specific materials such as cobalt-chromium structures are commonly used in prosthodontics but as highly dense materials, they are extremely hard to mill, requiring specialist and expensive tools and machinery. Therefore, many small laboratories tend to outsource their metal milling to milling centers. Depending on the focus and services offered by milling centers, other materials can be used such as zirconia, ceramics, PEEK or PMMA.

1.3.6 Financial Aspects of Digital Dental Clinics

The digital clinic can be more complex than a regular individual private practice, which generally presents lower complexity, operational costs, and levels of document digitalization and a smaller professional administration team. Therefore, the operation of a digital dental clinic is similar to a business company, something that dentists may not be used to. Potentially higher financial investments are necessary to equip a digital dental clinic, which makes it difficult for any clinic to enter the market. It is noteworthy that these issues are less likely to be experienced by larger dental clinics and hospitals.

A digital dental clinic can be potentially bigger than a regular practice, but not necessarily a more profitable business. As a practice grows and enlarges its operation, facilities, and employees, there is an increase in profits and liabilities in the same proportion. Therefore, in the real world, studies of economic viability of dental clinics, or related to some specific equipment incorporation, can determine if a company will perish or thrive. More than ever, a successful dental practice needs a combination of highly skilled dentists and entrepreneurial skills.

1.3.7 How to Calculate the Return on Investment (ROI)

The return on investment is a ratio between net income and the funds spent on the investment, over a period of time. Applied to a dental clinic, the ROI calculation may predict how long it will take to return the money to the entrepreneur.

The estimation of ROI is based on complex calculations comparing initial costs, earnings, and projected estimate of cost/benefit after making an investment. To achieve the same production end, more than one digital solution is available and can be compared [9].

Return on investment calculations have three aspects.

- *Earnings:* how much revenue will the investment bring? Will there be an increase?
- *Costs:* how much will the investment save (time, clinical steps, personnel costs, consumables)?
- With this information mapped, it will be possible to create a *break-even* estimation, which is the prediction of when in time the investment will return. Reaching anything more than the break-even is considered profitable.

Estimations of ROI must take into consideration that after the equipment is acquired, it may require regular maintenance and consumables. Additionally, the obsolescence of the equipment must be included as technology evolves over time and may need to be replaced with new financial investment. Finally, to represent a good inversion, the digitalization of dental care workflows should provide quantifiable advantages in terms of quality, time consumption, and personnel cost reduction. As ROI calculation can be complex, professional advice on these economic aspects should be taken.

1.3.8 Advantages of Digital Dentistry for Clinics

Before digital dentistry, it was common for the client to visit the dentist for multiple consultations to diagnose and plan dental treatments, while procedures could last long periods of time. However, dental practices are now able to diagnose, plan, and treat their patients much faster and with fewer clinical steps and less chair time using digital technology.

Chapter 2

Computer-Aided Design (CAD)

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SUMMARY

This chapter provides a step-by-step guide and research evidence on all computer-aided design (CAD) procedures involved in digital workflows in dentistry, from setting up digital imaging methods to work with digital design and treatment planning.

2.1 Digital Imaging Methods

2.1.1 Cone Beam Computed Tomography

Cone beam computed tomography (CBCT) is a technique that allows for three-dimensional (3D) observation of structures related to the maxillofacial area. CBCT uses a round or rectangular cone-shaped x-ray beam with a two-dimensional x-ray sensor to scan, performing 180–360° rotations around the head of the patient (Figure 2.1). During the scan, a series of projections is acquired, providing the raw data for volumetric reconstruction (3D). Multiplanar reformatting (MPR) of the primary 3D reconstruction allows studies of any selected plane in 2D or 3D views [1]. The CBCT image is a matrix composed of small cubic units called *voxels* (volume element, the 3D version of a pixel, described in the previous chapter). Similar to pixel values, each number assigned to a voxel represents the linear x-ray attenuation coefficient of the inside structure with a specific level of gray and numerical value (voxel value) [2].

2.1.1.1 Basic Knowledge

In recent decades, CBCT devices have been used in dentistry much more frequently than medical computed tomography (CT). The latter is an expensive device usually found in hospital settings. Medical CT devices can have single or multiple detectors that use a collimated, fan-shaped x-ray beam moving in a 360° circle within the detector ring (known as the "gantry"). The CT image is recorded and displayed as a matrix of individual 3D blocks that are the voxels. Similar to CBCT, multiplanar CT imaging acquired from axial scans (2D) may be reformatted by interpolation to render a 3D image [2].

When compared to medical CT, CBCT has advantages such as lower radiation dose, faster imaging, and higher spatial resolution of bone [3]. Modern CBCT devices can offer lower fields of view (FOV), which means that only the region of clinical interest is scanned, resulting in even lower radiation doses. The use of CBCT is well established in implant planning for the evaluation of bone thickness, height, density (estimated using pixel values), and volume [4–6], and others as endodontics [7], periodontology [8], orthodontics [9], oral and maxillofacial surgery [10], and temporomandibular disorders [11].

Images from MPR are usually available in three different orthogonal planes – axial, sagittal, and coronal – to be used in diagnosis and treatment planning. However, it is also possible to obtain curved images by using the axial scan to draw a curve following the shape of the dental arch. These images usually show coronal panoramic reconstructions and a set of transaxial/parasagittal images representing cross-sections of the alveolar

Digital Dentistry: A Step-by-Step Guide and Case Atlas, First Edition. Edited by Arthur R.G. Cortes.

Figure 2.1 A CBCT device integrated with cephalometric and panoramic radiographic functions (Cranex® 3D, Soredex, Tuusula, Finland).

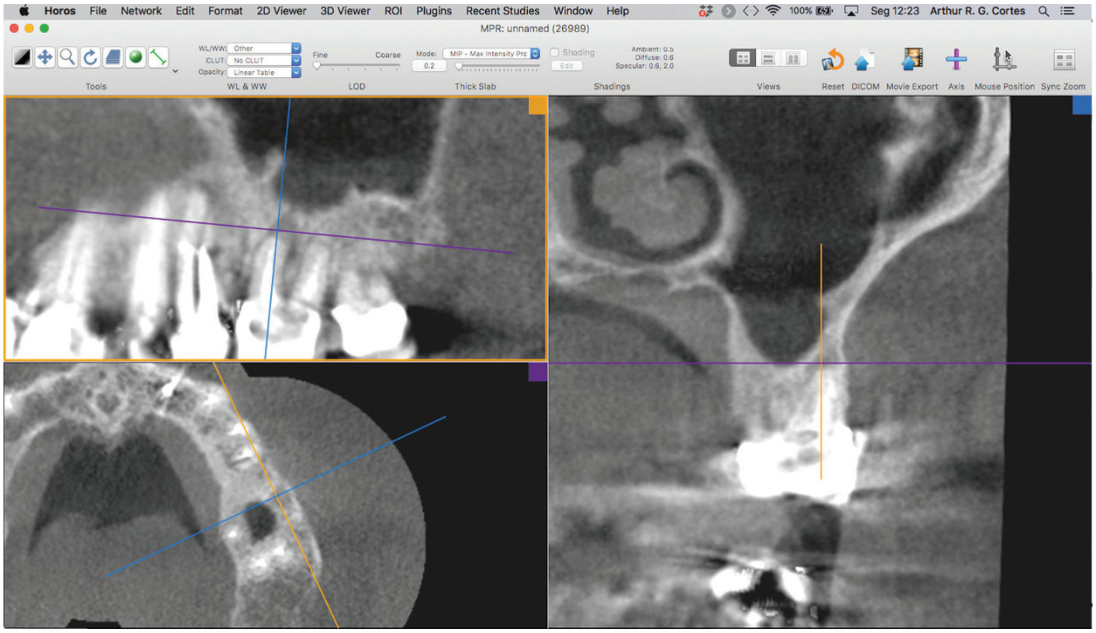

Figure 2.2 Screen capture of the Horos open-source DICOM viewer software (Horos Project), showing an MPR. Note the periapical lesion of the mesial root of a first molar located in the three orthogonal planes.

ridge (Figure 2.2). These cross-sectional images are commonly used for implant planning.

Another option is to use the raw CBCT axial images to render 3D reconstructed models to analyze the spatial disposition (angle, length, and diameter) of implants, screws, surgical or endodontic guides, prosthetic compounds, and orthodontic components. The raw data from CBCT or CT must be obtained in the DICOM® (Digital Imaging and Communication in Medicine) extension (described in the previous chapter) (Figure 2.3) to be read in the software and later exported as a 3D image in the Standard Tessellation Language (STL) extension.

2.1.1.2 Step-by-Step Procedure

- Prior to the examination, the patient should be asked to remove any metal objects, such as eyeglasses and jewelry. Removable prostheses should also be removed in most cases.
- Radiation protection measures (e.g., lead aprons, etc., as established by local regulations).

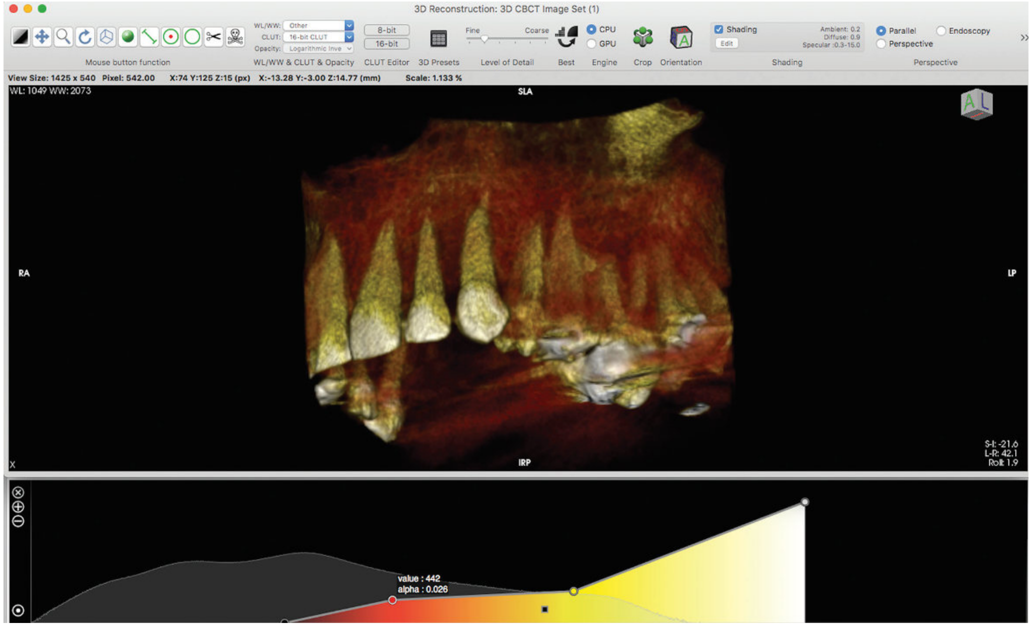

Figure 2.3 Screen capture of the Horos open-source DICOM viewer software (Horos Project) showing a 3D reconstructed model rendered from CBCT DICOM files. The threshold color edition tool (bottom of the screen) enables visualization of structures in the bone, such as the roots of the teeth.

- Patients should always be positioned properly in the CBCT device (Figure 2.4). It is suggested that the best position for image quality of the sinuses, mandible, and maxilla is the prone position, rather than supine and oblique positions [12]. The patient's face needs to be aligned in the scanner with the head positioned between the x-ray source and the sensor. This position should then be further adjusted to ensure the disposition of the desired anatomical structures within the limits of the selected FOV. Such adjustment is generally conducted with the aid of chin and head supports, and with a laser alignment beam that projects an illuminated line onto the face of the patient.

Figure 2.4 Patient positioning with adequate posture in the CBCT device.

- Explain the procedure and ask the patient to swallow and avoid moving during the scan. (For image-guided surgeries, it is important for the patient to use lip retractors in occlusion during the scan, as further explained in Chapter 6.)
- Define the imaging parameters and the FOV to be scanned on the scout image (Figure 2.5).
- Initiate the scan following the manufacturer's instructions.
- Save the scan in the DICOM format (a folder with one file per axial slice will be created), which can be opened using a DICOM viewer for diagnosis (Figures 2.2 and 2.3) or a CAD software dedicated for dental treatment planning (further discussed in the following chapters).

2.1.2 Intraoral Scanner

2.1.2.1 Basic Knowledge

The conventional workflow using trays and impression materials has been improved for many decades. However, a previous study found that about 50% of the impressions sent to a laboratory result in inadequate or inaccurate models. This can occur because, until the end of the service, many materials are used, each one with its particular work technique. Careful analysis is required at each stage of the process, as any failure will

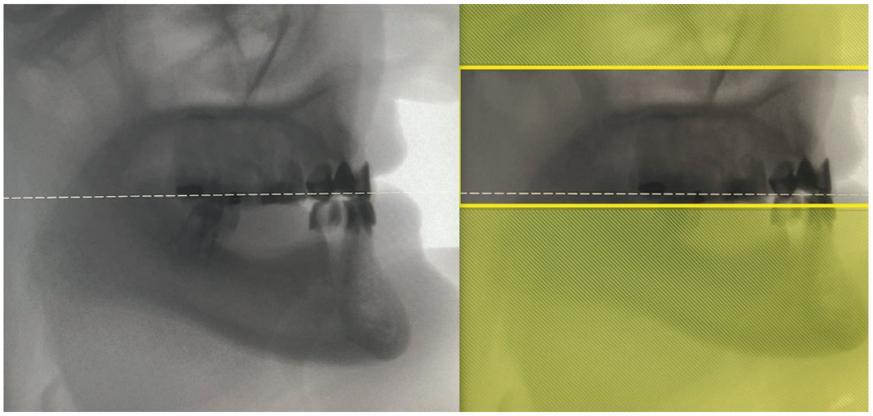

Figure 2.5 CBCT scout image (left) used to define the FOV of the scan (right).

not be corrected by the next stage, thus compromising the final result of this flow.

Currently, digital impressions, by the use of intraoral scanning, can generate an STL file, which represents the first step of the digital path, in which the clinical situation can be fully moved to a virtual environment. However, when necessary, physical molds can still be manufactured from the same STL files using rapid prototyping technologies.

Regarding patient-based outcomes, digital impression leads to less patient anxiety, is more comfortable, causes less nausea and allows the patient to observe the area of interest on the computer display. From the point of view of process agility compared to the entire process from molding to patient rehabilitation, digital flow, with intraoral scanning, reduces process steps and promotes fast communication with the laboratory.

Using intraoral scanning ensures immediate determination of print quality; virtual 3D models of patients are obtained, which can be saved to the computer without the need for a physical model. This economizes on time and space and provides the ability to easily send models to the lab using email, reducing time and costs. The clinician can save money on purchasing impression materials and manufacturing plaster models; it is possible to store virtual models of patients without having to dedicate a space inside the clinic to them. Not least, the clinician can have a powerful marketing tool for more effective communication with the patient.

Intraoral scanning technology has been developed very fast. Currently, there are more than 10 different intraoral scanners on the market and companies are developing devices and methodologies from more than eight countries.

- TRIOS® 4 (Figure 2.6) – 3Shape A/S (Denmark).
- CEREC® Omnicam (Figure 2.7) and Primescan – Dentsply Sirona (USA).
- CS 3700® – Carestream (USA).
- 3D Progress – MHT SpA (Italy) and MHT Optic Research AG (Switzerland).
- iTero – Align Technologies (USA).
- Bluescan®-I – A•TRON3D® GmbH (Austria).
- DPI-3D – Dimensional Photonics International, Inc. (USA).
- E4D – D4D Technologies, LLC (USA).
- IOS FastScan – IOS Technologies, Inc. (USA).
- Lava™C.O.S. – 3M ESPE (USA).
- MIA3d™ – Densys 3D Ltd. (Israel).
- DirectScan – HINT – ELS GmbH (Germany).
- Panda P2® – Pingtum Technologies (China).
- Medit i700® – Medit Corp (South Korea).
- Vectra 3D – Canfield Scientific (USA).

Figure 2.6 The TRIOS® 4 intraoral scanner (3Shape A/S), which uses confocal technology and enables integration with CAD software programs and CAM devices from other manufacturers.

Figure 2.7 The CEREC Omnicam intraoral scanner integrated with a milling device from the same manufacturer (Dentsply Sirona).

The intraoral scanner is a medical device consisting of a handheld camera (hardware), a computer, and software. Its purpose is to accurately capture the 3D geometry of an object.

The most widely used format of the 3D digital file extension of images captured by the intraoral scanner is STL. Among the main technologies for scanning an object are triangulation, confocal, AWS (active wavefront sampling), and stereophotogrammetry.

Triangulation

Triangulation is based on the principle that the position of a point on a triangle can be calculated, provided that two points of view have known positions and angles. Examples of intraoral scanners using triangulation technology are Cerec Omnicam (Dentsply Sirona), IOS FastScan (IOS Technologies, Inc.), Medit i700 (Medit Corp), and MIA3d (Densys 3D Ltd).

Confocal

Confocal imaging is based on acquisition of both focused and nonfocused images from different depths. This technology enables detection of image sharpness to infer distances in relation to the object, according to the focal length of the lens. The level of sharpness obtained in the scan is directly proportional to the dexterity of the operator. Examples of confocal intraoral scanners are TRIOS 3 and TRIOS 4 (3Shape), iTero Element2 and Element5D (Align Technologies), and 3D Progress (MHT SpA).

Active Wavefront Sampling (AWS)

The AWS technique enables the capture of a surface image using a camera and an aperture off the optical axis of a module that rotates around this axis. Distance and depth information can be derived and calculated from the outcome of each point. An example of an AWS intraoral scanner is the Lava C.O.S. (3M ESPE).

Stereophotogrammetry

Stereophotogrammetry estimates all coordinates (x, y, z) solely by using an image analysis algorithm. As this approach relies on passive light projection and software rather than active projection and hardware, the camera is relatively small and easier to handle, and it is less expensive to produce the images. An example of a stereophotogrammetric device is the Vectra 3D (Canfield Scientific).

Clinical differences have been reported among IOS devices employing the same technology. These differences are usually related to the time it takes operators to become familiar with the ergonomics and usability of the software for each intraoral scanner. It is noteworthy that the learning curve of intraoral scanning may be initially slow.

Dental tissues have several reflective surfaces, such as enamel crystals or polished surfaces. These surfaces could prevent the software from capturing a point of interest due to overexposure. To avoid this, professionals could slightly change the camera's orientation or employ systems that use cameras with a polarizing filter.

Scanning strategies refer to the order of intraoral scanner movements in relation to the dental arch to increase the quality and accuracy of the virtual model. Recent studies have shown the impact of the scan path on the accuracy of the resulting 3D models. During scanning, a regular and continuous movement should be maintained, ideally with a constant distance and centered in relation to the object. The main general steps for intraoral scanning are summarized below.

2.1.2.2 Step-by-Step Procedures

The following step-by-step procedure is described using a TRIOS 3 (3Shape) device. Most of the steps, however, are similar for most of the other systems and manufacturers.

- Connect the intraoral scanner to the computer with the specific software of the equipment to be used, which has a valid license key (for scanners attached to a cart, it will already be connected to the dedicated computer).

- Connect the equipment to power and turn it on.
- On the desktop screen, double click on the icon for the scanner software.
- On the initial screen of the intraoral scanner software (Figure 2.8), choose "new patient" to register an unregistered patient, or "new case" to perform a new scan on an already registered patient.
- Choose the laboratory (or email address) to which to send (export) the scan when it finishes.
- Define in the options that the software offers the type of restoration to be performed (scan only, implant planning, anatomy, abutment, bridge, etc.).
- Click on the "next" icon to proceed to the scan.
- Follow the steps indicated in the specific workflow bar that appears on the software's scan screen.
- Scan both maxillary and mandibular dental arches, always following a scanning protocol (Figure 2.9) and avoiding repeat scanning of the same regions (Figure 2.10). In addition, perform the digital bite registration.
- Correct any failures in the mesh as indicated by the software. After scanning both dental arches and bite registration, proceed with the other complementary scans (dental preparations, scan bodies, etc.), as well as recording the occlusion scan.
- Once the scans are finished, carry out the mesh postprocessing (Figure 2.11) by using software tools (some systems perform part of this process automatically).
- With the postprocessing done, we are ready to export the scans (Figure 2.12).
- It is possible to export or directly send the scan files to a laboratory or client using the specific tools of each software. All files could also be downloaded into folders on the computer hard disk or to temporary storage devices (memory cards or external hard disks).
- Choose the type of file extension of the scan to be exported (some software programs work only with STL files; others additionally allow for exporting polygon file format [PLY] or OBJ files).

Intraoral Scanning of Edentulous Patients

The scanning technique mostly recommended for the edentulous ridge is the "zigzag" scanning strategy. This technique helps to maintain the continuity of the images following the palatal vestibule direction, always starting from the left side toward the right side, or vice versa without interruption and complementation of the palate region during capture. Conventionally, most professionals who choose to scan the toothless arch use the file to make an individual tray that can be produced manually on printed work models or directly by additive manufacturing in special resins, after drawings made in the software. The individual tray would be able to capture the areas that might not have been captured by the intraoral scanner. Compared to the maxilla, the mandible usually presents greater difficulty when obtaining the scan due to the presence of a mucosa with greater mobility.

The recommended scanning technique that will ensure greater accuracy of results performed in a fully digital workflow, based on publications that used TRIOS scanners [13, 14], and related scientific evidence, follows the sequence below.

1) Prior selection of a U-shaped lip retractor with adequate dimensions for the patient and capable of

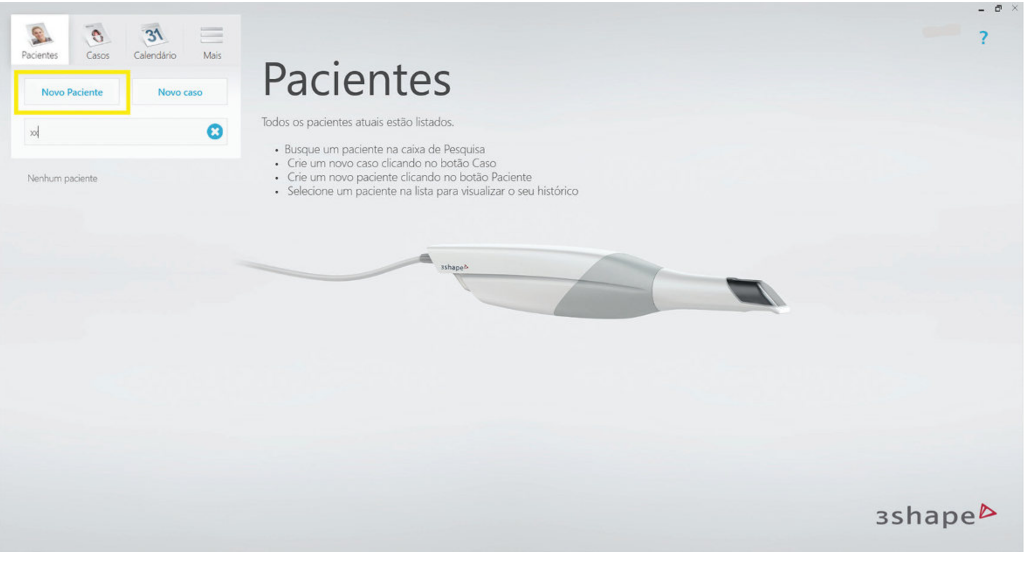

Figure 2.8 Screen capture of the main screen of the IOS software.