Faleh Tamimi • Hiroshi Hirayama
Editors

Digital Restorative Dentistry

A Guide to Materials, Equipment, and Clinical Procedures

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Editors
Faleh Tamimi
Faculty of Dentistry
McGill University Faculty of Dentistry
Montreal
QC, Canada

Hiroshi Hirayama
Goldman School of Dental Medicine
Boston University
Boston, MA
USA

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Introduction

1

Faleh Tamimi

Abstract
Digital technologies are disrupting dentistry at an unprecedented pace. This technological revolution is changing the landscape of the dental profession in terms of the treatments available, the training needed to perform those treatments, and the jobs involved in conducting the treatments. This chapter explains how our current book addresses these burning issues.

The arrival of 3D printing and artificial intelligence is driving humanity towards its fourth industrial revolution. The first three industrial revolutions were caused by the arrival of technologies that relieved the burden of physical human labour; however, this current revolution is the first in history in which technology is replacing human intellectual work. This is causing rapid radical changes in many industries, and almost every profession is being influenced one way or another by this disruption.

Dentistry is not immune to this drastic change we are going through. We are currently witnessing how dental techniques that are decades or even centuries old are becoming obsolete overnight through a rapid cycle in which new technologies replace old ones just to be replaced again as soon as a newer technology arrives. The Polish-British philosopher Zygmunt Bauman described this phenomenon as "liquid reality", a reality in which everything is changing constantly under our feet and there are no solid references to grasp onto. In this environment there is a need to keep up to date and adapt constantly to the arrival of new technologies, as the references of the past may become irrelevant. There is a clear risk that many of the procedures and services provided by dental professionals today could be replaced by machines in the digital era. This is already happening in the labour market for dental technicians, where the reduction of manufacturing costs brought in by digitalization

F. Tamimi (✉)
Faculty of Dentistry, McGill University, Montreal, QC, Canada
e-mail: faleh.tamimimarino@mcgill.ca

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has resulted in a drastic reduction in manpower needs, specially in high-wage regions such as Western Europe and North America [1]. Accordingly, dental professionals have to evolve and learn to co-exist with these new technologies so that they become tools for professional growth instead of threats to their jobs.

The arrival of the fourth industrial revolution to dentistry is mainly driven by three main parallel developments: computer-aided manufacturing, computer-aided design, and image digitalization technologies. These technologies are not new; their development started in the 1970s–1980s; however it is only after recent advances in computer processing power, artificial intelligence, robotics, optical engineering, and material science that these technologies have been able to surpass old manual techniques in terms of quality, costs, and efficiency.

Computer-aided manufacturing technologies such as 3D printing and computer-aided machining are replacing the skilful hands of dental professionals, whereas design software are gradually complementing and even replacing their intellectual skills in terms of treatment design. Of course, all this has been made possible by significant improvements in imaging tools such as cone beam computerized topographers (CBCT) and optical scanners, which allow for rapid and affordable digitalization of dental and craniofacial anatomy with and accuracy that has already surpassed the analog era. In summary the convergence of the three above-mentioned developments is carrying dentistry to a new era in a quantum leap.

Optical scanners and cone beam CTs are now applied in many areas of dentistry due to their increasing accessibility, affordability accuracy, and precision. Improvements in digital acquisition are allowing virtual treatment planning, multidisciplinary teamwork, and better communication with the patient when it comes to managing dental aesthetic problems and smile design [2]. Also, as these technologies become more accessible, automation of the digital workflow is growing in importance. Software based on artificial intelligence algorithms such as neural networks are now used to process the 3D images acquired. These machine learning algorithms can be trained to identify dental anatomical landmarks and design dental restorations by mimicking the work of dental professionals. This is going to take the dental profession into a whole new level of automation that will close the gap between digital acquisition with modern technologies and computer-aided manufacturing techniques [3, 4].

In the 1960s Gordon Moore noticed that the number of transistors in microprocessors was doubling every year since their invention. This phenomenon was later known as Moore's law, and it predicts that this continuous increase in computer power will continue into the foreseeable future. Moore's law also applies to digital dentistry. As microprocessors keep getting more powerful and less expensive, software will harness these improvements to come up with innovative solutions for dental problems. This results in a very short life cycle for digital technologies in dentistry. Subsequently, most of the digital dental products entering the market today have little or no clinical data backing them up. In this continuously changing environment, clinicians are struggling to keep up to date with the latest technology while making sure that incorporating these innovations into their clinical practice is supported by meaningful evidence [5].

As dentists are confronted with these technologies, they need to acquire new training and knowledge so they can benefit from these advances and avoid being left behind [1]. In this context, this book summarizes the three main developments that are spearheading the era of digital dentistry and addresses their clinical implications by discussing the different dental treatment modalities that can now be performed with digital technologies. The technologies described in this book are undergoing constant developments, so in order to prevent this book from becoming obsolete, emphasis is made on the fundamental concepts of digital dentistry rather than on constantly changing technicalities.

The book has two main parts, the first part addresses the basic concepts related to digital restorative dentistry and the second part the clinical applications of digital restorative dentistry. In the first part, Chap. 2 addresses image digitalization, the instruments used for digitalization, and the basic principles of how they function. Chapter 3 focuses on the different types of design software available for image processing and design of dental restorations, and Chap. 4 tackles the manufacturing techniques, namely, subtractive and additive manufacturing techniques.

In the second part of the book, we explain how to preform dental restorative procedures using digital technologies, ranging from the removable and fixed prosthesis to implant and endodontic treatments. It is very likely that eventually all dental restorative procedures will be performed using digital technologies. This will simplify the clinical procedures and the training needed to do them while improving treatment outcomes and reducing costs.

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Part I

Equipment

Digitalization in Restorative Dentistry

2

Guillermo Pradíes Ramiro, Bassam Hassan, Alberto Ferreiroa Navarro, Cristian Abad Coronel, Arthur Rodriguez Gonzalez Cortes, Otavio Henrique Pinhata Baptista, and Nataly Rabelo Mina Zambrana

Abstract

Digitalization is the first step involving a digital restorative dentistry workflow. Although the digitalization process was initially confined to CAD/CAM (computer-aided design/computer-aided manufacturing) dental procedures, nowadays a much wider range of dental procedures have been revolutionized by their ongoing digitalization. Digitalization consists basically of converting any physical 2D or 3D volume into an electronic information language codified in terms of only two possible digits (0 or 1) normally contained in an informatic file.

The number of digitalized procedures and devices that have been incorporated into restorative dentistry is substantially growing. Digital photograph cameras,

G. P. Ramiro (✉) · A. F. Navarro
Conservative and Prosthodontics Dentistry, Faculty of Dentistry, University Complutense of Madrid, Madrid, Spain
e-mail: gpradies@ucm.es; albeferr@ucm.es

B. Hassan
Prosthodontics and Restorative Dentistry, Acibadem International Medical Centre Amsterdam, Amsterdam, Netherlands

C. A. Coronel
Prosthodontics and Restorative Dentistry, Faculty of Dentistry, University of Cuenca, Cuenca, Ecuador
e-mail: cabad02@ucm.es

A. R. G. Cortes
Faculty of Dentistry, Ibirapuera University (UNIB), São Paulo, Brazil

O. H. P. Baptista
Oral Implantology, Area Military Hospital of São Paulo (HMASP), São Paulo, Brazil

N. R. M. Zambrana
School of Dentistry, University of São Paulo, São Paulo, Brazil
e-mail: natalyzambrana@usp.br

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spectrophotometers for tooth shade matching, intraoral and extraoral scanners and 2D/3D radiological devices, spectrophotogrammetry, facial scanners, and jaw track motion systems are the main devices used to obtain digital information in restorative dentistry. The aim of this chapter is to describe to the reader the characteristics of every single family of devices as well as their specific nomenclature, features, and the types of file used.

2.1 Introduction to Digital Technology Concepts

A German mathematician and philosopher, Gottfried Wilhelm Leibniz, proposed a binary computing system in the seventeenth century with interesting connotations to the "Yin and Yang" concept propagated by Chinese culture. The word "digital" comes from the Latin root "*digitus*" meaning finger, which is routinely used for discrete counting drawing similarities to the fact that digital technology only accepts discrete values. Wilhelm Leibniz is largely considered to be the first informatician. Digital technology is defined as a binary code of combinations with just 0 and 1 as possible values of codification [1]. It was developed in the mid-twentieth century by American engineers who based their calculations on two possible states: 0 or switch off and 1 or switch on. The combinations between 0 and 1 are called bits. In parallel, another innovation inspired by such numerical codes was the American Standard Code for Information Interchange (ASCII) that described objects with digits [2].

Digital technology is based on discrete values; however, the information represented can be either discrete (numbers and letters) or continuous (images, sound waves, etc.). Digital signals are generally associated with the binary electronic digital systems used in modern electronics and computing; however, it does not have to be binary or electronic. An interesting example of digital technology in nature is the discrete codification of DNA genetic code, which is considered as a natural form of digital data storage. In dentistry, digital technologies are utilized in two main ways: On one hand, all the electronical devices that are currently employed have computerized components, and on the other hand, this hardware technology produces digital files that can be read, edited, manipulated, and merged with other types of digital files. For this reason, this chapter addresses basic concepts about both digital technologies and information and communication technologies (ICT).

2.2 Digital Technologies in ICT

Since the 1980s, digital technology has been continuously replacing analog signals. Compared to analog transmissions, digital signal is less distorted and easier to duplicate. Currently, analog signals are converted to digital ones using PCM (pulse code modulation), whereas telecommunication-based fiber-optic technology is completely digital [3]. Analog signals are invariably susceptible to increased noise levels, while digital technology produces noise-free communications. As such analog signals are associated with reduced duplication fidelity, while digital technology permits high-fidelity duplication. Regarding the amount of information that is possible to transport, analog signals occupy less space in raw format than digital technology, but thanks to the capacity of digital signals to be compressed in the end, digital signal is capable of transporting more information, more rapidly and with higher quality. Dentistry does not shy away from all the possibilities that digital technology offers us, and in fact on many occasions without being conscious of that, dental offices are more digital than one might think.

For example, the normal flow that a patient goes through when arriving for their very first appointment includes recording personal and demographic data in a digital database. Modern practices provide the patient with a tablet to fill in the questionnaires and to provide digital signature. Subsequently, clinical photographs and relevant X-rays are taken using digital technology. Inside the office usually a standard photograph series with a digital camera is taken. In numerous cases, some of these pictures will be used to make a basic or advanced DSD (Digital Smile Design) by using presentation software like PowerPoint® or Keynote® or even dedicated software like Digital Smile Designer Pro®. In all these cases, in one way or another, digital manipulation of the pictures is done. Continuing with a standard workflow in implant cases, digital diagnosis is made using a 3D digital radiographic device (i.e., CBCT), and the information obtained in DICOM format is used for diagnosis and treatment planning. Digital resources are then used to analyze these DICOM images, merging them with 3D surface files from the dentition, placing virtual implants, and designing surgical splint that eventually will be produced by using CAM technology. Once the implants are placed, digital impressions can be obtained using intraoral scanners and even merging these 3D surface files with the ones taken prior to the surgery, in order to recreate the original emergence profiles, teeth size and shapes if they are in ideal positions. Subsequently, again digital technologies will be used for designing and manufacturing (CAD-CAM) of the final restoration.

2.3 Digital Dental Photography

Photography is a fundamental tool in dentistry; it is particularly useful for diagnosis, planning, documentation, communication, and backup information [4–9]. Dental photography aids in making more precise diagnoses through photographic records that allow the patient to be evaluated extra- and intraorally. Additionally, it facilitates treatment planning and self-reflection on the conducted procedures, thereby permitting a more rigorous approach. It also improves visual communication with the patient regarding treatment options and possibilities and with the dental laboratory regarding patient's prosthesis characteristics in terms of color, shape, textures, tooth size, smile line, and facial form. It also aids to guide other members of the multidisciplinary team regarding treatment objectives. Digital photography also allows clear illustration of dental treatments for teaching and academic purposes. From a legal standpoint, it serves as a backup to judicial requirements. Finally, dental photography fulfills a purpose of external and internal marketing for the clinic. Modern digital photography has become more accessible due to improved storage capabilities while eliminating the environmental burden of traditional film processing.

In digital photography, the film is replaced by an electronic sensor that captures the image. The sensor is made up of thousands of photocells that transform photons into electrical signals. Each individual photocell transforms the light of a point of the image into electrons, generating a two-dimensional digital interpretation of the original image. The sensors used in most digital cameras are CCD (charge-coupled device) or CMOS (complementary metal-oxide semiconductor). Digital photographs can be observed immediately on a digital display or a high-definition external monitor and stored as computerized digital image files of various formats detail herein:

- RAW: This is the native image format as captured by the camera sensor. It is a read-only format, and it contains all the image data without any compression or loss of information. It is ideal for dental photography and for legal purposes. However, even though this format provides the highest possible image quality, the files generated are very large and require increased storage space as well as special software to visualization, processing, and modifications (Table 2.1).
- JPEG (Joint Photographic Experts Group): It is a compressed format with a low dynamic range. These adjustments reduce the size of the files but also cause loss of information. These image files can be processed within the camera itself and shared directly without the need for post-processing.
- PNG (Portable Network Graphics): It is a compression format used to produce small image files supported by the color schemes RGB (red, green, and blue) and scales of grays.
- GIF (Graphics Interchange Format): This format uses image compression to generate very small files limited to only 256 colors.
- TIFF (Tagged Image File Format): It is a lossless compression image storage format that can be directly processed by the camera prior to external storage. The images have a large size of up to 4 GB.
- BMP (Bit-Mapped Picture): This format produces large files that can include up to 2–16 million colors.

Photography has become an indispensable tool in dentistry that is available for any dentist equipped with a smartphone, or a compact camera, although SLR professional cameras (single-lens reflex) allow a better image quality, even without

Table 2.1 Raw file depending on each type of brand

Brand	File extension
Fuji	.raf
Canon	.crw .cr2
Kodak	.tif .k25 .dcr. drf
Panasonic, Lumix	.rw2
Nikon	.nef .nrw
Olimpus	.orf
Pentax	.ptx .pef
Minolta	.mrw
Casio	.bay

post-processing. Light, exposure, depth of field, background, patient positioning, and the correct visibility of the field to be photographed are key factors to obtain a good photographic record (Fig. 2.1).

Proper dental photography requires a suitable light source and appropriate lenses according to each case. The purpose of the lens is to magnify the areas of interest including dentition, periodontal tissues, and surrounding structures, using focusing distance that is reasonable and comfortable for the patient. For extraoral photography, a 50 mm lens is recommended to allow greater aperture of the diaphragm and brighter photos. Lenses of 100–105 mm are perfectly suited for intraoral dental photography due to their optimal magnification radius (the radius of the image projected on the camera sensor compared to the original size of the object). The higher the magnification used, the larger the image of the object projected on the sensor. Thus lenses for dental photography are usually set at a configuration ranging from 1:1 for specific tooth acquisitions (e.g., anterior teeth) up to 1:10 for full face shots.

Supplementary illumination is usually needed to photograph the dark regions of the mouth, especially in intraoral shots (Fig. 2.2). Different shapes and arrangements of light sources are available for dental photography. The *circular flash* is

Fig. 2.1 Dental photography to visualize details of natural upper front teeth

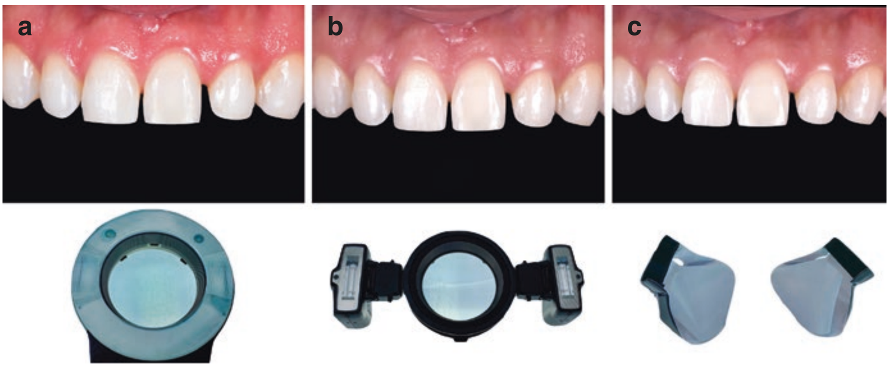

Fig. 2.2 Pictures with different light sources. (**a**) Ring flash. (**b**) Lateral flashes. (**c**) Lateral flashes with bouncers and light modifiers

considered the universal light system for the different scenarios of dental photography, although in some cases, *side flashes* mounted on the sides of the lens or on external posts can also be used. Light direction modifiers are used to avoid direct light incidence, whereas bouncers allow a smoother and more uniform light incidence on the object. Various textures and morphological contours can be obtained depending on the type of light used.

Dental photography is used to acquire both extra- and intraoral images (Fig. 2.3). Extraoral photography includes:

- Front photos, with or without separators
- Smile, very useful when evaluating the smile line
- Right and left profile, very useful when evaluating the smile line and with lips at rest

Intraoral photography includes:

- Separated upper and lower anterior dentition with an image contrast
- Upper and lower dentition in occlusion

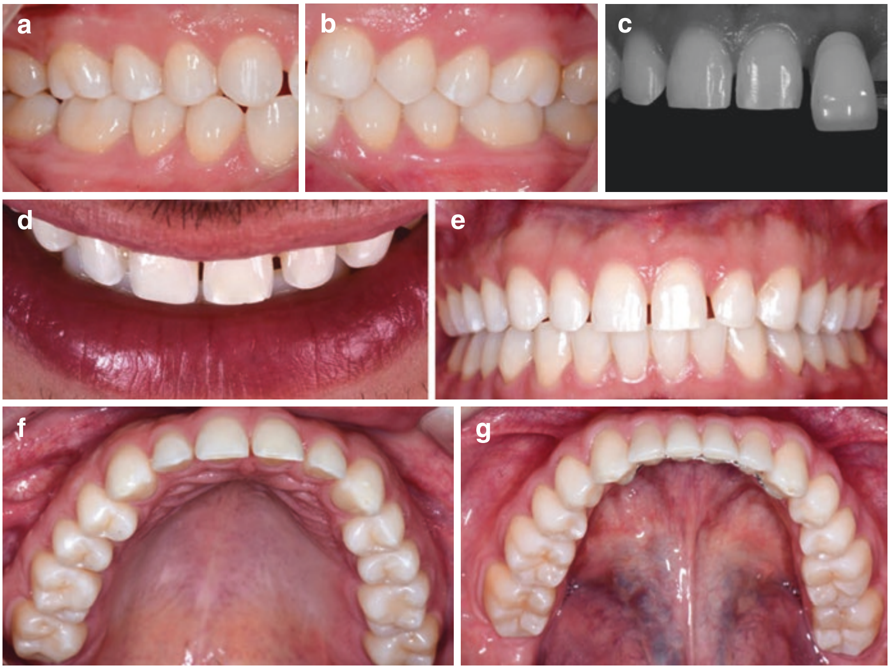

Fig. 2.3 Basic pictures in dental photography: (**a**) Right occlusion lateral view. (**b**) Left occlusion lateral view. (**c**) Black and white picture to assess the value, compared with a color guide. (**d**) Picture to evaluate the smile line with the reference of the lower lip. (**e**) Front occlusion view. (**f**) Upper arc occlusal view. (**g**) Lower arc occlusal view

- Posterior buccal segment both in occlusion and at rest
- Posterior lingual segment using mirrors
- Occlusal upper and lower arch

To take photographic records, the following aspects should be taken into account:

Determine and visualize the area to be photographed. This area must be completely dry without saliva, water, blood, or debris. Cheek retractors should be used to allow for maximum visibility of the area to be photographed. Mirrors must be clean, dry, and free of scratches. It is recommended to use mirrors covered with chrome, rhodium, or titanium to provide maximum reflection, avoiding distortions and duplicate images. It is important to avoid photographing the nostrils when taking pictures of upper-anterior teeth, as well as avoiding the beards. In the lower arch, the tongue should be retracted for better visibility of the lingual and occlusal areas. Fingers, mirror edges, and retractors should be outside the photographed area, or at least include them in an enlarged area to make their cropping more feasible. Select standardized image capture parameters at an appropriate distance for each specific lens and flash. For the posterior area (premolars and molars), the use of a circular flash with a power of 1/2 and an aperture (F-stop) of 29 is recommended: shutter speed (*S*) of 125 and an ISO value 100 or 200. For intraoral photos of the anterior segment, it is recommended to use side flashes with a power of 1/2, a F-stop of 29, and an ISO value of 100 or 200. It is necessary to mention that a higher ISO value might yield in higher image noise due to motion artifacts. Therefore, the lowest ISO value appropriate for the selected exposure must be selected.

In addition, most cameras currently have a video option, which are capable of generating high-definition (full HD) format. With video capture, the functional dynamic relation of incisal edge position in relation to the lower lip can be examined with respect to phonation and esthetics. Many mobile devices are able to capture video in full HD or 4K format permitting extraction of high-quality snapshot pictures from the video sequence.

Following image acquisition, post-processing software, such as Lightroom and Photoshop, can be used to improve and adjust the photographs without altering the content. It is important to notice that the image showed on the LCD screen of the camera does not represent the image recorded in the RAW file, since the LCD screen only represents a JPG version of the file with a very limited information. The same problem happens if you import the file to any non-specific post-processing software that does not support all the information that the raw file contains.

2.4 Digital Radiology

The wide adoption of digital radiography within the last two decades has revolutionized the practice of dentistry. This technology eliminated several disadvantages associated with conventional radiography including chemical processing and hazardous waste disposal while providing several decisive advantages in terms of digital storage and computer post-processing (digital enhancement). In radiography the emitted X-ray beam is attenuated (absorbed and scattered) by interaction with body tissues, and the resulting beam is projected on a detector. Most digital detectors used in dentistry are either indirect such as photostimulable phosphor plates (PSP) or direct solid-state detectors which include three subtypes: charge-coupled devices (CCD), complementary metal-oxide semiconductors (CMOS), and flat panel detectors (FPD) (Fig. 2.4) [10–12].

Indirect digital receptors (PSP) operate on the principle of photoluminescence; X-rays reaching the detector stimulate a plate containing photostimulable phosphor, which absorbs and stores this energy to form a latent image. The plate is then placed in a digital reader to release this energy as light photons when exposed to a light source of a different wavelength in a process known as (phosphorescence). The light photons are subsequently converted to electrical energy which, in turn, is quantified using an analog/digital converter and stored and displayed as a digital image. PSP detectors are thin and flexible and can be easily inserted intraorally without excessive patient discomfort (Fig. 2.5). However, they do require an intermediary step to read out the latent image from the sensor and are prone to wear and scratch development resulting from repeated and extensive use.

Among solid-state detectors, the CCD and CMOS are used for intraoral radiographs, while FPD are reserved for extraoral use. A CCD detector consists of a thin silicon wafer with an electronic circuit with a matrix of millions of light-sensitive cells arranged in a rectangular array on the face of the sensor. The active sensor area roughly corresponds to the size of the intraoral film. The X-ray photons falling upon the material in the sensor create an electric charge that is converted into a digital signal representing the gray values of the different tissues. CCD detectors were also made available for panoramic and cephalometric X-ray machines as thin slit receptors (narrow in width but extended in length) for extraoral use. CMOS receptors are also silicon-based, yet they differ fundamentally from CCD receptors in that each pixel is read individually by a coupled transistor to form an electric charge. CMOS detectors are cheaper to produce than CCD and are becoming increasingly more widely adopted in the dental office. The advantages of intraoral solid-state detectors include real-time digital image display and consistent image quality. However, these detectors are typically bulky and rigid and cannot be easily applied intraorally. In

Fig. 2.4 An example of the different types of receptors in dental radiography. An E-speed film (left), a photostimulable plate (middle), and a charge-coupled device (right)

Fig. 2.5 An example of a bitewing radiograph obtained using a digital PSP detector

addition, sterilization of solid-state detectors is rather cumbersome, and any damage to the detector is expensive to repair.

Extraoral imaging devices can utilize PSP or CCD technology for image acquisition. In addition, flat panel detectors (FPD) are also used in panoramic and cephalometric imaging. The detection of X-rays occurs in a scintillator layer composed of thallium-doped cesium iodide. The X-ray beam is converted into light photons, which are then used to create an electrical signal by an array of photodiodes. The advantages of FPD include their high spatial resolution, X-ray detection efficiency, and reduced noise levels. However, FPD receptors are susceptible to damage and are expensive to install and to maintain.

The performance of digital detectors can vary in terms of contrast and spatial resolution and dynamic range or image latitude. Image contrast refers to the ability to distinguish among different tissue densities, which is influenced by both subject and detector contrast. Subject contrast is the result of the differential attenuation of the X-ray beam by the subject being imaged. As X-ray radiation passes through the patient's tissue, bone, and teeth, it is partially absorbed depending on the type of tissue it encounters. Detector contrast refers to the capacity of the receptor to record different densities, and it varies per detector type. Spatial resolution refers to the ability to distinguish the fine details in an image, and it is defined as the shortest detectable distance between two points or the size of the smallest pixel in the image.

2.5 Digital Spectrophotometers

Digital spectrophotometers are devices that are used to determine the shade and color of dental tissues. The use of electronic color measurement devices has many advantages over classical visual techniques with conventional shade guides (i.e., Vita Classic Shade Guide, Vita Toothguide 3D Master; Vita Zahnfabrik, Postfach, Germany) because they provide quick objective measurements; compared to naked-eye or conventional techniques for shade assessment, digital spectrophotometers seem to be at least 33% more accurate and 93.3% more precise. Thus, the use of digital spectrophotometers is recommended for determining tooth color in esthetically demanding restorations [13–15].

These devices measure the energy of light reflected by an object at intervals of 1–25 nm along the visible spectrum. A spectrophotometer consists of a light source, a light-scattering medium, an optical measurement system, a detector, and a contraption to convert the captured light to a signal that can be analyzed. The device produces a spectral reflectance or transmission curve as a function of the light wavelength. The shade measurements are represented as a brightness curve and compared with the brightness curves of the color guides. The measurement made with these devices is not affected by ambient light, yielding an objective record [16–18].

The dental spectrophotometers have a database with different color guides for defining tooth shade. The color data obtained by the spectrophotometer is translated to a matching color in an existing shade guide to facilitate clinical use. Also, these devices offer the data of the color space following the $L \times a \times b$ or the $L \times C \times H$ coordinates, which allows to assess differences in colors indiscernible by the human eye [19, 20]. These tools have many clinical applications that range, among others, from assessing the effectiveness of a whitening treatment to evaluating the color differences between restorations, and they are widely used for scientific research [21–24].

Besides recording the shade across the tooth or in specific area using a probe, some of these devices can capture a photograph of the tooth and assign individual colors to each tooth third (incisal, bulk, and cervical) (Figs. 2.6 and 2.7 and Table 2.2). They are also capable of making a chromatic map of the tooth, which helps improve the stratification of ceramic or composite restorations of the esthetic zone. The chromatic maps obtained with these devices are usually very detailed and sometimes allow the customization of the guides [25]. Images and/or spectral data can be transferred via USB, wireless LAN, or SD card and sent to the laboratory in real time.

Since the technology utilized in spectrophotometer is similar to that employed in intraoral scanners, several digital impression systems are currently capable of recording the actual tooth shade concurrently with the 3D topology, yielding similar results to those obtained with spectrophotometers. At the time of writing this book, both the Trios 3 and the Omnicam intraoral scanners have this capability [26].

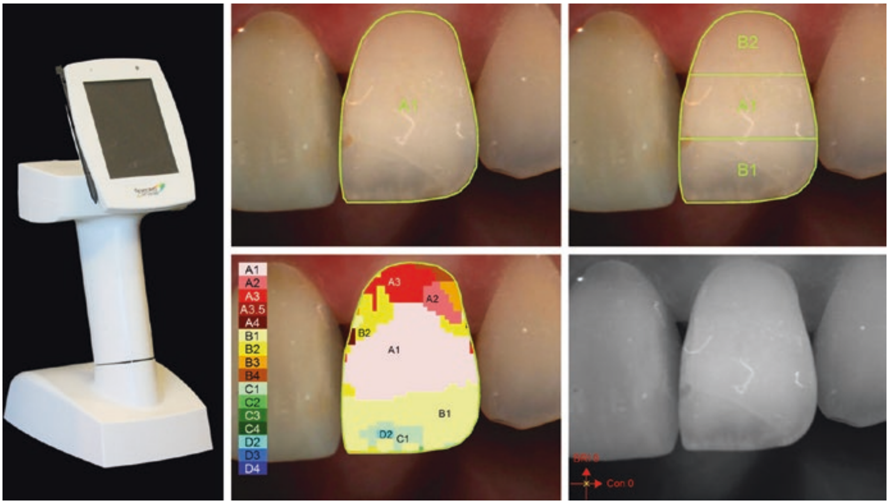

Fig. 2.6 Record of a spectrophotometer with an image of the tooth recording. With this type of measure, the operator can analyze the basis color of the tooth, the color by thirds (cervical, medium, and occlusal). Moreover, the image can be converted in an image in gray scale for analyzing the different visual effects, and the chromatic map of the tooth can be obtained

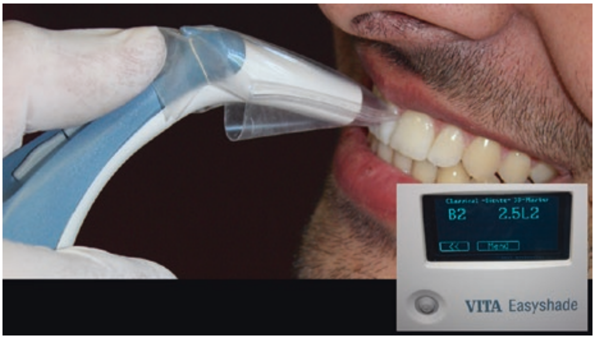

Fig. 2.7 Spectrophotometers with a probe tip. This type of device allows us to obtain information about the areas, but we cannot obtain an image of the tooth analyzed

Table 2.2 Type of spectrophotometers available

Spectrophotometer	Manufacturer	Technology	Photo
Easyshade	Vita (Bad Säckingen, Germany)	Intraoral reflectance spectrophotometer with a 5 mm probe tip	No
Rayplicker	Borea (Limoges, French)	Digital camera with a LED spectrophotometer	Yes
SpectroShade	MHT (Verona, Italy)	Digital camera with a LED spectrophotometer	Yes

2.6 Extraoral Scanners

A 3D scanner is an electronic device capable of capturing and processing information from the surface of an object or terrain, in order to build a three-dimensional digital representation of it. In dentistry, nowadays it is possible to obtain digital models of the dentition by either direct 3D scanning of the oral cavity, using intraoral scanners, or by indirect 3D scanning of cast models made from conventional impressions, using laboratory scanners [27].

Extraoral laboratory scanners are either tactile or optical. Tactile scanners, also known as contact scanners, capture surface topographies through mechanical contact between a detection unit and the cast model. Optical scanners, also known as noncontact scanners, capture 3D images using laser or structured light technologies [28] (Table 2.3). Contact scanners are more precise, albeit slower than noncontact types. The main advantage of the latter is that there is no mechanical contact between

Table 2.3 Extraoral scanners currently available, with the information of the accuracy they have, classified according to the type of technology on which they are based

Technology	Scanner	Manufacturer	Accuracy
Structure light	AutoScan-DS300	Shining (Hangzhou, China)	10 μm
	Cara Scan	Kulzer (Hanau, Germany)	15 μm
	Cendres+Metaux	Cendres Metaux (Biel, Switzerland)	5 μm
	Ceramill Map 400	Amann Girbach (Koblach/ Austria)	6 μm
	D2000	3shape (Copenaghen, Denmark)	8 μm
	Dental Scanner MDS 550	Maestro (Pisa, Italy)	10 μm
	Deluxe 3D Optical Scanner	Open technologies (Rezzato, Italy)	5 μm
	inEos X5	Dentsply/Sirona (Bensheim, Germany)	2.1 μm
	Identica T500	Media (Incheon, South Korea)	7 μm
	IScan L1	Imetric (Courgenay, Switzerland)	<15 μm, depending on the type of case
	Kavo LS3 Scanner	Kavo (Biberach, Germany)	Up to 4 μm
	S900 Arti	Zirkonzahn (Gais, Italy)	10 μm
	Vinyl	Smart Optics (Bochum, Germany)	6 μm
	Evolution Plus	Zfx (Munich, Germany)	9 μm
Laser	7 series	Dental Wings (Montreal, Canada)	15 μm
	ConoScan 4000	Optimet (Jerusalem, Israel)	10 μm
	Cyno Prod i3.5	Numeq Inc (Quebec, Canada)	30 μm
	OpenScan 100	LaserDenta (Berghain, Germany)	20 μm
	Orapix 3D scanner	Orapix (Seoul, South Korea)	20 μm
	ShapeGrabber	ShapeGrabber (Ottawa, Canada)	40 μm
	Zeno Scan S100	Wieland (Pforzheim, Germany)	50 μm
Contact	Procera Forte	Renishaw (Gloucestershire, UK)	1–2 μm
	Renishaw Incise	Renishaw (Gloucestershire, UK)	1–2 μm

the object and the detection units, so they can scan faster and are not influenced by the hardness or dimensions of the object.

2.6.1 Contact Extraoral Scanners

Contact scanners were the first type of extraoral scanners to appear on the market, and they are still the most accurate type of scanners. Yet, they are the slowest scanners because they rely on the very slow process of mechanical contact between a moving probe and the entire surface of the object to be scanned. Although nowadays the are rarely used for lab practice, they are still needed for some special indications in implants.

Contact scanners employ a probe made of a very resistant material, such as ruby, that continuously comes in contact or dragged over the surface to be measured [29]. These scanners are not affected by the optical characteristics of the surface of the object, but they can be affected by their physical characteristics. For example, scanning silicone impressions would inevitably lead to surface deformation caused by probe impingement on the impression surface leading to reduced accuracy.

There are two types of contact extraoral scanners:

- Coordinate measuring machines
  Coordinate measuring machines (CMM) consist of a wide horizontal platform and a robotic arm that moves along a few lanes in the three axes of space. The arm holds a probe with a ruby/metal ball on its tip, and it moves until it comes into contact with the object to be measured, registering with great accuracy the position of the arm at that moment. It is generally used to make measurements on the shape and dimensions of an object and to compare them with the dimensions of its CAD design. The precision of a CMM is usually 1–2 μm, which is significantly higher than the precision of an optical scanner in the *X*–*Y* axis. In the *Z* axis (height), the scanner precision can be similar to an optical extraoral device. CMM scanners are slow; in the same amount of time that an optical scanner measures millions of points, a CMM measures only a dozen of them. Another disadvantage of this kind of device pertains to the difficulty of measuring objects with very complex shapes.
- Articulated arm
  It is an articulated arm with a probe on one end and very precise angular sensors at the joints. From the orientation of these joints, the position of the tip of the probe is reconstructed. It is useful for measuring free forms or complex objects.

2.6.2 Noncontact Extraoral Scanners

These scanners use some type of electromagnetic wave, typically light, to capture the information of the models. These types of scanners, compared to the contact scanners, are very fast and do not distort the scanned surface, because the emitted light is the only thing that contacts the surface. However, light can be affected by the surface characteristics. Translucent surfaces return light to the scanner not only by reflection but also by refraction, which can alter the measurement. They can also be affected by very bright surfaces. Noncontact extraoral scanners can perform point-to-point measurements, capture lines, or scan entire surfaces. The scanners that capture entire surfaces collect much more information at the same time and can therefore be more precise. Also, they do not have the problem of having to line up with other lines, as in the case of those that project a single line. In this last case, another reference system is needed to correctly combine these lines [30].

There are different extraoral noncontact scans:

- Structured light scanners
  The optical scanners that employ light as a source of radiation are referred to as structured light scanners. The principle of action of these devices is the projection of a narrow band of light on a three-dimensional surface that produces a line of illumination that is distorted if viewed from a perspective other than that of the projector. Structured light scanners use that information to geometrically reconstruct the surfaces of a model [28]. To avoid interference from ambient light, these scanners use specific light colors, white or blue and a lesser extent green or red, and some scanners also use light filters and shutters. The color of the object also influences the scanning. For instance, a blue surface will hardly be seen when scanned with a blue light. This issue affects to a lesser extent white-light scanners since they span a wider spectrum of light, but it remains a challenge when scanning completely black objects.
- Laser light scanners
  These scanners work by projecting a point of light on the object and register its position with a set of cameras to triangulate the three-dimensional position of the point. To accelerate scanning time, these scanners can actually project a line of laser light instead of a point [31]. This type of scanner produces fewer reflections on the surface of the model, which reduces the quality of the obtained scan.
- Confocal microscopy and confocal holography scanners
  These are a subtype of structured light scanners or laser scanners that allow reading narrow details of the study model. These scanners are based on an optical technique used to increase the resolution and contrast by using a very small spatial pinhole lighting spot to eliminate out-of-focus light.

2.7 Intraoral Digital Scanners

Intraoral scanners for the direct digital impression of the dental arches were introduced for the very first time by Mörmann and Brandestini in the 1980s. Concurrently and independently, Francoise Duret was developing this kind of technology since 1971 [32]. Direct intraoral digital impressions provide a decisive advantages over conventional methods with elastomers in terms of increased procedure comfort, and improved communication between patient, clinician, and dental laboratory, while could be proprietary or open source and often includes a suite of different work modules. Most design software are acquired in a standard version that allows to design common dental and implant restorations such as single copings or bridge frameworks or even in some systems post and cores. All systems have add-on modules that can be acquired independently, which extend the range of indications and design capabilities. Underneath we discuss the main modules usually included in design software:

- *Smile design*: As described earlier in the chapter, smile design software can process 2D photos and/or 3D files of the patient face and teeth; it could also merge intraoral scans with facial scans for a more comprehensive results (Fig. 3.4). With this module, the dental care provider can edit reference points and lines, in order to determine the ideal dental proportions, and select teeth from an electronic library to simulate the final results of the proposed treatment [9].
- *Virtual wax-up*: This module allows dental care providers, especially technicians, to create virtual wax-ups of the cases in a very efficient manner that replaces the traditional hot wax laboratory procedures. From these virtual wax-ups, physical mock-ups can be 3D printed for assessment in the patient's mouth. Besides their use for restorative mock-ups, this type of modules is also used to design splints for surgical procedure such as crown lengthening [10].
- *Tooth library*: Usually, design software would include a library of different forms of teeth that the operator can use across the different modules. These libraries

Fig. 3.4 Digital smile design made with design software in which the information obtained was combined with an intraoral scanner, a facial scanner, and the photographs of the patient. This planning was made through Dental CAD 2.2

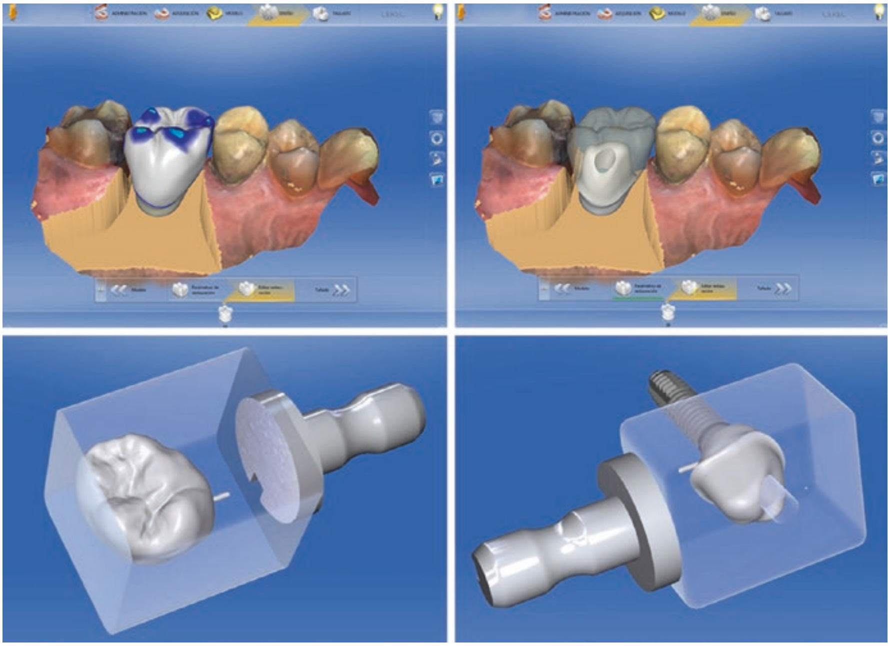

Fig. 3.6 Design of a cement-retained implant restoration, including the customized abutment and the crown for fabrication by machining a monolithic restorative material. This case was prepared with the SW CEREC 4.5.2 software

3.5 Virtual Tools in CAD Software

All available CAD software systems have different tools for design automation. In fixed dental and implant prosthesis, CAD software can automatically detect the margins of the tooth preparation or the implant emergence profile, the tapering of the abutment axial walls, the interocclusal space, the path of insertion, and the thickness of the final restoration, depending on the material selected. In implant-supported prosthesis, the CAD software can control the path of insertion across multiple implants and manage unfavorable screw access and malalignments of up to 30° with tools such as the Dynamic Abutment® Solutions.

The software can propose designs for the anatomy of the final restoration through mathematical algorithms, by relying on the anatomy of another tooth in the patient's mouth, also known as bio-referencing, or by relying on a scan of the provisional prosthesis or the original tooth prior to extraction, also known as bio-copying [20, 21]. Different virtual tools are available to improve the position and the occlusal contacts of the restorations by allowing the operator to move, stretch, or rotate them, as well as by adding or removing material and smoothening the surfaces (Fig. 3.7) [22]. In overdentures, complete dentures, or removable partial dentures, the CAD bridges, dental implants, and maxillofacial prostheses [3]. Below we address the main dental applications for the laser melting technology in dentistry:

Removable Dentures

The metallic frameworks of partial removable dental prostheses (PRDPs) can be processed effectively using the laser melting technology (Fig. 4.12). Cobalt-chromium (Co-Cr) alloys processed by laser melting have shown superior mechanical and physical properties for partial removable dental prostheses (PRDPs) compared with the traditionally cast Co-Cr alloys [75]. Moreover, titanium alloy processed by laser melting technology presented a good quality for PRDP framework [76, 77]. In addition, a randomized controlled clinical trial showed that patients wearing laser-sintered (laser-melted) PRDPs presented better outcomes in terms of patient satisfaction than those treated with conventional PRDPs [60, 78, 79]. Co-Cr and Ti alloy base plates for maxillary complete denture were also fabricated effectively by laser melting technology, and they were suitable for clinical use [80, 81].

Fixed Partials Dentures

The metal copings for dental crowns and bridges can be successfully processed by laser melting technology, and the copings achieved high internal fit and high marginal accuracy [60, 61, 82, 83]. In addition, the Co-Cr and Ti dental copings manufactured by laser melting technology have presented better mechanical properties and adhesion to ceramic coatings than the conventional cast Co-Cr alloys [84–89]. Clinical studies assessed the efficiency of metal-ceramic fixed dental prosthesis by laser melting technique, and they showed high survival rate and promising results for clinical use [90, 91]. In addition, Co-Cr post-cores were fabricated effectively by laser melting technique [92].

Dental Implants

Dental root implants and implant prosthodontic framework can be produced by laser melting technology. This technology allows to create customized implants or

Fig. 4.12 Photographs showing the metallic framework of a partial removable dental prostheses (PRDPs) processed by the laser melting technology

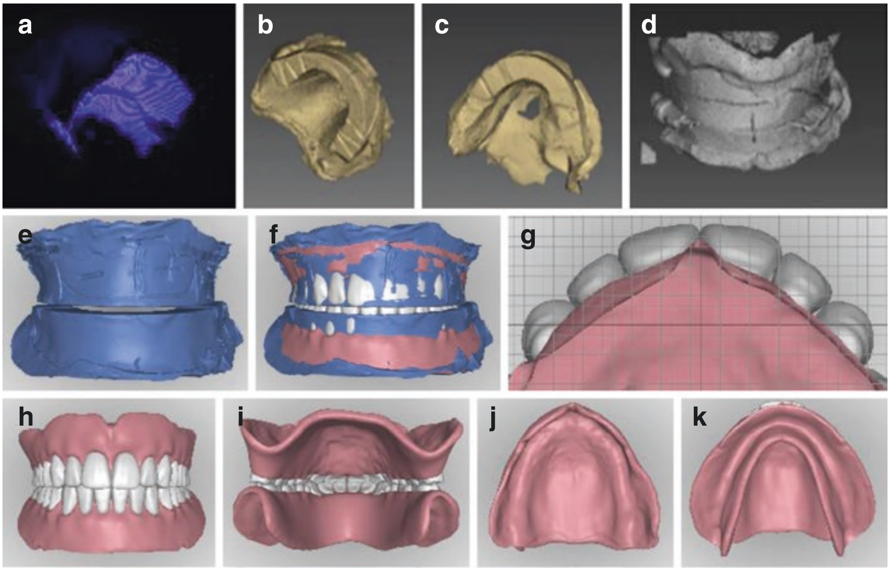

Fig. 6.6 (**a**) Scanning wax rim IOR, (**b**) scanned maxillary wax rim, (**c**) scanned mandibular wax rim, (**d**) best-fitted merged view of wax rims and IOR, (**e**) scanned wax rims IOR, (**f**) frontal overlap view of proposed teeth setup and scanned wax rims, (**g**) anterior teeth position view, (**h**, **i**) proposed denture teeth setup of frontal and rear views, (**j**, **k**) maxilla and mandibular intaglio surface views

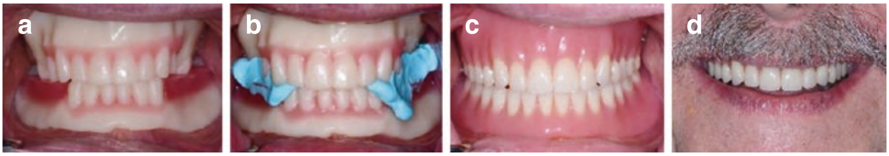

Fig. 6.7 (**a**, **b**) WTI frontal view and smile view of the final DRCD with wax rim impression technique, (**c**) front view of wax rim technique final DRCD, (**d**) smile view of wax rim technique final DRCD

In the presented clinical case (Fig. 6.7), there was a discrepancy on the wax rim IOR, and it was decided to use a WTI for confirming IOR and possible rearrangement of denture teeth. The WTI process could be very useful to reconfirm IOR without adding an extra clinical visit if the dentist or the laboratory technician found problems in the IOR. Anterior teeth were rearranged, and a new IOR was registered for fabrication for final DRCD (Fig. 6.7a, b).

Step f: Delivery of the final DRCDs would follow the same delivery protocol as conventional RCDs. However, since the DRCD technique does not have any mounted cast, a clinical remount may be necessary (Fig. 6.7c, d).

Fig. 6.8 (**a**) Duplication flask, (**b**) duplicated dentures, (**c**) replication technique impressions and IOR front view, (**d**, **e**) scanning of maxillary duplicate denture on intaglio and cameo surfaces, (**f**, **g**) best-fitting process, (**h**, **i**) scanned BTI front and lateral views, (**j**, **k**) overlap front and lateral views of BTI scan and proposed DRCD teeth setup of replication technique, (**l**, **m**) front and lateral views of proposed DRCD design, (**n**) modified BTI and a new IOR front view, (**o**) revised overlap views of final proposed denture setup of front view, (**p**) new proposed denture teeth setup front view, (**q**, **r**) overlap views of first BTI mandibular try-in denture and final proposed mandibular denture setup

6.3.4 DRCD Try-In Denture

Optional denture try-in can be carried out by different methods. It can be milled or 3D printed in one piece or only the base leaving the denture teeth for setup with pink base plate wax. Try-in denture milled or printed in one piece present limited

Fig. 6.9 (**a**) Final denture front view of replication technique, (**b**, **c**) final denture smile frontal and angled views of replication technique

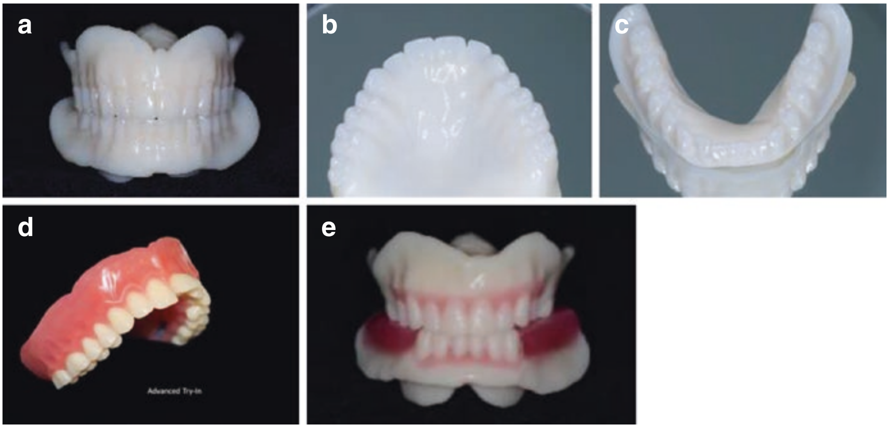

Fig. 6.10 (**a**) Functional BTI (Biofunctional Try-In), (**b**, **c**) Dentca try-in dentures, (**d**) ATI (AvaDent Try-In), (**e**) WTI (Wagner Try-In) frontal view

freedom to rearrange tooth position. Often, additional IOR and try-in dentures would be required due to incorrect occlusion. AvaDent BTI can order only monolithic milled dentures and cannot be used for the bonded denture teeth technique. WTI teeth setup uses lip measurements, and the WTI includes individualized maxillary anterior teeth and a one-piece mandibular anterior teeth block, which seems to be too flat without providing proper anterior arch curvature. Therefore, often times it needs to be modified by splitting in half or disassembling. The WTI comes with maxillary one piece first and second molars and mandibular posterior wax rim for IOR. The try-in step would still provide the dentist with some freedom to retake IOR and make additional impressions to correct some deficiencies of border extension and on intaglio surfaces (Fig. 6.10a–e).

6.4 Conclusion

The DRCD is still in the developing stages of the digital technology movement in dentistry. It will be streamlined, and the use of this technology is already expanding. Some of the limitations and disadvantage will be overcome once we have enough

Fig. 8.3 Placing grooves on proximal surfaces will increase the resistance form

Fig. 8.4 Example of preparation design for zirconia-ceramic FDPs. Note the rounded line angles

subsurface lesions in the tooth structure and improves the marginal adaptation of the restoration (Fig. 8.6) [5].

7. A single path of insertion should be created when preparing abutment teeth to support a fixed dental prosthesis (Fig. 8.7).

Specific considerations should be taken into account regarding tooth preparation depending on the material that will be used in the final restoration. Underneath we detail the specific guidelines for each type of material:

Guidelines of tooth preparation for monolithic polycrystalline (i.e., monolithic zirconia) and all-metal restorations (i.e., gold):

1. Chamfer lines of 0.3 mm depth should be adequate.
2. Knife edge (vertical preparation) can be considered.

Fig. 8.5 Example of preparation design for zirconia-ceramic prostheses following the removal of old fixed dental prostheses

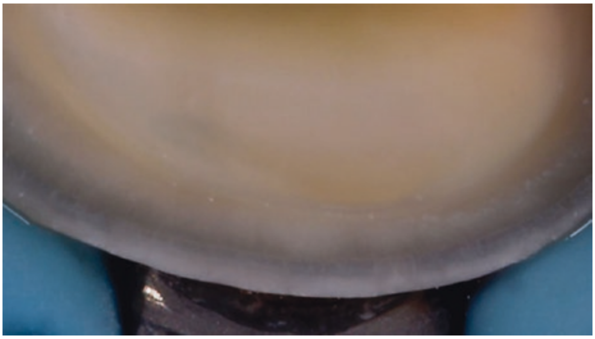

Fig. 8.6 A close-up showing a marginal finish line prepared with extra fine/fine diamond burs

3. Axial and occlusal reduction should be at least 0.5 and 1.0 mm deep, respectively.

Guidelines of tooth preparation for particle-filled ceramics (i.e., lithium disilicate) and layered restorations (i.e., metal-ceramic, zirconia-ceramic):

1. Chamfer or shoulder depths should be of 1–1.5 mm when particle-filled ceramic materials or layered restorations are used.
2. Occlusal/incisal reduction should be 2 mm.

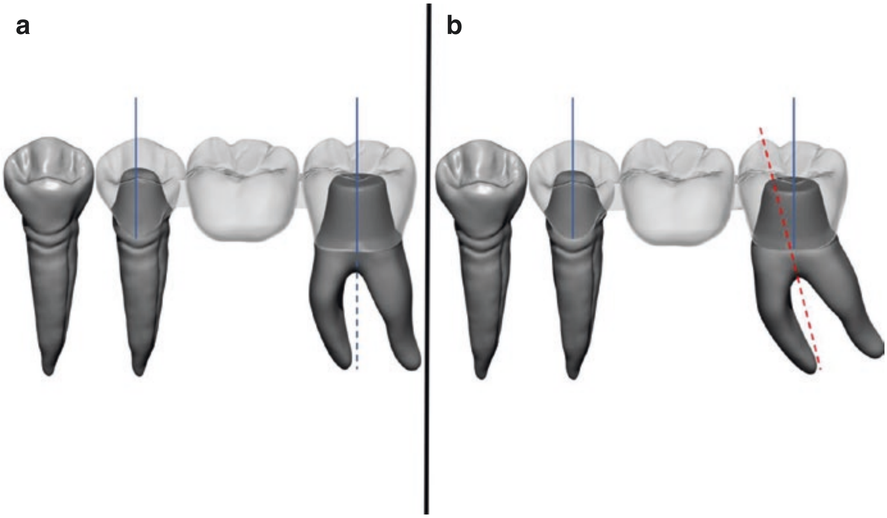

Fig. 8.7 The preparation design on the abutment teeth should create a single path of insertion. (**a**) The roots of both abutment teeth are parallel. (**b**) The preparation design on the molar compensates the mesially tipped tooth in order to respect the path of insertion

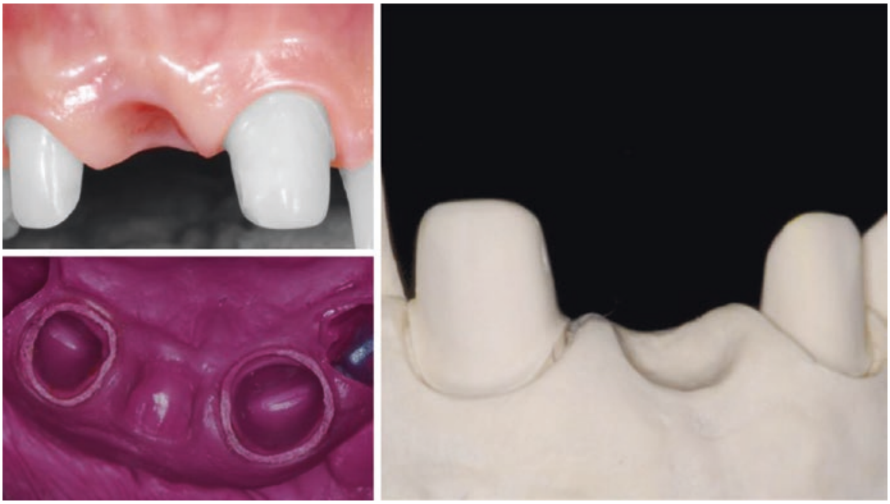

Fig. 8.8 Analog impression and master cast

8.2.2 Impression

The conventional treatment approach includes making analog impression and the fabrication of casts in order to manufacture the prosthesis using the lost-wax technique (Fig. 8.8) [7]. The advent of digital technology has been instrumental for the development of CAD-CAM fixed dental prostheses, and digital impression

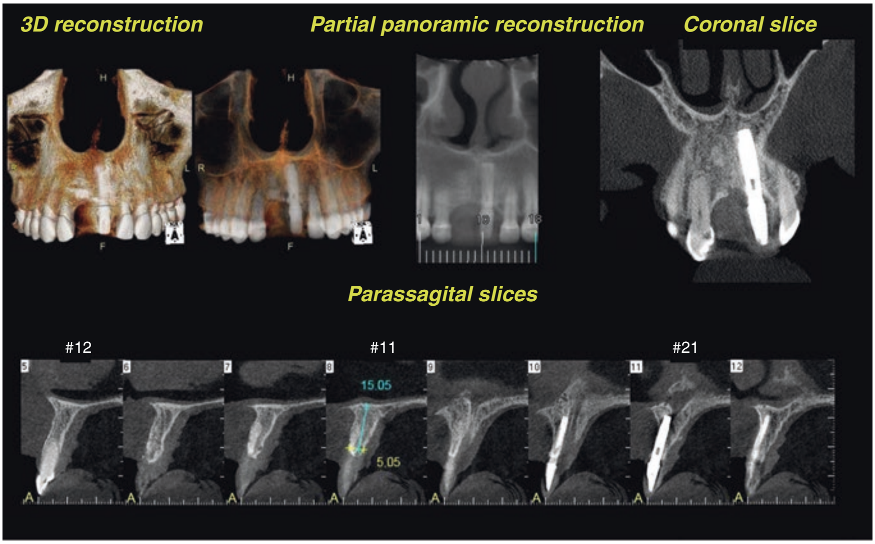

Fig. 9.1 Example of a CBCT 2D template used for implant planning

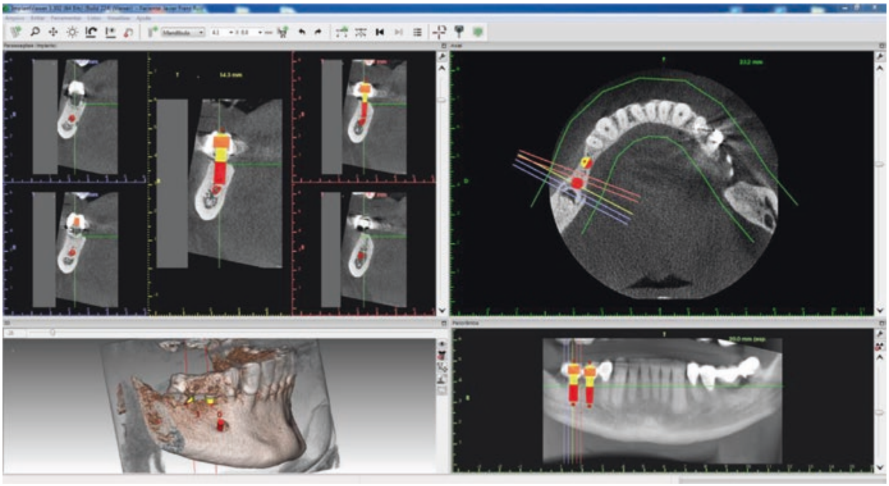

Fig. 9.2 Virtual implant planning using CBCT data only (ImplantViewer software, Anne Solutions, Sao Paulo, Brazil)

9.2.2 Implant Planning Software

In contrast with printed CBCT images or JPG files, implant planning software allows for interactive 3D assessment to achieve accurate implant surgical planning (Fig. 9.2). 3D multiplanar reconstructions generated from CBCT (axial, coronal, and sagittal) may also include a curved plane (i.e., coronal panoramic images) and

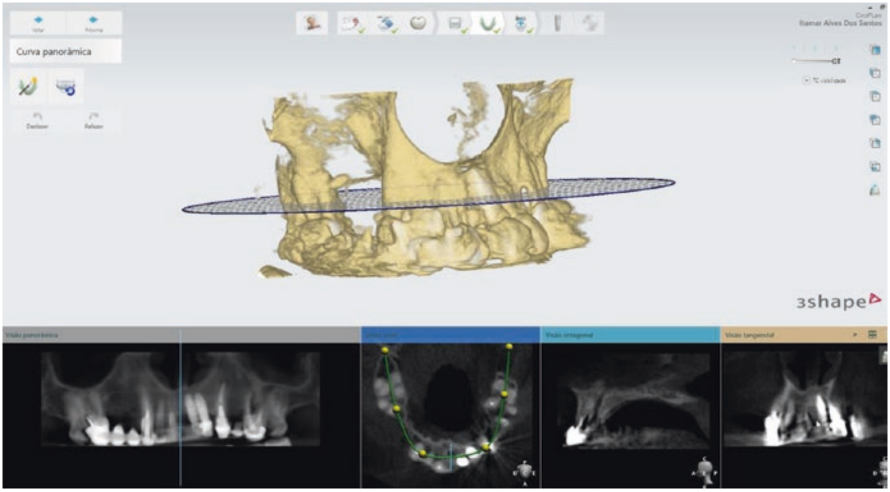

Fig. 9.7 Metal artifacts preventing adequate superimposition of DICOM and STL images

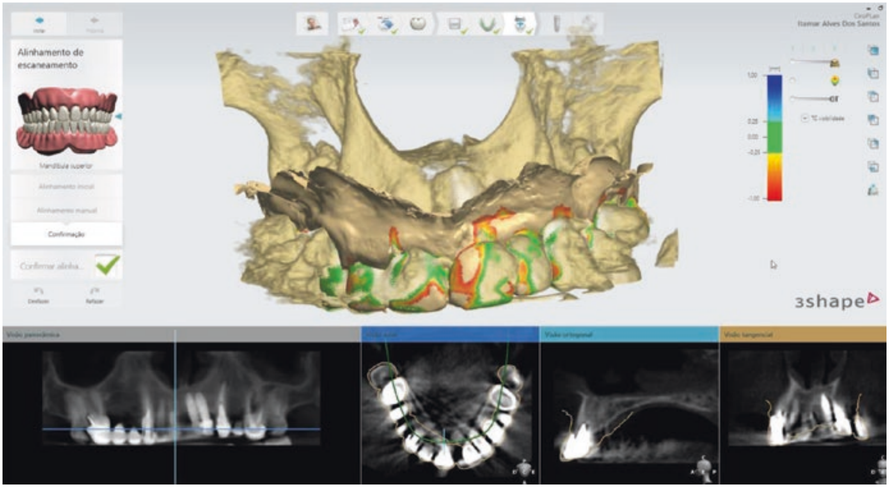

Fig. 9.8 Manual superimposition for adequate STL and DICOM merging

9.4.3 Virtual Prosthetic and Dental Implant Planning

The ultimate objective of placing dental implants is to support a final prosthetic restoration. In other words, patients seek teeth and not implants; thus a restorative-driven mind-set should always be maintained. The prosthetic treatment should be designed to restore esthetic, function, and occlusal stability while considering implant position and angulation.

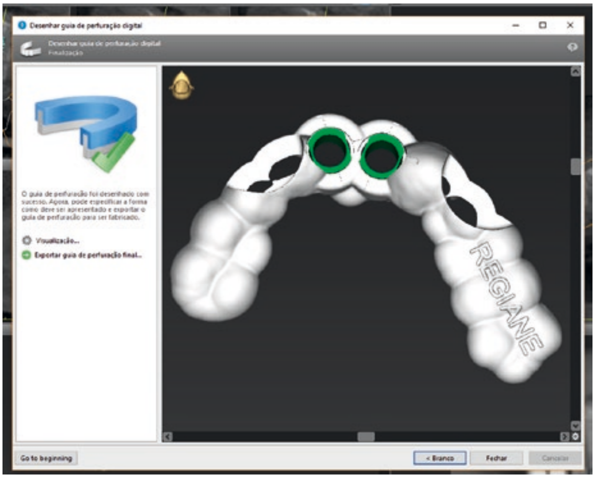

Fig. 9.19 Surgical guide resulting design of the same case shown above

Fig. 9.20 CAD/CAM fabricated surgical guide

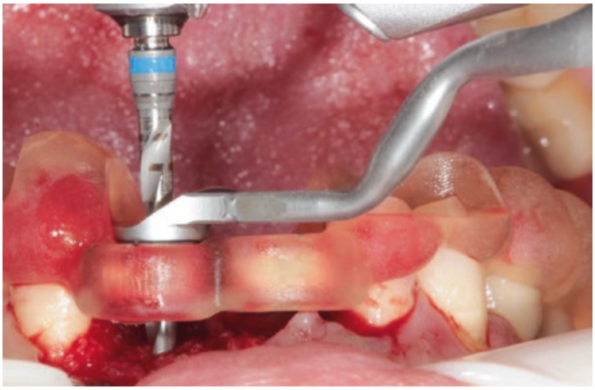

Fig. 9.21 Image-guided implant surgery

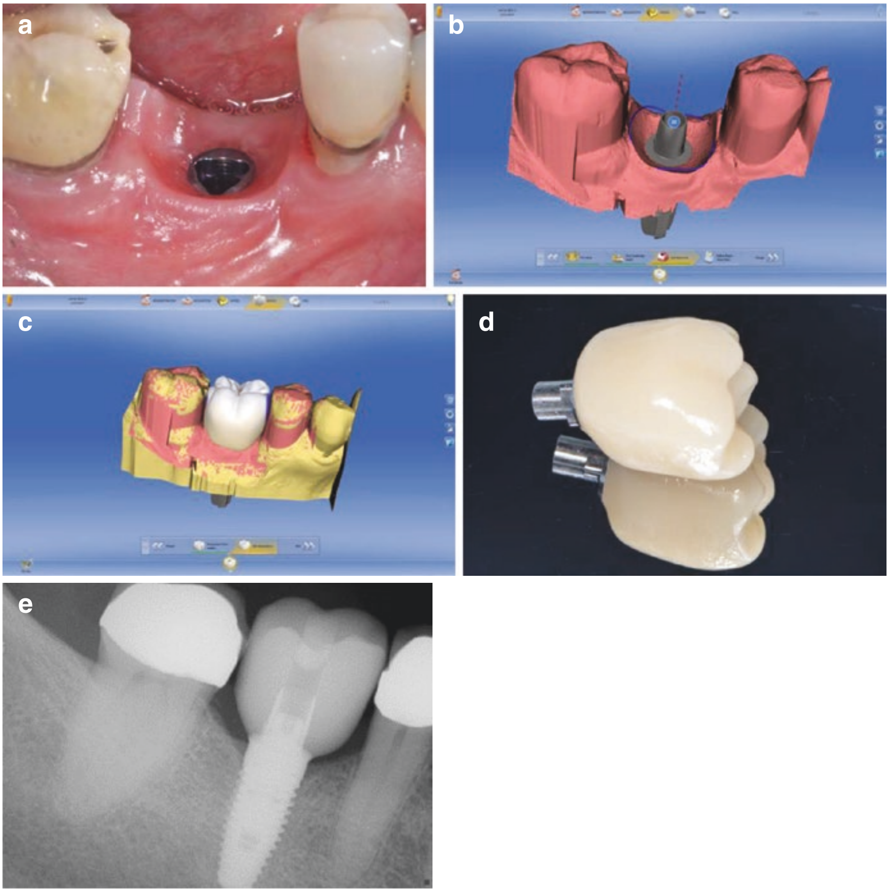

Fig. 10.6 (**a**) Nobel Biocare Replace Select 5.0 in the position of #30. (**b**) Determining the emergence profile with the chairside CEREC software v 4.4.4. (**c**) Designing the screw-retained crown with the chairside CEREC software. (**d**) Enamic hybrid abutment crown (screw retained). (**e**) Radiograph of final restoration in place

screw channel is then blocked using a cotton pellet or Teflon tape and then sealed with composite resin. Figure 10.6a–e shows a clinical case with a Nobel Biocare Replace Select 5.0 implant in position #30.

10.5.2 Cement Retained

10.5.2.1 CEREC Hybrid Abutments with Veneering Crown (Fig. 10.7)

As explained earlier, the hybrid custom abutment is designed alongside the veneering crown. The location of the abutment margin can be modified to achieve the desired esthetic outcome. The veneering crown is designed just like a conventional

Fig. 11.2 Occlusal view of the first right mandibular molar. Note vertical root fracture extending from mesial to distal. This fracture was detectable with the help of magnification (microscope). No signs of the fracture or bone lesions were detectable on CBCT

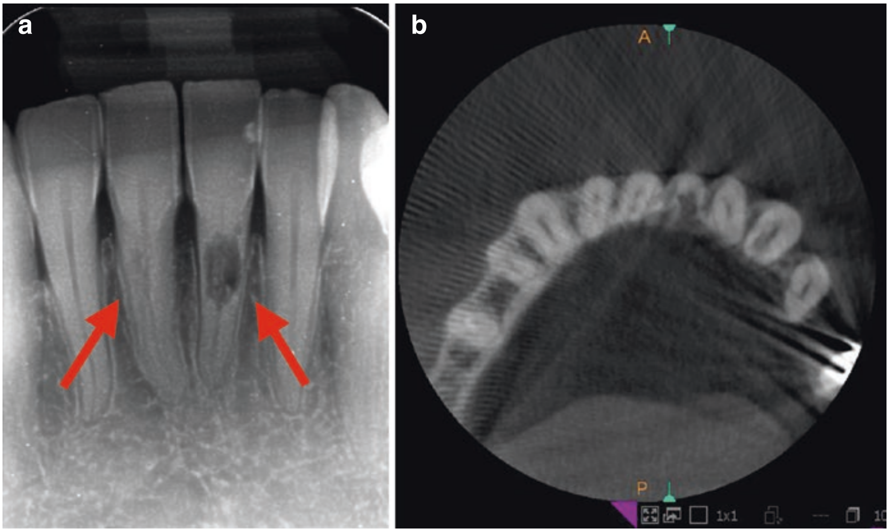

Fig. 11.3 Radicular root resorptions of the central mandibular incisors are visible on the conventional 2D periapical radiograph (**a**). The CBCT helps clinician to know the extension of the resorption (class IV Heithersay) (**b**). In this clinical case, the left central incisor cannot be treated because of the extension of the resorption (class IV Heithersay)

11.2.4 Radicular Root Resorption

Conventional radiographic detection and assessment of root resorption may be challenging. CBCT helps clinicians determine the location and extension of root resorptions. CBCBT allows distinguishing between internal inflammatory and external cervical root resorption. Ultimately, data collected by CBCT can help determine whether conventional treatment, surgery, or a combination of both is required (Figs. 11.3 and 11.4).