Digital Restorative Dentistry

A Guide to Materials, Equipment, and Clinical Procedures

Faleh Tamimi
Hiroshi Hirayama
Editors

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1 Introduction

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

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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

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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,

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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

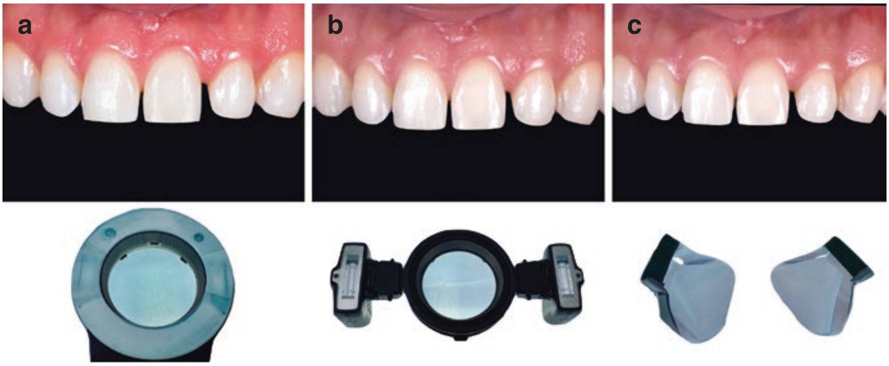


Fig. 2.2 Pictures with different light sources. (**a**) Ring flash. (**b**) Lateral flashes. (**c**) Lateral flashes with bouncers and light modifiers

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

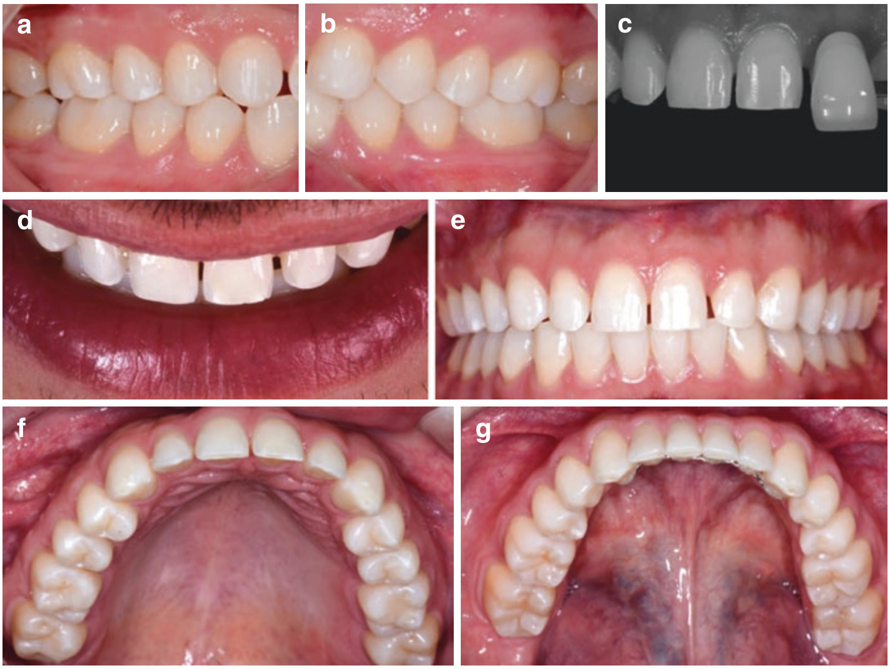


Fig. 2.3 Basic pictures in dental photography: (**a**) Right occlusion lateral view. (**b**) Left occlusion lateral view. (**c**) Black and white picture to assess the value, compared with a color guide. (**d**) Picture to evaluate the smile line with the reference of the lower lip. (**e**) Front occlusion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

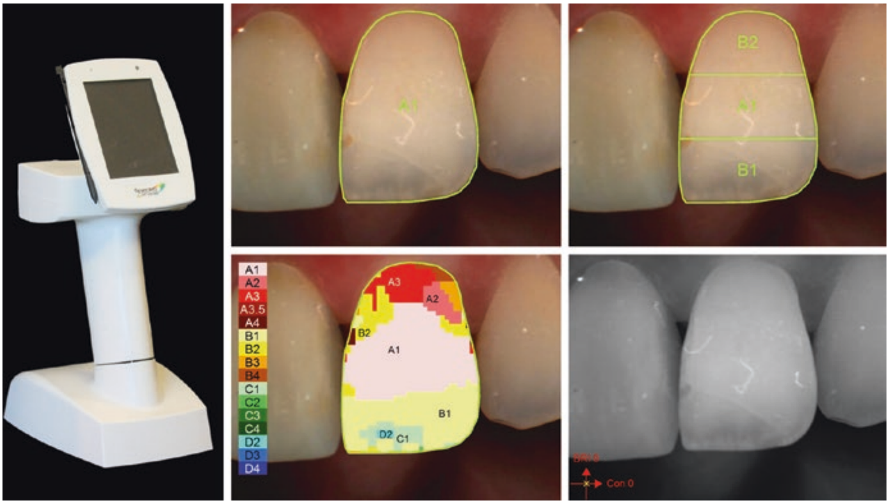


Fig. 2.6 Record of a spectrophotometer with an image of the tooth recording. With this type of measure, the operator can analyze the basis color of the tooth, the color by thirds (cervical, medium, and occlusal). Moreover, the image can be converted in an image in gray scale for analyzing the different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

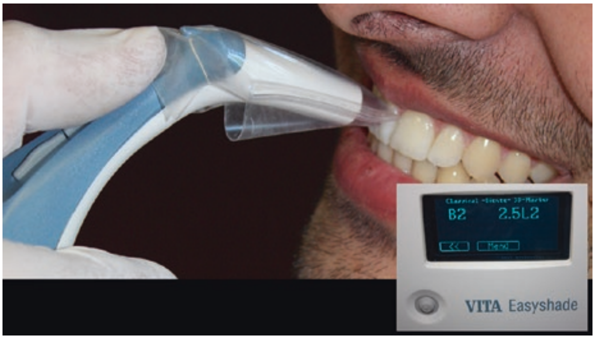


Table 2.2 Type of spectrophotometers available

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 virtually eliminating all problems related to elastomer deformation (shrinkage/expansion) thereby resulting in added accuracy.

For many years, the CEREC system was the only commercially available intraoral scanner. However, the last decade witnessed a rapid increase in the number of manufacturers, and currently, several digital intraoral impression systems based on different scanning technologies are available. Irrespective of the technology used, all intraoral digital scanners construct 3D models by capturing and stitching to each other multiple images taken from the oral cavity. The stitching process is critical, and it is done through a best-fit alignment in which a series of errors may arise and compromise accuracy [33–35]. These stitching errors can be corrected by mathematical algorithms within the control software of the scanner, although this process is sensitive to other factors [36–43] such as operator's experience in handling the device. Indeed, inexperienced operators tend to produce less accurate scans than more experienced operators [36, 37].

The resolution of the STL files generated by scanners depends on the number of triangles used to represent the object surface, which may vary according on the scanning control software used [35]. This factor can affect, for example, the visibility and accuracy of the finish line in abutment preparations for fixed prosthesis, hence compromising the quality of the final restoration [39–41]. Thus intraoral scanners with similar hardware can perform very differently depending on variations in the control software [42].

The scanning strategy applied by the operator is another factor that could affect scanning accuracy, especially in full-arch cases. Depending on the scanners' technology, a specific scanning protocol is usually recommended by the manufacturer. Nevertheless, most protocols usually start by scanning the arch where the restoration is located, followed by two subsequent scans, one for the antagonist arch and another one for the teeth in occlusion. The occlusion or (bite) scan automatically aligns both upper and lower jaw scan into centric occlusion. If necessary, additional scanning can be done, for example, for digital impression of peri-implant soft tissues [44].

Another important factor for accurate scanning, regardless of the type of scanner used, is the control of soft tissues and saliva. To achieve a proper scanning, separators should be used to retract the lips and cheeks for isolation of the treatment field, and retraction cords should be used to expose the finish lines of crown preparations when needed [39–41]. The accumulation of saliva and blood are among the most common reasons behind alterations in the accuracy of the scan, and therefore they need to be controlled.

Regarding digital intraoral impressions of dental implants, the depth, the inclination, the number, and the distance among implants could influence the final result, especially in cases of full mouth rehabilitations with multiple implants [36–38, 42, 43]. Digital intraoral impressions of dental implants are done using a specific abutment known as a scan body that is used to register the 3D spatial position of the implant. Scan bodies have a specific geometry that is recognized by the design software to accurately determine the position of the virtual implant analog/replica and generate a 3D model with the position of the implant. Hence, the dental

Table 2.4 Features of different intraoral digital scanners, including type of capturing technology, use of powder, and the possiblity of chromatic scanning

Intraoral scanner	Manufacturer	Technology	Powder-free	Color
True Definition	3M (St. Paul, MN, USA)	Video	No	No
AC Cerec Omnicam	Dentsply/Sirona (Bensheim, Germany)	Video	No	No
AC Cerec Prime scan	Dentsply/Sirona (Bensheim, Germany)	Video	Yes	Yes
Trios 4	3Shape (Copenhagen, Denmark)	Video	Yes	Yes
Itero Elements	Align Technologies (San Jose, CA, USA)	Photo	Yes	Yes
CS 3700	Carestream (Rochester, NY, USA)	Video	Yes	Yes
Planscan Emerald	Planmeca/E4D Technologies (Richardson, TX, USA)	Video	Yes	Yes
DWIO	Dental Wings (Montreal, Canada)	Video	Yes	No
IntraScan	MHT (Verona, Italy)	Photo	Yes	No
Condor Scan	Condor (Gent, Belgium)	Video	Yes	Yes
Aadva 200	Gc (Tokyo, Japan)	Video	Yes	No

laboratory should be equipped with CAD software that includes virtual libraries of the scan bodies used in the clinic in order to create 3D virtual models with the correct position of the implants. The scan bodies are manufactured using metal alloys or polyether ether ketone plastic (PEEK) through high-precision milling [45].

Intraoral scanners used in clinical practice nowadays can be classified into two categories: (1) those that require the deposition of a layer of powder on the surface to be scanned to eliminate light reflection from the teeth and (2) those that do not require powder coatings (Table 2.4). Both types of scanners are detailed herein.

2.7.1 Coating Scanners, Powder Scanners, or Monochromatic Scanners

First-generation scanners based on active triangulation technology or active wavefront sampling technology require coating the surfaces of teeth and soft tissues with titanium oxide powder to prevent light reflection, since reflected light could saturate the scanners' sensors and compromise image precision. Depending on the type of scanning technology, the use of powder may be required for the entire surface or restricted to certain regions of interest [36, 37, 39, 46].

Scanners based on active wavefront sampling technology rely on capturing images through a group of lenses. When the image is focused in the scanner sensor, the focal length of the lens matches the distance to the object; however, if the image is out of focus, the distance from the lens to the object can be calculated by a mathematical formula using the size of the blurred image [34] (Fig. 2.8).

Active triangulation scanners project a pattern of stripes on the object. The rays of light, generally a LED light, are reflected to the sensor, and the distance between the projector and the reflected pattern is measured using the Pythagorean theorem [34].

Fig. 2.8 Powder-based scanning of a multiple-implant case using metallic scan bodies in order to obtain a monochromatic 3D model

Powder scanners are very accurate; however, they present some disadvantages including patient discomfort due to powdering of the mouth and scanning inaccuracies caused by excessive use of powder in some areas or removal of the powder layer by the saliva or the tongue [47]. To avoid such problems in full-arch intraoral scanning, it is recommended to apply the powder and scan by sextants, performing an S-shaped sweep on the buccal, occlusal, and lingual sides of each tooth [47].

2.7.2 Non-coating Scanners, Powder-Free Scanners, and Chromatic Scanners

Currently, there are several technologies that allow powderless scanning, enabling the operator to obtain a 3D model with the color of the teeth and the soft tissues [48, 49]. However, in some cases it is still recommended to apply powder on some surfaces because many materials used in dentistry, like dental alloys or ceramics, are highly reflective. A typical case would be the clasps of removable partial dentures that require a thin layer of powder for proper scanning [33].

Powderless scanners capture images using the principles of parallel confocal imaging; thus, the production of images is achieved by parallel confocal microscopy associated with the projection of structured light. The scanner emits light, and the object surface at a certain distance will reflect the light back to the tube. The device eliminates the out-of-focus images, and the appropriate images are converted into digital data. The type of light used can vary depending on the technology used by the scanner [34, 42].

Other powderless scanners use ultrafast sectioning technology to capture up to 3000 images per second [41, 44], and use these images to create real geometries, based on real data, instead of forming artificially interpolated surfaces. Another possibility includes the use of full color 3D video for continuous image acquisition (Fig. 2.9). Some 3D video scanners include optical triangulation technology in combination with confocal microscopy for scanning without powder and in color [50].

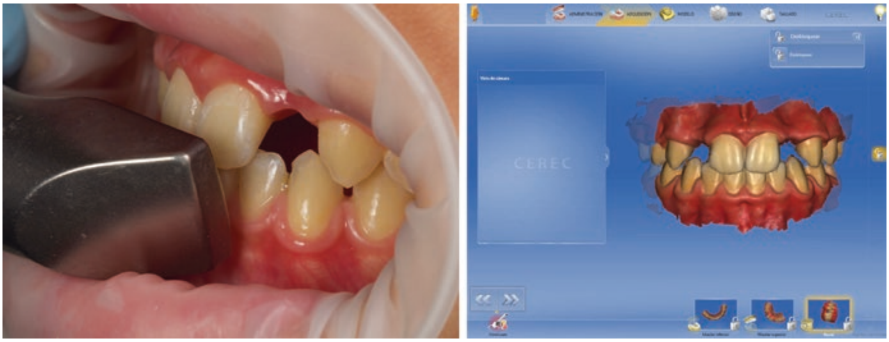


Fig. 2.9 Powder-free intraoral digital scanner. In this case, the file obtained contains the information of the color of soft and hard tissues

The recommended protocol for scanning a full arch with powder-free scanners is a linear trajectory on all occlusal-palatal surfaces followed by the occlusal and buccal surfaces [44].

2.8 Digital Stereophotogrammetry Technology

Stereophotogrammetry is a technology with a high level of accuracy that allows to determine the spatial position of different objects by taking multiple photographs from different angles. This technology has been in use in engineering and architecture for terrain topography mapping since the mid-nineteenth century. In dentistry, it has been used since the 1990s in several in vitro studies for assessing the accuracy of different conventional elastomeric impression techniques on implants [51–54].

More recently, this technology has been used for direct data capture to generate files providing information on the 3D spatial position of multiple implants in the oral cavity, without making any physical contact. The spatial position data obtained by this technology has a marginal error of only 10 μm, so it is possible to obtain implant framework with an adequate passive fit [55]. In addition, this promising technology is not sensitive to operator experience.

The available systems consist of three components:

1. *A laptop* with specific CAD software to control the camera and manage the personal data of the patient and the implants, indicating positions and type. The software contains a library with the geometry of different connections and platforms of various implant brands.
2. *Abutments* with a black surface and some white spots over it that are placed in different positions for unique identification purposes.
3. *An extraoral stereo camera* that consists of two infrared charge-coupled device cameras.

To make the impression, the cameras are situated at a distance of 20 cm from the patient's mouth, and the device takes around 64 photographs in less than 20 s [55–59]. Depending on the system used, the cameras will be placed in a fixed position or moved by the operator until the position of the implants is properly recorded. Following image capture, a digital file is generated with the 3D information of the spatial position of each implant (Fig. 2.10). The information obtained with this device is combined by best-fit alignment with 3D scans of the soft tissues and teeth obtained from either extraoral or intraoral digital scanning. For correct alignment of both types of 3D images, it is necessary to take the impressions with the healing abutments, and capture reference points that allow the operator to combine the digital file containing the position of the implants, with the digital file containing the data on the soft tissues and teeth. At this point, the lab technician can design the future framework of the prosthesis and manufacture a 3D printable model with the analog implants for final processing of the prosthesis [58]. Advantages of this technology include improved comfort for the patient as the operator does not take an impression with an elastomeric material, as well as getting a fast and accurate procedure for the 3D spatial position of the implants [60]. Disadvantages include the restriction to large implant cases as it is not possible to acquire an impression for a single implant. In addition, the technology can only be applied on implants and not on teeth or soft tissues. As such, it requires integration with other digital impression techniques to capture the dentition and surrounding tissues [60].

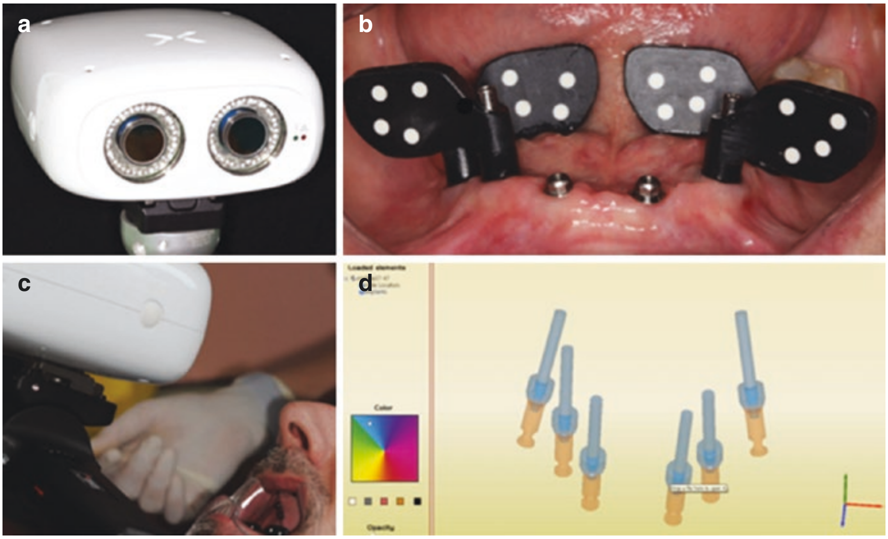


Fig. 2.10 (**a**) Image of the camera. (**b**) Abutments with white spots for taking the measurements. (**c**) Positioning of the camera with respect to the patient's mouth. (**d**) File with vectors of each implant and the 3D spatial relationship between them

2.9 Jaw Motion Tracking

Recording jaw movement is a diagnostic and therapeutic tool used for determining the dynamic jaw path to evaluate functional disturbances and occlusal interferences when providing extensive prosthodontic and orthodontic rehabilitation [61]. Recent advances in information technology have enabled the use of multiple fiducial markers to record the movement of the mandible directly on the patient in real time and to overlay this position on 3D surface models of the jaw to facilitate individualized prosthesis design based on the patient's specific occlusion and functional patterns [62]. There has been a burgeoning interest in integrating jaw motion (4D) data in dentistry for the purpose of individualizing the prosthetic teeth setup [63]. The main concept is to incorporate patient-specific border jaw movements (protrusion, retrusion, medio-trusion, latero-trusion) in CAD-CAM software to design a functional prosthesis that would be fully individualized to the patient's specific chewing, speaking, and bruxing patterns, thus eliminating the need for intraoral occlusal adjustments often deemed required in full mouth rehabilitation while reducing the risk of prosthesis chipping or fracture (Fig. 2.11).

Several commercial systems are currently available to record jaw movements utilizing magnetic, ultrasound, electronic, or optical tracking technologies (Fig. 2.12). These systems also vary in their technical procedures, clinical workflows, jaw recording precision, patient comfort, ease of application, integration with other methods, and costs [64].

Some systems combine analog and digital methods in which dental casts are digitized using extraoral laboratory scanners before digital jaw recording data can be applied to the virtual models. Other systems provide fully digital workflows eliminating the need for a physical teeth setup. Additionally, some jaw tracking systems relate the motion to the condylar hinge axis position using either kinematics or anatomical references, while other systems record the jaw motion with no skeletal references. Due to lack of evidence in the literature regarding the accuracy

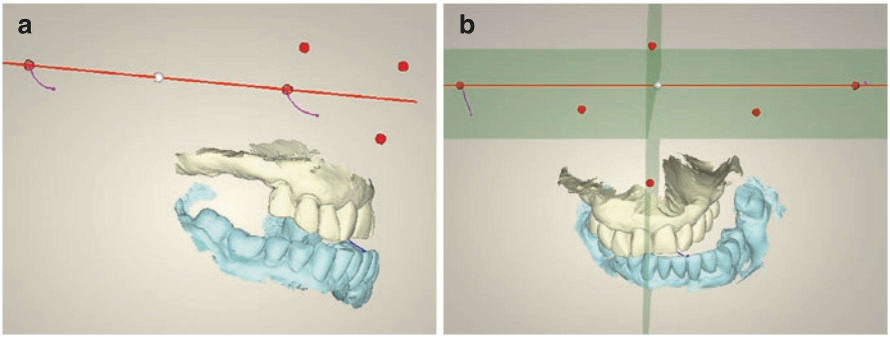


Fig. 2.11 An illustration of protrusive (**a**) and lateral excursions (**b**) jaw movements carried out on 3D models generated from intraoral scans

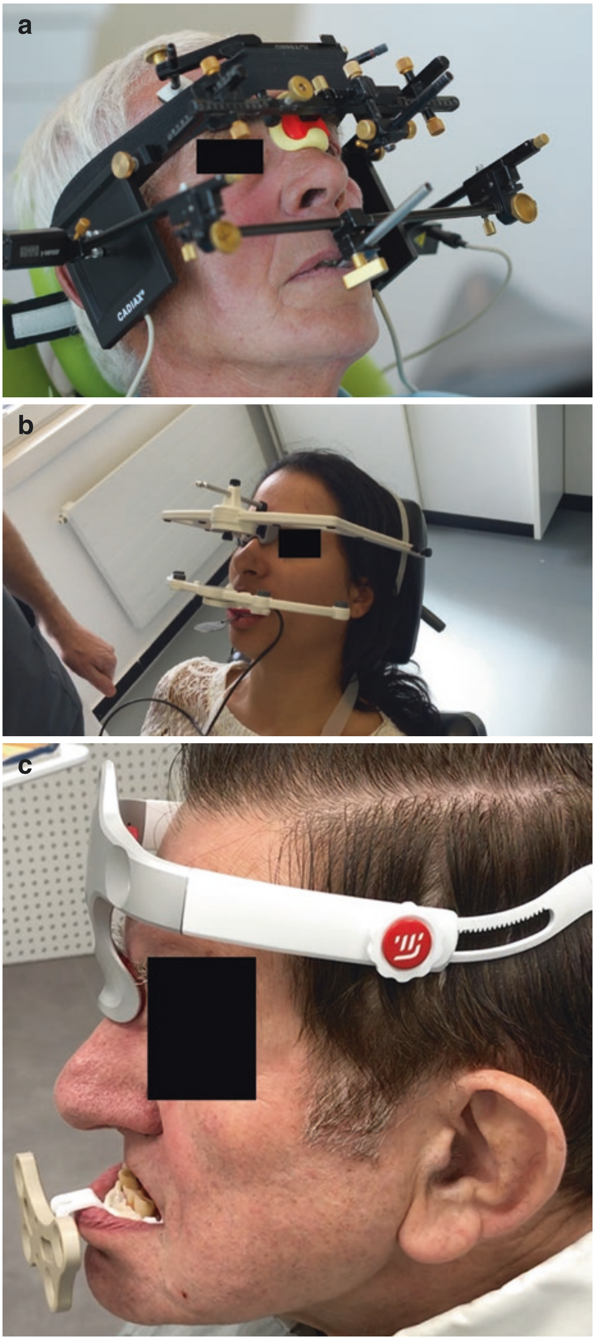


Fig. 2.12 An example of different jaw tracking systems. (**a**) Cadiax (Gamma, Austria), (**b**) SICAT Function (SICAT, Germany) (**c**) M-JEE (Modjaw, France)

of these systems, clinical recommendations for a particular system or technology cannot yet be made (Fig. 2.13).

Digital functional diagnosis can improve bite registration procedures by determining the centric position on 3D models and through visualization of occlusal contacts in maximum intercuspation. This could prove essential when attempting to increase vertical dimension of occlusion in case of partial edentulism or excessive tooth wear. Using jaw motion data, an appropriate new vertical dimension of occlusion can be identified for use in the CAD-CAM environment. Visual demonstration of premature contacts on the virtual teeth setup might lead to early identification of occlusal interferences during the prosthetic design phase. Finally, an important development in recent years includes the integration of jaw motion data with intraoral digital impression and CBCT to create a fully functional dynamic virtual patient replica that can be used to simulate different treatment scenarios (Fig. 2.14) [65].

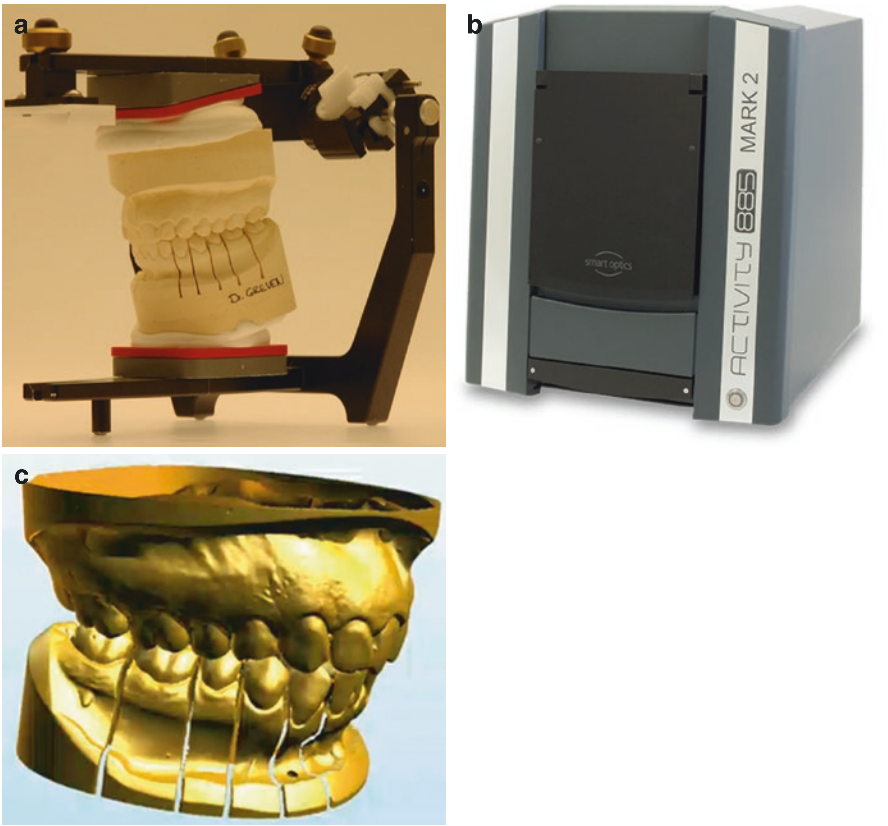


Fig. 2.13 Cast models in an adaptor (**a**) digitized using an extraoral scanner (**b**) in the correct coordinate system to generate 3D models in the correct frame for applying jaw motion data (**c**)

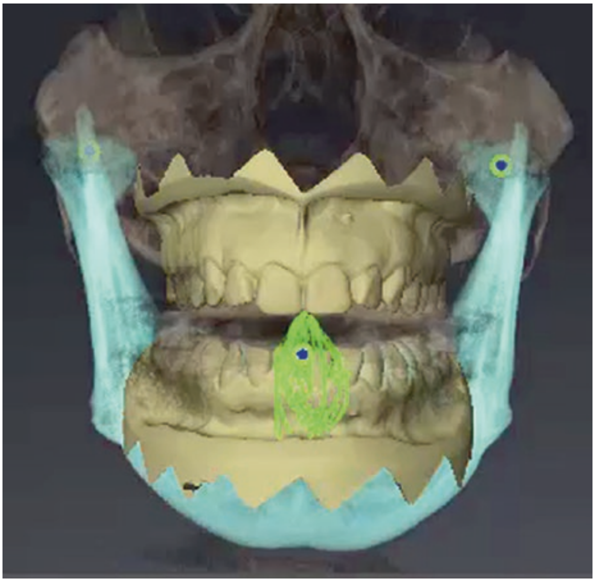


Fig. 2.14 Integrating CBCT with intraoral and jaw motion data

2.10 Facial Scanning

Facial scans can be done using digital stereophotogrammetry, as described above, or using laser beam scanning technology. The basic setup consists of a laser light source, a camera, and the object to be scanned “the face.” The laser is primarily projected onto the face, and the deflected beam is captured by the camera sensor which is placed at a known distance from the laser source. The distance between the laser beam and the surface of the face can then be triangulated (Fig. 2.15). Laser beam scanning is rapid and highly accurate, and the device is lightweight which means that it is suitable for limited office space. However, since the image is not captured all at once, the technique is inevitably sensitive to motion artifacts, and it could therefore lead to reduced geometric accuracy. In addition most systems do not provide 2D color texture information [66, 67]. Structured white-light technology operates on similar principles of trigonometry, but instead of the laser, a safe (white or blue) light in a specific pattern is projected onto the face. The fringe light pattern is bent and twisted following the natural curvature of the facial topology. This deformed light pattern is observed through the camera, and a 3D facial coordinate map is formed (Fig. 2.16). Simultaneously, high-resolution texture 2D photographs can also be captured and integrated onto the mapped 3D surface in order to generate a full color 3D model of the face. Single camera systems are limited to a narrow angle necessitating multiple acquisitions to completely cover the face. However, this means inevitably that the scan is prone to motion artifacts and that further post-processing is required to align the different views to obtain a single 3D mesh. Multiple cameras systems are also available which instantly capture the face across and angle of almost 180°, thus eliminating the need for multiple acquisitions.

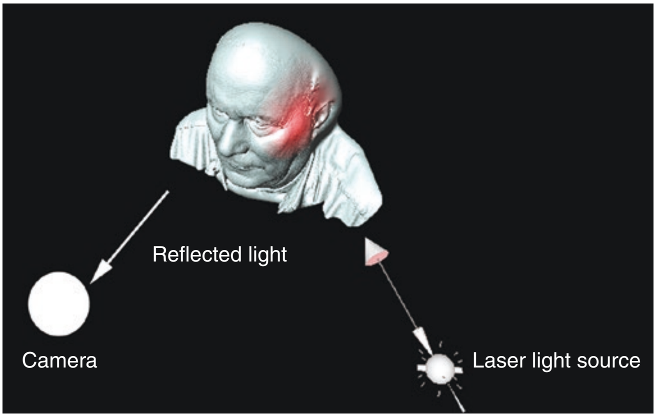


Fig. 2.15 Laser surface scanning system. The incident laser light is reflected from the object and captured by a camera system

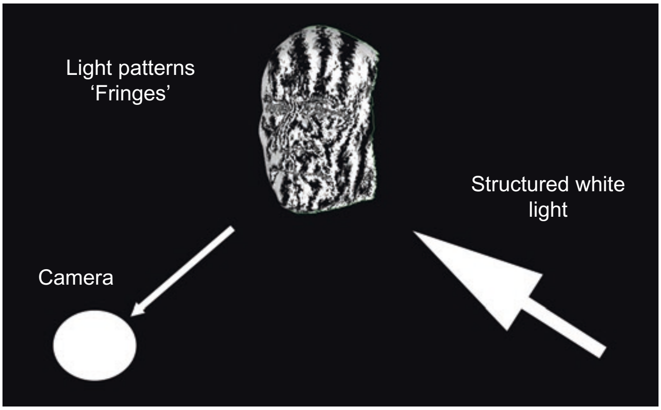
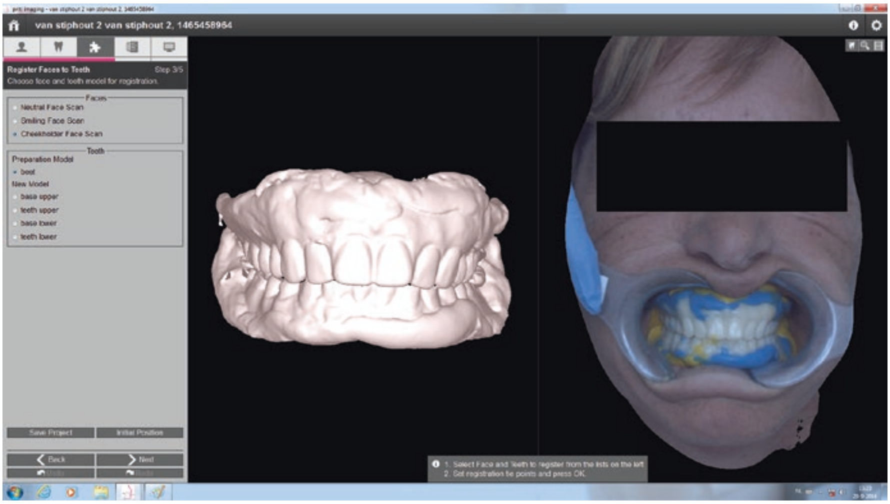


Fig. 2.16 Structured light scanning system. The light pattern is projected onto the face forming the light and dark patterns (fringes) which are observed by a camera system

Structured light remains at present the most clinically applicable technology for acquiring 3D facial surfaces in the maxillofacial region owing to its high accuracy (within 0.2 mm) and short scanning time of under 1 s [68, 69]. Passive stereophotogrammetry technique merges a pair of high-resolution, 2D digital photographs obtained from different angles to create a dense 3D point cloud, which eliminates the need for light patterns or laser scanning. This technique has the advantage of being extremely rapid and uncomplicated. The procedure resembles capturing ordinary photographs; multiple digital cameras need to instantaneously capture multiple images to form the stereopair, and post-processing is required although it is largely automated. The accuracy of such system for dimensional imaging (Di3D) was recently found to be within clinically acceptable limits.

Facial scans are merged with digital intraoral impressions to provide information regarding the facial soft tissue lip profile, smile line, and facial planes. To correctly align both scans, the labial surfaces of the teeth are used as a common reference (Fig. 2.17). In some recent systems, facial scans are simultaneously obtained together with CBCT. The digital setup consisting of CBCT and intraoral and facial scanning can then be used to create a virtual patient replica which can be used to plan complex prosthodontic cases. Assembling all this digital information to form a digital 3D copy of the patient provides an invaluable tool for cost-effective communication with the patient, the dental technicians, and collaborating colleagues. Also, it can reduce chair time, increase productivity, and help achieve more predictable esthetic and functional outcomes (Fig. 2.18).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Register Faces to Teeth Step 3/5

Choose face and tooth model for registration.

Faces
○ Neutral Face Scan
○ Smiling Face Scan
● Cheekholder Face Scan

Teeth
Preparation Model
● boet
New Model
○ base upper
○ teeth upper
○ base lower
○ teeth lower

1. Select Face and Teeth to register from the lists on the left
2. Set registration tie points and press OK

Fig. 2.17 Registration of the facial scan with digital intraoral scans


[redacted]
[redacted]
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Fig. 2.18 3D digital smile design and final prosthesis in situ

2.11 Cone Beam Computerized Tomography (CBCT)

Two decades after the introduction of computerized tomography (CT) by Sir Godfrey Hounsfield, the first cone beam computerized tomography (CBCT) device developed for the dental field was installed. CBCT, such as other CT methods, is a digital radiographic examination that provides an image with no significant magnification or distortion. Compared with medical CT methods, CBCT offers advantages such as shorter acquisition times, reduced radiation doses, easier imaging, and lower costs (Table 2.5) [70].

As a result, the professional becomes able to obtain precise and accurate information on the alveolar ridge height, thickness, and bone density (Table 2.6).

The use of CBCT in dentistry is of particular interest for dental implantology and graft surgical planning, endodontics, maxillofacial surgery, and orthodontics. Its widespread use has led to several discussions regarding justification and optimization of CBCT exposure protocols, as well as training of oral and maxillofacial radiologists and dental professionals to operate CBCT scanners. For this reason, all dental professionals working with CBCT should completely understand CBCT technical principles to benefit from the technique while minimizing radiation-related patient risk, as much as possible [70]. Clinical indications for CBCT scans must meet the patient selection criteria of the American Academy of Oral and Maxillofacial Radiology, as well as the principles of ALARA (“as low as reasonably achievable”) [71] to control the levels of radiation dose received by patients.

Table 2.5 Differences between medical CT and CBCT

Category	Medical CT	CBCT
Positioning	Sensitive	Not an issue
Availability	Lower	Higher
Contrast scale	Longer	Shorter
Main indication	Hard and soft tissues	Hard tissues
Design	Hospital	In-office
Radiation doses	Higher	Lower
Cost	Higher	Lower

Table 2.6 Main history of CBCT

Year	Discovery	Observations
1967	Introduction of CT by Sir. Hounsfield	Both detector and source rotated in a single degree (“pencil” beam)
1978	Development of a multi-detector CT device	A circle of detectors was used, instead of a single detector
1982	First CBCT device built for angiography by Dr. Robles	First image obtained with a 2D detector using a single rotation
1996	First CBCT device dedicated for the dental field, developed in Italy	Bulky, required a scan time of 75 s
2001	A compact CBCT device is developed in Japan	Less than 400 kg in weight. More scanning protocols

2.11.1 Hardware

Similar to conventional radiographic methods, the basic principle of CBCT is the generation of X-rays in a vacuum tube by passing an electron beam between two oppositely charged electrodes (i.e., a cathode and anode). The area of the anode where the electron beam collides is called focal spot, which is usually 0.5 mm wide in CBCT devices. The emitted X-ray beam is collimated, limiting the exposure area and, consequently, the size of the field of view (FOV). Different CBCT devices have different FOV options. Modern CBCT devices with small FOV options can offer lower radiation doses to the patients along with high image quality and higher ranges of exposure parameters [71].

The resulting X-ray beam undergoes different types of filtration to eliminate the low-energy photons before they leave the X-ray tube. Low-energy photons do not contribute to the radiographic image, while they still present health risks for patients. CBCT typically uses aluminum or copper filtration with a material thickness ranging from 2.5 to 10 mm. Ultimately, filtration also leads to reduction in entrance exposure and beam hardening effects.

Most CBCT systems dedicated to dentistry use a fixed gantry with a C-shaped arm, in which the X-ray tube and detector (responsible to convert the incoming X-ray photons to electrical signals) are connected. This setup rotates in the horizontal plane, allowing the patient to stay either seated or standing during the acquisition procedure. Scanners allowing for seated positioning usually possess a built-in chair or table, occupying a larger space (Fig. 2.19).

The distance between the X-ray source and the object being scanned, as well as the distance between such object and the detector, may also affect the image quality and usually vary among the available scanners.

2.11.2 Acquisition and Reconstruction

Typical CBCT image acquisition occurs during a rotation taking from 10 to 40 s. Such rotation provides a cone-shaped X-ray beam that captures the entire volume of an object at once (Fig. 2.20) in several hundred 2D X-ray projections. Such projections are the raw CBCT data and are provided in DICOM (*digital imaging and communications in medicine*) files. Such files can be then reconstructed into three-dimensional (3D) images or models of the scanned object.

Most acquisition parameters such as rotation angle, exposure time, mA (tube current), kVp (peak kilovoltage), voxel size, and FOV size can be adjusted in the CBCT device in order to achieve better image quality. In general, adjustments in the scanning parameters that improve image quality will also lead to higher radiation doses for the patient. The image quality can also be improved after acquisition by using certain algorithms such as the X-ray scatter correction algorithms.

Image quality is basically defined by four important parameters: spatial resolution, contrast resolution, noise, and presence of artifacts. Spatial resolution is also referred as sharpness. It is described as the ability to distinguish small structures in

Fig. 2.19 A modern CBCT device (PreXion 3D, PreXion Inc., San Mateo, USA) installed in a radiology center (courtesy by CIRO radiology center and Dr. Nataly Rabelo Mina Zambrana)

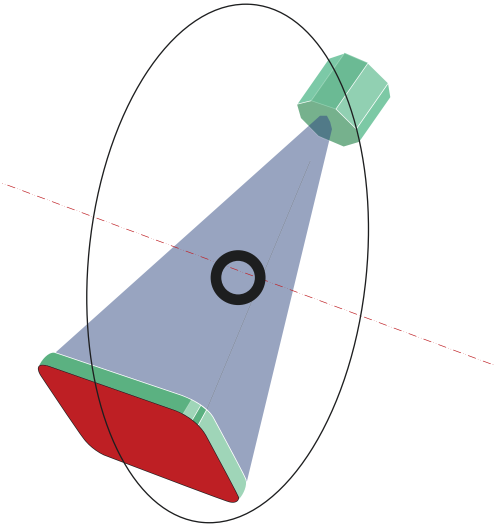

Fig. 2.20 Cone-shaped X-ray beam emitted to a flat 2D detector (in red) during the scan of an object (O)

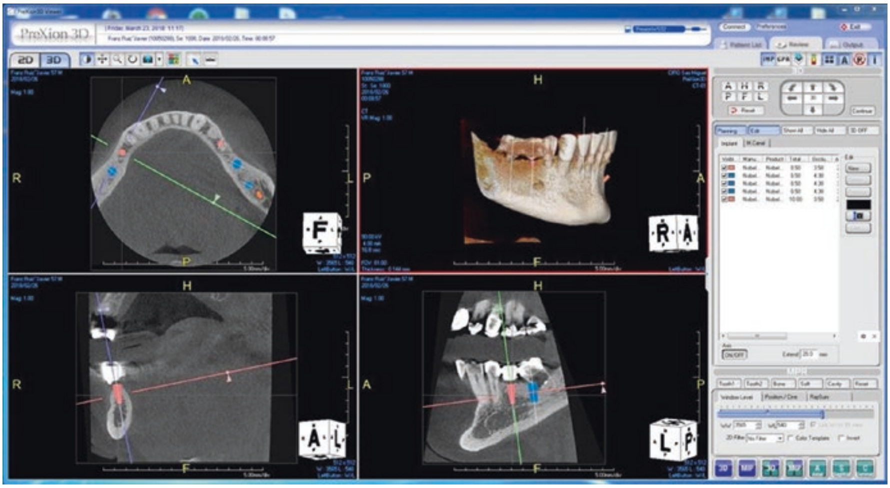

Fig. 2.21 PreXion 3D software (PreXion Inc., San Mateo, USA)

an image. CBCT has been reported to offer higher spatial resolution than multi-detector medical CT. Contrast resolution, in turn, is the ability to recognize different tissues of different densities in an image. Most of the CBCT devices have a bit depth of 12 bit, leading to $2^{12} = 4096$ gray-scale pixel intensities. Such contrast scale is short if compared to those from medical CT scans.

The smallest component of the digital image is the pixel (picture elements). Each pixel is assigned a number (related to the X-ray attenuation of the tissue) corresponding to a gray-scale value. Such numbers can be used for bone quality and other types of tissue assessments. In the case of 3D reconstructions, pixels are grouped and reformatted into 3D models composed of volume elements named voxels. The voxel size will depend on the pixel size and on the slice thickness. In general, smaller voxels and FOV will lead to better image quality.

CBCT images can be reconstructed with high contrast resolution in any of the three orthogonal planes (axial, coronal, and sagittal) (Fig. 2.21). CBCT images can be assessed with a DICOM viewer (i.e., software that open DICOM files) or with a software dedicated to dental treatment or implant planning. To do so, DICOM files usually need to be converted to the extension of the software, in order to use its treatment planning tools (see Chap. 9). In addition, such type of software allows for visualization of parasagittal slices (i.e., cross-sectional images following the arch curvature of the alveolar ridge) that are useful to perform buccal-lingual measurements of coronal panoramic slices [72].

2.12 Conclusions

Many dental image and data acquisition procedures have been digitized, and this has opened the door for a new way of making better and a more efficient restorative dental treatments. For example, digital photography, spectrophotogrammetry, and facial scanners allow for better treatment planning of esthetic cases. Digital radiography, especially the CBCT, is playing a critical role in implant dentistry and more recently in endodontics. Jaw motion tracking systems could eventually replace traditional articulators and facebow transfers in occlusal restorative assessments. And, intraoral and extraoral scanners are becoming the preferred method to take impressions of the oral cavity.

The combined use of the abovementioned digital acquisition methods is set to result in a fully digital workflow that is revolutionizing clinical practice, patient's experience, and communication between dentists and dental labs. Nonetheless this new technologies require special training by the dental team, as well as good understanding of the specific strengths and limitations offered by each type of technology in order to achieve the desired clinical outcomes.

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Computer-Aided Design in Restorative Dentistry

3

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Abstract

As 3D printing, computer-aided machining, and optical scanners keep improving and are becoming more accessible, design software is rapidly becoming the next frontier in digital dentistry. Rapid prototyping technologies in dentistry were initially operated with generic software that was not specifically designed for dental applications. This was very inefficient and a limiting factor for digitalization of dentistry. The arrival of specialized software for different dental applications has made digital dentistry a reality by making it efficient and bringing it to its full potential. This chapter addresses the different types of software that has been developed for restorative dentistry. This includes software for fixed, removable, and implant prosthodontics as well as software for treatment planning.

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3.1 Introduction

Computer-aided design is a fundamental step in any dental intervention involving digital technologies. Images registered through different acquisition systems such as scanners and CBCTs are managed in specialized computer files able to store 2D, 3D, and even color information. These files can then be processed with specialized software in order to virtually plan treatments and design prosthetic restorations.

This chapter introduces the main types of computer tools and files that can be used to plan and design restorative treatments. This type of software can be used, for instance, by dentist to plan esthetic and implant cases in the office or by dental technicians, to design prosthetic restorations in the laboratory.

3.2 2D Photography: Digital Smile Design

Dental treatments require esthetic and functional predictability. In this context, restorative treatment planning should integrate the esthetic framework of the patient's face and the dynamics of smile, mastication, and phonation. Digital smile design (DSD), originally proposed by Coachman and Calamita, pursues two-dimensional analysis of the smile through intraoral and extraoral videos and photographs. Undoubtedly, this resulted in a palpable improvement in digital case planning. Treatment objectives such as corrections of incorrect tooth proportions and analysis of tooth form and size in relation to facial profile in smile and resting positions were achieved, thanks to digital design of the smile. Communication with the patient regarding the projected treatment outcomes was also improved by the application of DSD because it provides dentists with a visual tool to discuss patients' wishes and expectations prior to therapy. The digital design also allows multidisciplinary teams to better assess prospective treatments. For example, periodontists may benefit by digitally outlining the border of the gingivectomy required for a crown lengthening procedure, which makes it easier to coordinate with the restorative treatment [1]. The communication of the expected results with the laboratory is another advantage of DSD by providing the technician with the dimensions, shapes, textures, and contours of the restorations planned by the clinician, integrated with the face and smile of the patient—a key information often overlooked by dentists and dental technicians.

Digital design consists of performing first a digital facial and dental analysis on which the horizontal, bipupillary, nasal, and labial commissure lines are marked, along with the smile line. Digital design on two-dimensional smile photographs should be taken into account three important issues: the size of the photograph, to correlate the extraoral photographs with intraoral ones, the parallelism of the photo with the horizontal plane, and the position of the incisal edges and the position of the midline (Fig. 3.1: d1, d2, and d3). After correlating this information, the size of the teeth is determined by an appropriate proportion for each patient taking into account the visagism, which consists of a series of characteristics related to the patient's biotype. The teeth taken from a virtual library including various

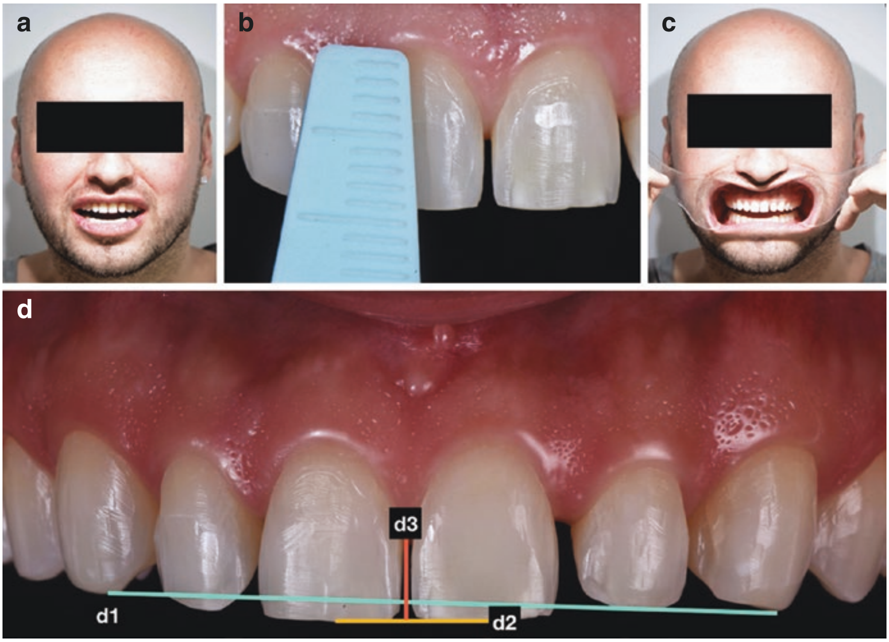


Fig. 3.1 Basic pictures and measurements for digital smile design. (**a**) Smile rest position. (**b**) Real length of right upper central incisor. (**c**) Picture of interocclusal space with lip retractor. (**d**) Front upper teeth. (d1) Line to register parallelism of the photo with the horizontal plane. (d2) Line to register the position of the incisal edges. (d3) Line to register the midline

morphologies (triangular, square, ovoid) are adapted to the digital design, and after calibration with a digital ruler, the new dimensions and proportions of the restorations are determined.

This includes the dental axes, its relation with the smile line, gingival margin, face midline, height of the interdental papillae, and incisal embrasures (Fig. 3.2).

Digital planning can be of two types: (1) additive, which usually involves reversible changes by adding restorative materials onto the remaining tissues, and (2) subtractive, which involves irreversible changes by eliminating hard and/or soft tissues to achieve an expected result. Once the design is determined, a report is prepared for patient's approval. The fabrication of the physical form makes the digital planning tangible and more real to the patient. This is usually done by preparing a diagnostic wax-up based on the predetermined measurements and then using a rigid condensation silicone matrix to copy the wax-up and fabricate a temporary restoration that can be transferred to the patient's mouth.

Two-dimensional analysis of the smile is gradually being replaced by three-dimensional smile analysis, which could perform digital simulations by incorporating depth as a third dimension. Moreover, integration of 3D images of the face and the smile of the patient, with the planned restorations, enables more predictable facially guided digital smile design and simulations. Scanned 3D images of the face

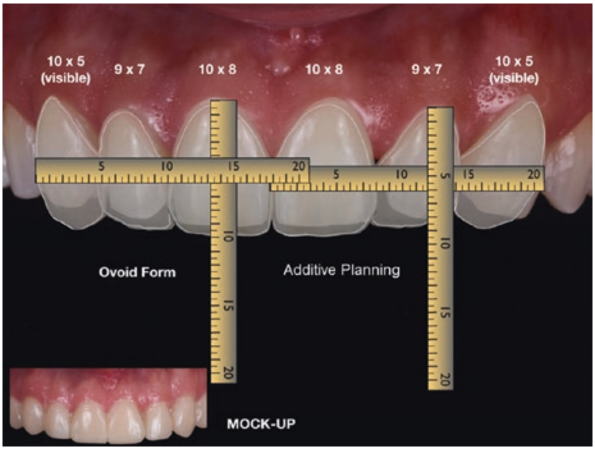


Fig. 3.2 Final recommendation sheet to send to the dental technician and mock-up


[redacted]

Fig. 3.3 CEREC smile design function. New restorations integrated with the face of the patient

and the dental arch are correlated to make a digital design that then must be materialized so that the patient gives his approval or disapproval, to avoid inconveniences with the final result of the treatment. These results can even be integrated directly into the digital workflow, designing and machining the mock-up, temporaries, or even the final restorations using CAD/CAM technology (Fig. 3.3). In order to evaluate the results, the mock-up can be presented to the patient.

There are several types of software in the market, from the simplest ones like Keynote, PowerPoint, and Photoshop [2], which allow a two-dimensional analysis, to other more specific ones (RealView from 3Shape, Nemotec, Smile design from CEREC, etc.) that directly facilitate the entry of the obtained training and allow a simplest workflow.

In conclusion, the digital smile design [3, 4] is a concept of diagnosis and reversible planning and susceptible to modifications of clinical cases during the execution of the treatment. It contributes to improving communication among the members of the patient care team. In addition, it facilitates communication between the dentist and the patient. The digital smile design is a valid tool for documenting and archiving clinical cases in an orderly manner. This concept should be handled with carefully in order to meet the real needs and expectations of the patient, as well as the intrinsic limitations of the dentist, his team, and the therapy. Finally, it should be noted that the digital smile design is a concept that requires learning, training, and understanding its fundamentals, objectives, and sequence [5, 6].

3.3 3D Files

Patients' dental topography and morphology captured with optical scanners are usually saved in the form of 3D image file that are crucial in the process of treatment planning, execution, and documentation. There are different types of 3D image files, and it is important to know the differences among them. The best known and the most commonly used within the field of dentistry is the STL file. This kind of file was created by the company 3D Systems [7], and the acronym stands for stereolithography or Standard Triangle or Standard Tessellation Language. This type of file stores information regarding the geometry of a given 3D object, but it does not include information regarding texture and/or shade. For this reason, this file is not excessively popular beyond the field of dentistry. Another limitation of this kind of file is that it does not include any "metadata" or personal information about the patients. For this reason, although this could be beneficial from a legal standpoint, there is a tendency toward replacing STL files with files that store patient data such as the DICOM files.

Another commonly used 3D image file is the OBJ file, the acronym of "Object," which was developed by Wavefront Technologies. Unlike STL files, OBJ files contain information on texture and color of 3D objects; they are used by some facial scanners in the field of dentistry [7]. PLY file is another 3D image file used in dentistry. It is known as the Polygon File Format or the Stanford Triangle Format, because it was developed at Stanford University. This file stores graphical objects described as a collection of polygons, and it contains the exact description of the object along with its color, texture, and transparency [8]. Some intraoral digital scanners export the scanning data on this type of file.

It is important to mention that all of the abovementioned files can be encrypted or closed. This is often done by manufacturers in order to force the technician or the dentist to remain within a specific workflow, in which all devices and software are supplied by the same company (i.e., scanner, design software, and production unit).

3.4 3D Designs

After acquisition with a scanner, 3D image files can be imported to a design software that would have different tools for manipulating, editing, and designing the 3D model or the final future restorations. It is important to note that this software 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

can sometimes be expanded by incorporating additional anatomical forms from scanned teeth [10].

- *Model builder or creator*: This module is used to fabricate a physical model from the 3D files generated by intraoral scanners. The module would export the file for fabrication using a 3D printer or CAM device. The operator can design the models to be hollow, to reduce printing costs, and with detachable segments to facilitate handling (Fig. 3.5). In implant cases, the models can be designed with premade holes for the implant analogues and detachable segment for the gingival masks that are to be manufactured using a different type of material than the rest of the model [11].
- *Provisional*: Various software modules can be used to design temporary restorations based on preoperative scans. This type of software can be used to design the temporary restorations by replicating the original anatomy of the tooth, if acceptable, or by relying on in-house tooth digital libraries [12].
- *Virtual articulator*: This type of module is used to digitalize the relation between the upper and lower arch replacing the traditional physical articulator. There are different types of virtual articulators with various degrees of automatization. Some of this software, such as the Zebris System, can import and incorporate information on the dynamic movements of the patients obtained from a jaw registration system [13].

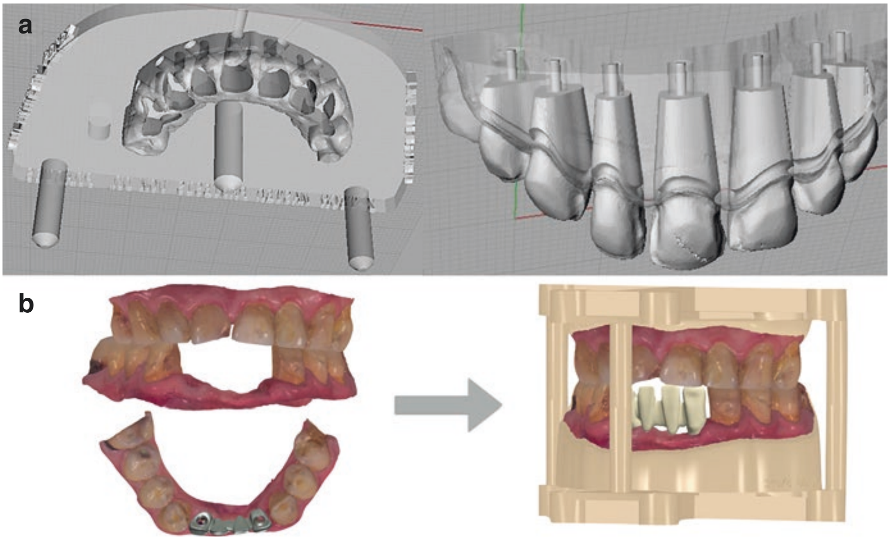


Fig. 3.5 (**a**) Model with detachable segments created with the model of Dental Systems. (**b**) With the model builder module, it is possible to design models for implant-supported prosthesis. The lab technician can design the framework of the future prosthesis and a model with holes for the implant analogues, as well as the bases and the occlusal supports for the manual veneering of the ceramic onto the framework. This virtual model was designed with Dental System

- *Full denture*: This type of modules allows technicians to fabricate complete denture digitally. The software can be used to design the denture base as well as other elements of the treatment such as customized impression trays or baseplates. It also allows to identify critical land marks (i.e., alveolar ridge, the midline, the occlusal plane, etc.) and would propose possible tooth setups that could be edited and ultimately exported for denture fabrication using 3D printers or milling units [14].
- *Partial framework module*: This type of modules is designed to replace the classical lab technician work related to the fabrication of the wax patterns used to cast metal frameworks of removable partial dentures. This technology in combination with additive manufacturing allows for much faster and more accurate results than those achieved with classical manual techniques. Usually, partial framework modules consist of a paralleling tool to determine the path of insertion, identify the line of contour, and block out the undercuts, as well as additional tools to design the various components of the frameworks (i.e., major connectors, clasps, and occlusal rests). Moreover, this type of modules often allows to combine partial framework designs with crown and bridge design elements [15]. The designs generated by these modules are ultimately exported for additive manufacturing either by 3D printing burnout wax patterns for subsequent casting or by direct 3D printing using laser sintering technology.
- *Implant module*: This type of module allows clinician to diagnose and plan treatments with dental implants. The software can be used to combine radiological information with intraoral examination by merging DICOM files from the CBCT with 3D files generated by extraoral or intraoral scanners. With these modules, we can design a surgical splint for guided surgical procedures and provisional restorations with different implant systems, depending on the libraries available in the software [16].
- *Implant prosthetic module*: This type of module enables the design of the customized abutments and the prosthetic frameworks for both cemented and screw-retained implant-supported restorations (Fig. 3.6). To be able to design these implant prostheses, the CAD software includes a library of different types of implant connections and scan bodies for digital impression that can be updated with new designs as they are introduced to the market [17].
- *Bar module*: This module usually includes a library of different types of bars that enables custom design of bars for overdentures. These designs can range from simple bars with standard cross sections, such as Dolder, Hader, or Ackermann sections, to bars for complex cases, where additional attachments or retentions can be added. Prefabricated attachments consisting of cylindrical holes or even arbitrary geometries with various paths of insertion can be added to the design [18].
- *Bite splint*: It is possible to design Michigan or other types of splints and mouthguards with CAD software. Some software allows synchronization with the virtual articulator's module in order to adjust the occlusion of the splint with the antagonist arch and optimize the final design [19].

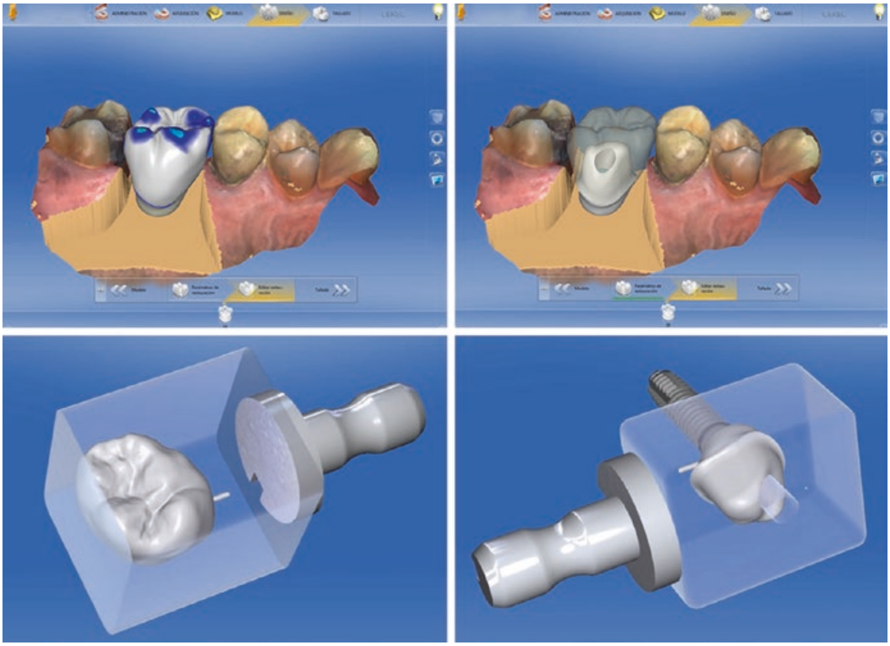


Fig. 3.6 Design of a cement-retained implant restoration, including the customized abutment and the crown for fabrication by machining a monolithic restorative material. This case was prepared with the SW CEREC 4.5.2 software

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

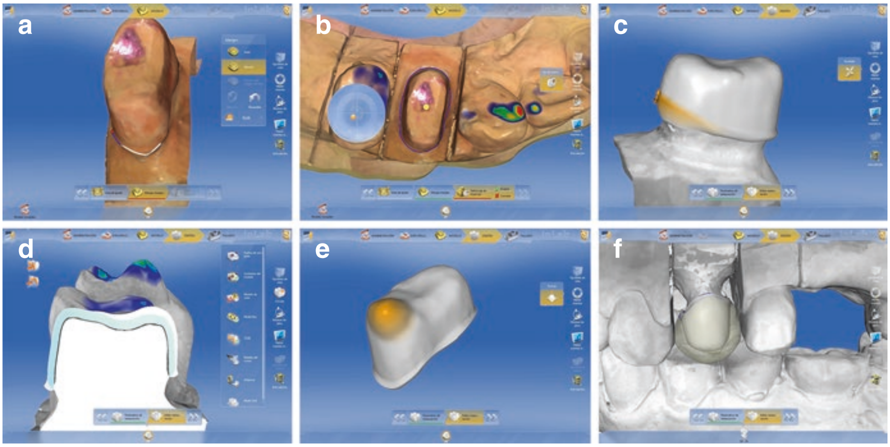


Fig. 3.7 Example of the 3D virtual CAD tools used to design a zirconia coping using the inLab 16.0 software. First the finish line (**a**) and the path of insertion (**b**) are determined. Then, different tools (**c**–**e**) can be used to create and modify the design. (**f**) Final design of the zirconia coping ready for porcelain veneering

software can help identify the flanges, the tuberosity, and the retromolar areas, as well as the final position of the teeth in the prosthesis.

All CAD systems are able to export the designs as a portable document format file (pdf). With this file, the dentist can evaluate the design and validate it. This tool is very useful to improve the communication between technician and clinician (Fig. 3.8). When the final design is accepted by the clinician, the lab technician can use a CAM software to nest the restoration in the block or disc of material to be milled and control the manufacturing strategy (Fig. 3.9). In the case of additive manufacturing techniques, for example, laser sintering deposition, it is also possible to determine the location of the restoration, the number of layers, the width of every layer, etc.

3.6 CAD Software Currently Available

There are different programs available for dental CAD that include the tools and applications described above. Underneath we discuss the best-known available software.

3.6.1 Dental System (3Shape, Copenhagen, Denmark)

Dental System is a software created by 3Shape, a Danish company, and the last version at the point of this book's edition is Dental System 2019. This software has a suite of add-on modules with a wide range of indications that include all the

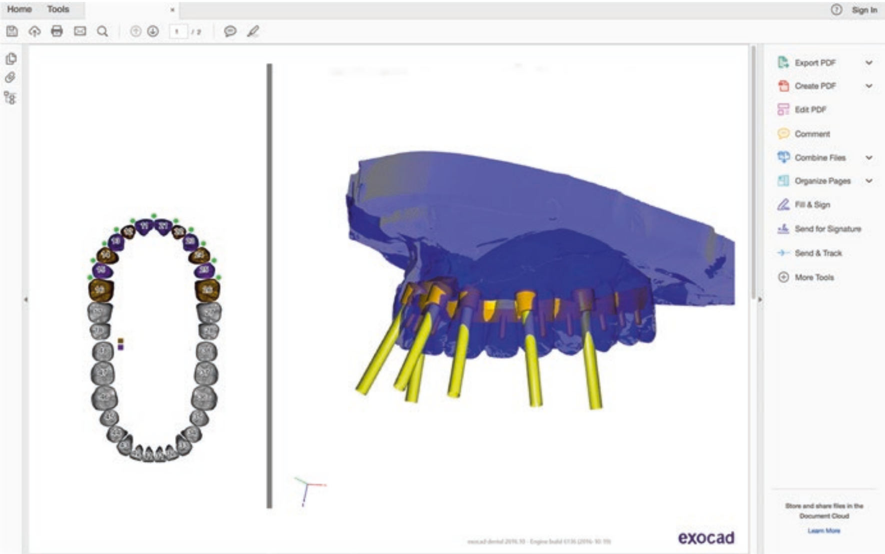
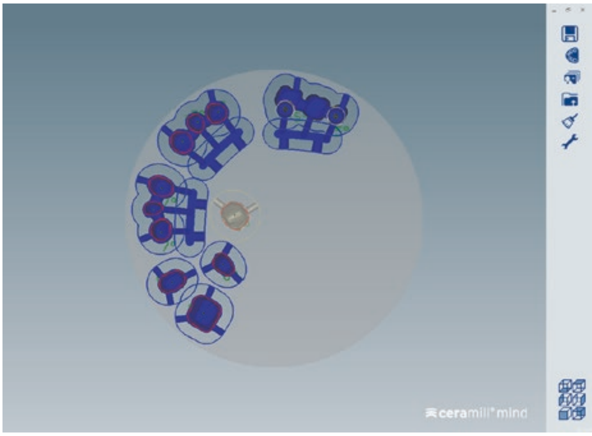


Fig. 3.8 Screenshot of PDF file sent to the clinician with the 3D information of the CAD design of a framework for a case with multiple implants, with the emergence of the implants and the relationship with the position of the teeth. This PDF file was exported with Dental CAD 2.2

Fig. 3.9 Virtual placement of several restorations inside a metal-alloy disc for machining



abovementioned modules. Dental System has a powerful work module for digital smile design known as RealView, where the 2D and 3D information is combined, obtaining very real photographic montages, which help in planning the case and communicating with the patient. Dental System can import STL files from different extra- and intraoral digital scanners. The designs obtained with the software can be exported to an open STL file for manufacturing in any milling unit, laser sintering unit, or 3D printer.

It is worth mentioning that if you scan intraorally by using their own company product Trios, the 3D information obtained is stored in a proprietary format called IMG that not only contains the STL information but also the texture and color of the different surfaces in the patient's mouth. Dental System is available for purchasing in different versions, from a premium version that includes all the modules to more basic versions. Recently, 3Shape has created a specific design software for clinicians, known as Design Studio. This software is intended for designing simple restorations that are manufactured with chairside milling units in a single appointment.

3.6.2 DWOS (Dental Wings, Montreal, Canada)

Dental Wings Open System, known as DWOS, is a CAD software from the Dental Wing company, which was founded in 2007. The open architecture of this CAD software allows users to work with clinical information, design processes, and downstream production processes. This software has a wide range of modules, materials, implant libraries, and anatomies. DWOS can be used in combination with the coDiagnostiX CBCT planning software in order to link radiographic data with intraoral or extraoral scan data, to optimize implant position and final design of the prosthesis. In addition, this software has a version for dental lab and another one for clinics, which allow dentists and lab technicians to work together in real time.

3.6.3 DentalCAD (Exocad, Germany)

This software was created by the Exocad Company, which was founded in 2010 as a spin-off company from the Fraunhofer Organization. The software was developed for dental technicians, and it has wide range of indications, functionalities, and work modules. With the standard version of Exocad DentalCAD, the lab technician can design anatomic crowns, anatomic/simple copings, attachments, bridge frameworks, inlays/onlays, veneers, wax-ups, and telescopic crowns. Moreover, with add-on modules, it is possible to make more complex works. The acquisition of these additional modules is flexible and can be done according to the needs of the lab technician, without the need to acquire all of them. More recently, Exocad has developed a simplified version of the software for use in the dental office that can be used to prepare chairside with different milling units.

Exocad is an open software that can easily incorporate free libraries of forms and implants, and it produces the designs in open STL files that can be manufactured with any CAM system of additive or subtractive technology. For these reasons, many manufacturers and distributors of extraoral scanners have partnered with this software.

3.6.4 inLab and CEREC (Dentsply-Sirona, Germany)

Sirona has three design software, the SW inLab for dental labs; the simplified SW CEREC for dentists, which is coupled to an intraoral scanner; and the Premium SW CEREC, which is a software for dentist but with almost identical features as the inLab version. The SW inLab software includes a basic configuration as well as additional modules for removable and implant prosthodontics, respectively. The basic configuration can be used for many indications such as inlays, onlays, veneers, crowns, and the digital smile design. The module for removable prosthesis enables the design of all types of removable prostheses, as well as splints and custom trays. The implant module allows the lab technician to design implant-supported prostheses and surgical splints for guided surgery in implantology. The Chairside version of the software was originally developed by Mörmann and Brandestini in 1985, and it is the first CAD/CAM dental system used in the world. Nowadays, it consists of a complete digital CAD/CAM solution that is the easiest to use for chairside restorations. It is integrated with an intraoral scanner, and a chairside milling machine, for design and manufacture of dental restorations and screw-retained and customized abutment restorations for single implants and simple surgical splints [23].

3.7 Conclusions

Computer-aided design software is rapidly replacing many of the manual procedures performed by dental technicians, and by doing so, it is transforming the profession and the dental laboratories. Many laboratory procedures such as wax-ups, mounting models in articulators, and preparing frameworks for removable partial dentures can now be done virtually using specialized software. In addition, predesigned teeth and prosthetic components such as implant bars and abutments are available in the form of virtual digital libraries that can be used for facilitating treatment design. In addition, specialized software is also penetrating the dental office by facilitating esthetic treatment planning using smile design software, in-office design of permanent and temporary prosthetic restorations, and treatment planning of implant surgeries and prosthetic rehabilitations.

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Fabrication of Dental Restorations Using Digital Technologies: Techniques and Materials

4

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and Faleh Tamimi

Abstract

Digital technology such as computer-aided design/computer-aided manufacture (CAD/CAM) is rapidly expanding and transforming dentistry at an unprecedented pace. CAD/CAM technology in dentistry can be classified as either "subtractive" or "additive" manufacturing methods. Subtractive manufacturing method includes machining and milling (CAM) and laser ablation technologies, while additive manufacturing method includes 3D printing and laser melting technologies. Different materials (polymers, metals, and ceramics) and equipment are commercially available for various dental applications such as custom trays, surgical guides, temporary or definite fixed or removable dental prostheses, and orthodontic or maxillofacial appliances. This chapter reviews the main systems including production processes, dental applications, available materials and equipment, and advantages and limitations of the technology.

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4.1 Introduction

CAD/CAM (computer-aided design/computer-aided manufacture) technology was developed in the 1960s for industrial applications, and it was introduce to dentistry by Dr. Francois Duret in 1971 [1]. Dr. Duret introduced the concept of producing a dental crown using an optical impression of the prepared tooth by an intraoral digitizer and a digitally controlled milling machine [1, 2]. In 1983, he performed the first CAD/CAM restoration, and later he developed the Sopha system [1, 2]. Dr. Mörmann invented the first commercial CAD/CAM system, named CEREC (computer-assisted ceramic reconstruction), in collaboration with Dr. Marco Brandestini, an electrical engineer, who had the idea of using an optical dental scanner [3]. In 1985, the team performed the first chairside dental inlay using an optical scanner and a milling machine system [1, 3, 4]. In addition, Dr. Andersson also developed the Procera system in 1983 for fabrication of dental crowns, and he was the first person to use the CAD/CAM technology for composite dental restorations [1].

Although the CAD/CAM technologies were first introduced in dentistry in the 1970s for long time, their use was very limited. In the past few decades, CAD/CAM technologies' usage has grown dramatically, and they are expected to grow further in the near future [3, 5]. For instance, 3D printing market for US healthcare is expected to grow by 18–22% between 2015 and 2025 exceeding $5 billion dollars by 2020 [6–9]. Digital technology has many benefits in dentistry such as it is faster, more accurate, and more economical than the traditional procedures [10]. Digital technology in dentistry can eliminate the need for some or all of the manual processes such as pouring casts, die fabrication, restoration wax-ups, investment process, metal casting, or pressing porcelain [1]. Therefore, digital technology is rapidly spreading into dental laboratories and clinics around the world, and it is transforming dentistry at an unprecedented pace [11]. In dental laboratories, the traditional equipment (such as, furnace and casting machine) is being replaced by computers, scanners, and 3D printers or digital machines. Now, dentists do not need to take an impression and wait a few weeks to fabricate appliances or restorations; instead, they only need to scan the teeth and email the digital file to dental lab for printing the prosthesis, which may take less than an hour.

In dentistry, CAD/CAM technology consists of three systems:

1. Data acquisition that can be obtained from different scanning technologies such as 3D scans [3, 9].
2. Data processing CAD (computer-aided design) system that creates and manipulates the digital data of a 3D object [3, 9].
3. Data manufacturing CAM (computer-aided manufacturing) system that manufactures the designed structure in the desired materials [3, 9].

CAM technologies available in dentistry can be classified as either "subtractive" or "additive" manufacturing methods. With subtractive methods, also known as machining and milling, dental parts are created by subtracting the undesired material from a block with the use of burs, disks, or lasers [3, 5]. On the other hand, additive methods, such as 3D printing and laser melting technologies, build dental objects layer by layer [3, 5]. Additive manufacturing process is also known as rapid manufacturing, and it is more recent technology than the subtractive manufacturing process [3]. However, subtractive methods are currently more precise and accurate, while additive methods are more versatile [12, 13]. There are a wide range of available machines for both methods [9]. Each technology presents some differences in the process and materials used, and they have different advantages, limitation, and applications [9]. Details about each technology will be explained in this chapter.

4.2 Subtractive Manufacturing

4.2.1 Machining and Milling

4.2.1.1 Overview of Machining and Milling

Machining and milling, also known as subtractive manufacturing, refers to a process in which a block of raw material is cut into a desired final shape by a controlled material removal technique [3, 5]. The cutting process involves power-driven sharp cutting tools such as saws, lathes, and drill presses with different sizes designed to remove small chips from the block of material until achieving the final desired shape [3, 5, 13, 14]. The industrial improvements in software and a reduction of size and costs of CAD/CAM machinery have allowed the application of CAD/CAM in dentistry [4].

The CAD/CAM systems for subtractive manufacturing methods can be classified into chairside systems and laboratory systems [5, 13, 15]. For chairside systems, the fabrication of dental restorations by CAD/CAM can be done in the dental clinic without a laboratory procedure [5, 15]. For the laboratory systems, the CAM production takes place in the dental laboratory or production centers [5]. The CAD/CAM systems can also be classified into open and closed systems [5, 13]. Open systems allow all the CAD/CAM components, including data acquisition, design by CAD software, and the manufacture by CAM system, to be provided by different companies, while closed systems are restricted to a single supplier [13].

4.2.1.2 Dental Applications of Machining and Milling

Machining and milling have many dental applications in the fields of prosthodontics and restorative dentistry [13]. These include crowns, copings, inlays, onlays, veneers, frameworks for fixed dental prostheses, and implant abutments and bars [13]. In addition, machining and milling can be used as burnout pattern for casting, pressing, or overpressing [13]. Moreover, splint and orthodontic retainers, complete prostheses, verification jigs, diagnostic wax-ups, and digital models can also be fabricated with machining and milling methods [13].

4.2.1.3 Milling and Machining Production Process

The production process starts once the designing step of the final prosthesis is completed using an appropriate CAD software (Fig. 4.1). The CAD model is then translated by the CAM software into a tool path for a computer numerical control (CNC) machine. Following this step, the software will run a simulation in order to confirm the capability of the milling unit to process the designed prosthesis (Fig. 4.2). Once the software confirms the feasibility of the designed prosthesis, the CNC machine can be initiated. The CNC machine is composed of several

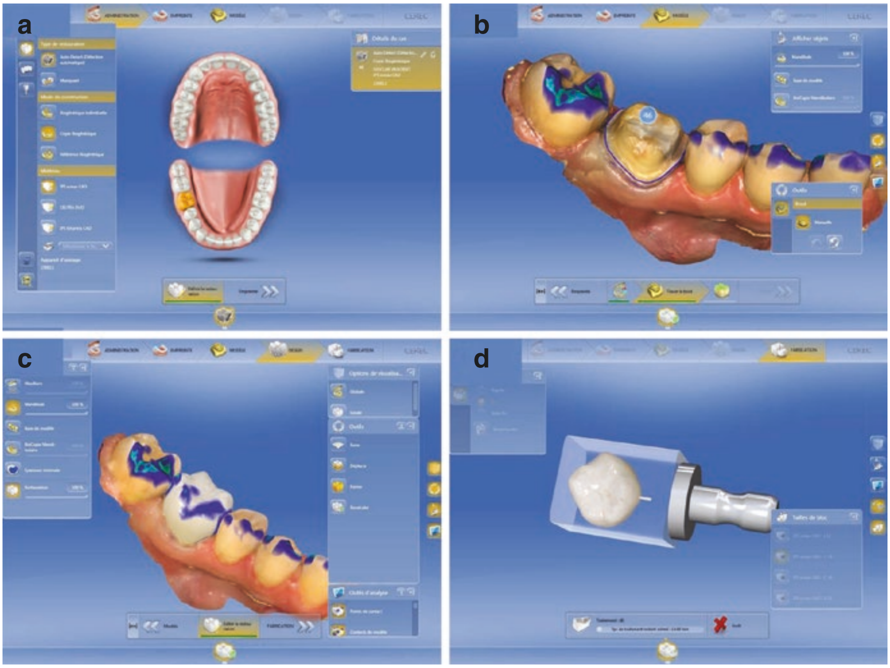

Fig. 4.1 Photographs showing the designing of a dental crown for milling through different steps: (**a**) administration, (**b**) modeling, (**c**) designing, and (**d**) fabrication

Fig. 4.2 Example of calculations and simulation before milling and machining

machining sequences, and each sequence is a group of calculated machining tool paths, which are automatically calculated with specific machining algorithms [14, 16]. The CNC machines are composed of multiaxis milling units operated in 3-axis, 4-axis, or 5-axis (Fig. 4.3).

Three-Axis Milling Machine

The 3-axis milling machines are the most commonly used in dentistry (Fig. 4.4) [14]. This type of milling machines can move in three spatial directions that are defined by the values *X*, *Y*, and *Z*. The block can also turn 180° during manufacturing to allow the milling of the external and internal surfaces [14]. Thus, 3-axis milling units are faster than other milling units because they have short calculation and cumulative milling time [14]. Also, the simplified control of the 3-axis renders them

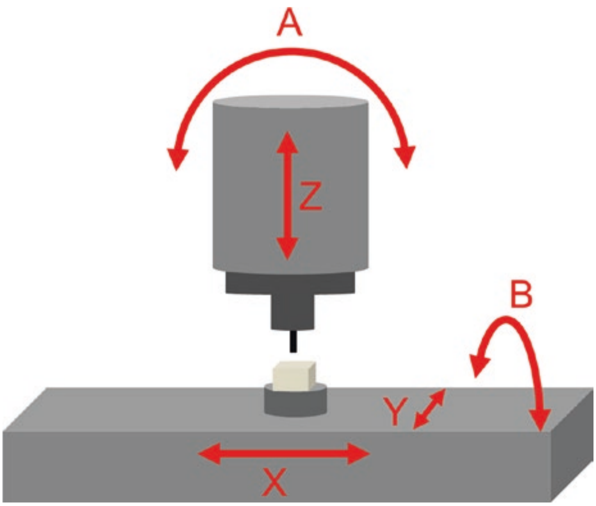

Fig. 4.3 Representation of different possible axes: 3-axis includes *X*, *Y*, and *Z* directions; 4-axis includes *X*, *Y*, *Z*, and A directions; 5-axis includes *X*, *Y*, *Z*, A, and B directions

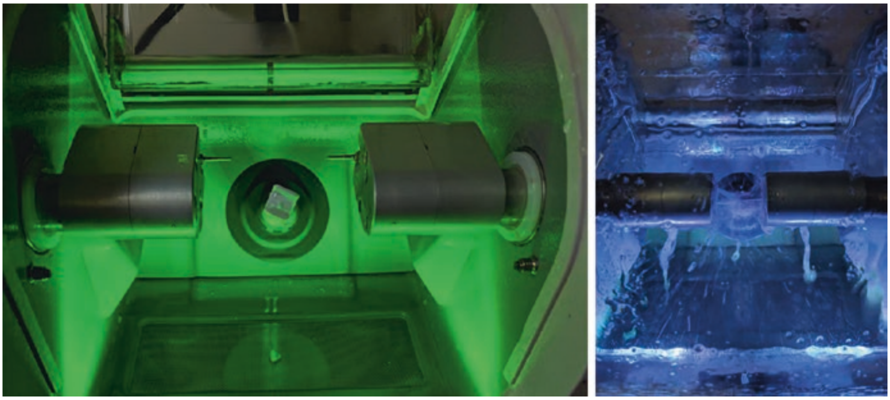

Fig. 4.4 Photographs showing the 3-axis milling machine during drilling sequence

less expensive compared to machines with more axes [15]. However, 3-axis machines are limited when it comes to produce divergence, convergence, and highly defined features [14].

Four-Axis Milling Machine

The 4-axis milling machines involve an additional axis to the three spatial axes, and it can allow the block to rotate around the *X*-axis. The forth axis is defined as tension bridge A. This is useful for milling large blocks for long span frameworks [14]. The tension bridge for the component can also be turned infinitely variably. As a result, it is possible to adjust bridge constructions with a large vertical height displacement into the usual mold dimensions and thus save material and milling time [15]. The 4-axis milling machine can be used for crowns, veneers, inlays, onlays, copings/frameworks, and fixed partial dentures [13, 14].

Five-Axis Milling Machine

The 5-axis milling machines contain additional two axes that can rotate the block around the *X*-axis and around the *Y*-axis (Fig. 4.5). The fifth axis is defined as tension bridge B. This enables the milling complex geometries and smooth surfaces with subsections. The 5-axis machines can produce objects with higher accuracy than three or four axial milling machines since it can mill undercuts in all directions [13]. The 5-axis milling machine can produce digital models, implant attachments, denture base, implant abutments, bars, and splints [13, 14].

The milling process can be done in different conditions and forms according to the materials used. It can be done in wet or dry conditions, and also it can be done with soft or hard materials. Dry processing and soft machining are usually applied without cooling liquid, and it is used for machining unsintered zirconium oxide, composite resin, and wax [11]. Wet processing, usually hard marching, uses spray of cool liquid to protect the milled material and milling burs from overheating; it is used with pre-sintered zirconium oxide, metals, and composite resin [11, 13]. Dry processing is less expensive and produces less moisture absorption than wet processing, but it might result in higher shrinkage than wet processing [11, 13].

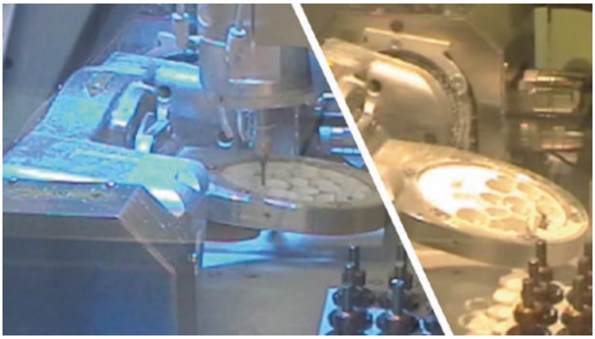

Fig. 4.5 Five-axis milling machine during drilling sequence

4.2.1.4 Advantages of Milling and Machining

There are some advantages to using milling and machining in dental applications in comparison with conventional dental laboratory technologies.

1. High accuracy [15].
2. Standardized manufacturing process [15].
3. Efficient quality control system [15].
4. Increased production capacity [15].
5. Fast production [1].
6. Enable the use of new materials, such as zirconia and titanium [15].
7. Transforming laboratories from simple fabrication sites into computerized production centers [15].

4.2.1.5 Disadvantages of Machining and Milling

1. The initial cost of a CAD/CAM system can be higher than the traditional dental equipment [11].
2. Machining and milling is very wasteful procedure in which more material is removed compared to what is used in the final product [3, 5].
3. The milling procedure accuracy is dictated by the diameter of the smallest bur. Therefore, any surface details less than the diameter of the milling bur will be overmilled, and it will contribute to low retention of the restoration [13].
4. The possible uses CAD/CAM are limited by the capability of the software and the digital scanners available [11].
5. Many current CAD/CAM technologies still require conventional laboratory processing. For example, zirconia frameworks fabricated by CAD/CAM in machining centers require manual veneering with conventional porcelain using by dental technicians [2].

4.2.1.6 Potential and Future Direction of Machining and Milling

Considering the advantages of milling and machining, the application of this technology has become essential in providing appropriate treatment to patients. With the cost of manufacturing units dropping, many laboratories and clinics are acquiring CAD/CAM units for faster fabrication of dental restorations. However, this method of manufacturing is very wasteful as more material is removed compared to what is used in the final product. Around 90% of a block material is removed to create the dental restoration [5]. Accordingly, there has been a major transition from subtractive manufacturing to what is referred to as additive manufacturing. Using additive methods for manufacturing is more advantageous as many problems associated with milling can be readily overcome. The main advantage of this type of manufacturing is the ability of the technique to create fine detail [3]. However, additive manufacturing is incapable of producing restorations with certain materials such as zirconia, glass ceramic, and composite.

4.2.1.7 Materials

Different materials can be milled by CAD/CAM systems (depending on the system used), and these materials are offered and sold in block form for CAD/CAM systems. Metals including titanium, titanium alloys, and chrome-cobalt alloys can be used with CAD/CAM systems. Noble metal alloys are not used for cost reasons [15]. Resins can be milled into frames for use in lost-wax casting, and they can also be used to make crowns and long-term provisional fixed partial dentures [15]. Polyurethane is used for the fabrication of digital models [13]. Ceramic blocks are available for the fabrication of inlays, crowns, and veneers, and they can be monochromatic or colored [15]. One such ceramic group is silica-based ceramic such as lithium disilicates that produce natural-looking restorations, thanks to their translucency resembling that of real teeth eliminating the need to add veneering porcelain [15]. Another group of ceramic is the infiltration ceramic blocks such as alumina (Al_2O_3), zirconia (Al_2O_3,ZrO_2), and spinell ($MgAl_2O_4$) [15]. In addition, aluminum oxide (Al_2O_3) and zirconium oxide (ZrO_2, Y-TZP) are milled at the pre-sintered stage and is then sintered; this provides superior mechanical properties such as high strength and high tenacity that are excellent for crowns and fixed partial dentures, as well as implant abutments [15].

4.2.1.8 Equipment

Available systems are designed to mill or grind either in dry or wet conditions as dictated by the type of material used. The selection should also take into consideration the number of axes (3, 4, or 5 axes) and is dictated by the design of the dental restoration [13]. Main dental CAD/CAM systems available are Etkon (Etkon AG), Everest (KaVo electrotechnical work GmbH), Lava (3M ESPE Dental AG), Procera (Nobel Biocare Germany GmbH), Hint ELs DentaCAD system (Hint-ELs GmbH), and CEREC3/inLab (Sirona Dental of system GmbH) [2].

4.2.2 Chairside Solutions

4.2.2.1 Overview of Chairside Solutions

Recent developments of CAD/CAM systems allow the fabrication of dental restorations at the dental chairside without the need for a laboratory procedure [15]. In this context, all CAD/CAM components, such as the scanner, the CAD system, and the CAM system, are allocating in the clinic that saves time and allows the fabrication of the restorations within one appointment [11, 17]. The scanner is used to acquire topographic information of the oral cavity, preparation of the tooth, adjacent teeth, and occlusion. The CAD system is used to design the restorations, while the CAM system is used to convert the information into an actual restoration [17]. Chairside CAD/CAM systems are capable of scanning, designing, and milling within the chairside workflow.

There are two categories of commercially available digital systems for CAD/CAM chairside dentistry: chairside digital impression systems to transfer images to the laboratory and chairside milling machines for same day restorations [4, 17]. The digital impression systems were developed to replace the traditional impression methods. These digital chairside impression systems include both the hardware for scanning and the software for data analysis. The software captures and stores the digital data from the intraoral scan, and it also records personal information regarding the patient which will allow the replacement of traditional written laboratory prescriptions by including a comprehensive electronic prescription form. The digital impression can be archived and transmitted to the lab via the Internet. Once the data is transmitted, the restorations can be designed directly from these digital impressions and, then, produced by the CAM system [1, 15, 18].

4.2.2.2 Dental Application of Chairside Solutions

With advances in chairside scanner systems and the ability to image full arches, orthodontic applications of CAD/CAM dentistry have expanded significantly. Intraoral digital impressions allow the creation of digital models for diagnostic, documentation, analysis, and treatment planning purposes. The chairside CAD/CAM systems allow same day fabrication of inlays, onlays, crowns, and veneers, and with improvements in dental material science, they also allow the fabrication of multiunit restorations, implant abutments/restorations, temporary restorations, and surgical guides [4, 19]. Furthermore, when combined with 3D cone beam computed tomography (CBCT) imaging, the CAD data aids substantially in complex planning surgical treatments [4].

4.2.2.3 Advantages of Chairside Solutions

1. Eliminates the need for a second appointment. Patients appreciate the convenience of having restorations placed in one appointment instead of having to come back for a second delivery appointment [17, 20].
2. Patient information is digitally stored. This saves physical storage space and eliminates the risk of breaking the casts [1].
3. Allows the dentist to have total control of the artistic and creative expression and the manufacturing process without the involvement of the laboratory [17, 20].
4. CAD/CAM systems improve the efficiency and productivity of dental clinics once the initial learning curve period is overcome [17, 20].

4.2.2.4 Disadvantages of Chairside Solutions

1. The high initial and maintenance cost of chairside CAD/CAM system [20].
2. These chairside systems require special training, and learning curve varies from user to user [20].
3. The possible uses of these systems are limited by the capabilities of the software and milling machines [15].
4. CAD/CAM technology is constantly being upgraded and improved; these alterations must be dealt with as they arise ensuring additional cost in the future [20].
5. Tooth preparations may need to account for limitations of the milling system [21].
6. Closed-data chairside systems in which all components are linked by a unique data format prevent different systems from interacting [21].
7. Chairside CAD/CAM systems have limited materials.

4.2.2.5 Potential and Future Direction of Chairside Solutions

With newer generation of intraoral scanners, an improvement in efficiency of scanning provides a better patient experience that treatment results [22]. Most recently, the introduction of portability to intraoral scanning systems has allowed clinicians "plug-and-play" ability. They can use the scanner to obtain data for the designing software that is retained on a central server, using an existing computer and network infrastructure. These plug-and-play style scanners eliminate the need for the traditional cart-based system that houses the CPU, viewing monitor, software, and digital intraoral scanner [4].

With this technology becoming readily available, more manufacturers will offer open architecture CAD/CAM systems. Open architecture refers to the format of the data that is acquired during digital scanning as being compatible across multiple, different manufacturers of both software and hardware. An open system allows for transfer of data across multiple devices for design and final restoration [4]. This will give practitioners the opportunity to combine features from different manufacturers to better meet the needs of their clinical practice.

To provide more sophisticated restorative and prosthetic devices, future prostheses are expected to be designed and fabricated with improved function related to jaw movements. The analysis of multiple-axis mandible movements in order to reproduce the oral functions of patients has already been widely investigated in prosthodontics. Production of dynamic occlusal morphology during the CAD process is still challenging but must be made practical in the near future to offer restorations that respect the oral function [22]. Additionally, dental CAD/CAM is being used for educations and training purposes to produce explanatory and diagnostic materials for students and patients and for simulations of surgical and reconstructive procedures.

4.2.2.6 Materials

Chairside materials can be categorized as follows:

Predominantly Glass Ceramics

The principle features of predominantly glass ceramics are that they contain a glass phase and have excellent translucency and moderate strength. The glass component allows them to be etched with hydrofluoric acid and adhesively bonded to the tooth [23]. Some examples of materials in this category are Vitablocs Mark II and CEREC Blocs [19]. These materials are available in monochromatic or polychromatic multicolored blocks offering the possibility of creating restorations mimicking the transition from dentin to enamel layer. Further customization of either type can be accomplished by shade characterization and glazing [23]. They are commonly used for inlays, onlays, and veneers.

Leucite-Reinforced Ceramics

These blocks contain a leucite crystal phase which increases their flexural strength without losing their capacity to adhesively bond to the tooth. The percentage of leucite particles varies from 30% to 45% depending on the supplier. Some examples in this category are IPS Empress CAD from Ivoclar and Paradigm C from 3M ESPE. The IPS Empress CAD blocks are available in different monochromic shades of high translucency (HT) or low translucency (LT) or as polychromatic blocks. The Paradigm C is a radiopaque ceramic available in six shades that exhibits a chameleon effect once seated in the tooth due to its enhanced translucency and fluorescence [23]. Customization for both systems can be achieved through staining and glazing. They are commonly used for inlays, onlays, veneers, partial crowns, and crowns.

Lithium Disilicate

This ceramic presents 2–3 times the flexural strength of predominantly glass ceramics. Lithium disilicate (IPS e.max) was initially developed as a substructure material that offered greater translucency compared with other ceramic core materials, and it uses as a monolithic restoration for chairside CAD/CAM systems as it has gained popularity due to the enhanced strength [24]. The CAD/CAM block form is available in four translucency levels (high translucency, medium translucency, low translucency, medium opacity) and in different shades for each category [17, 24].

CAD/CAM lithium disilicate is acquired as blue violet partially crystallized blocks that are easily milled without excessive damage to the material. After milling, the restoration must undergo a firing process in a porcelain oven to complete the crystallization of the lithium disilicate. This process converts the blue shade of the pre-crystallized block to the selected tooth color and increases the flexural strength of the restoration to its final level [24, 25]. This material can be used for inlays, onlays, veneers, partial crowns, single crowns, three-unit fixed dental prostheses in the esthetic zone, and implant superstructures, as well as hybrid abutments and hybrid abutment crowns.

Zirconium Oxide and Lithium Silicate

Zirconium oxide and lithium silicate glass ceramics (ZLS) are available in a fully crystallized or pre-crystallized [26]. The fully crystallized ZLS ceramics are more difficult for machining, while, pre-crystallized ZLS ceramics are easy to machine. ZLS ceramics contain 10% of zirconium dioxide and lithium metasilicate and lithium disilicate crystals. ZLS ceramics are more recent, and they are comparable with the lithium disilicate glass ceramics [26].

Composite Resin and Polymers

Composite blocks can be used for CAD/CAM fabrication of inlays, onlays, and veneers. A popular block is Paradigm Z100 form 3M ESPE (Paradigm Z100 documentation 3M ESPE). This material is based on the Z100 composite from the same company. Paradigm Z100 has zirconia-silica filler particles and is 85% filled by weight with an average particle size of 0.6 μm. It is radiopaque and available in six shades, as well as a more translucent enamel color [27].

4.2.2.7 Equipment

Below we discuss some examples of chairside CAD/CAM solutions and digital impression systems. The most popular chairside CAD/CAM systems are CEREC (Dentsply Sirona, York, PA) and Planmeca (Planmeca Oy, Helsinki, Finland). Carestream Dental (Atlanta, GA), Dental Wings (Montreal, Canada), and Zfx (Dachau, Germany) are available as chairside solutions systems [28].

CEREC System

The CEREC system was the first commercially available chairside CAD/CAM system and is currently the most popular one [17, 19]. This system was originally developed by Mörmann and Brandestini in 1985, and it was commercially under the name CEREC 1 [1, 3, 4, 29]. The currently available CEREC system includes the CEREC Omnicam scanner and CEREC MC, X, and XL. In 2012, Sirona unveiled

Omnicam in which image capture is done via digital streaming and is in full color. The data collected by the scanner is processed by the CEREC software (new CEREC software 4.5). The true highlight of the CEREC Software is the “Biojaw” function. Based on the teeth scanned, the software generates a patient-specific restoration proposal taking into account the existing dental morphology. The software allows modification of morphology, occlusal contact adjustment, and marginal detection and has a user interface that can be operated effectively. Once the designing step is completed, the production can be completed using the CEREC MC, MC X, or MC XL Premium Package milling and grinding unit (Fig. 4.6). This system was originally developed for wet chairside milling, but the newer units offer the possibility of dry milling zirconia and chairside lithium disilicate restorations and also include a sintering and glazing unit to finalize the restorations.

Planmeca System

The Planmeca system was introduced on the market in 2008 under the name of E4D and has undergoing several reiterations. This system offers two intraoral scanning possibilities: the Planmeca Emerald and the Planmeca Planscan. The data collected is in STL open format allowing the possibility of using designing software and manufacturing form other systems (planmeca.com). The captured data is then analyzed by the Planmeca PlanCAD that is also open CAD software. The software is easy and fast to use and is ideal for designing prosthetic works from a single crown to bridges. The process is divided in five steps from work description to milling (planmeca.com). Once designing is completed, manufacturing can be done by the milling unit Planmeca PlanMill 40S. For certain materials (i.e., E.max), the process of production needs to be completed in a sintering oven which needs to be purchased from a third party.

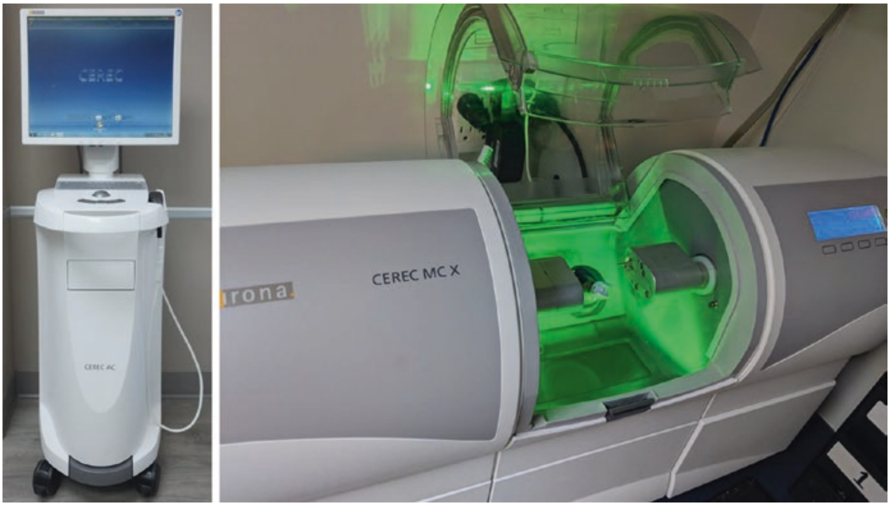

Fig. 4.6 Photographs showing the CEREC system

4.2.3 Laser Ablation

4.2.3.1 Overview of the Laser Ablation

Laser ablation or laser milling is the process of removing material from a solid surface using a laser beam [30, 31]. The laser ablation milling system is similar to the traditional milling systems, but it uses the laser beam to remove the excess materials instead of cutting tools, such as burs. This technology is relatively new in dentistry, and it was introduced to dentistry by Dental Wings Inc., in 2015 (Dental Wings Lasermill™). Laser ablation can be used to produce various dental restoration such as crowns, bridges, inlays, onlays, and veneers by milling a block of ceramic, polymer, or composite materials [30, 32, 33].

4.2.3.2 Laser Ablation Process

The process of fabricating a 3D object by the laser ablation milling system starts with designing the 3D model on the scanned model using the computer-aided design (CAD) software [30]. After uploading the CAD file into the system, the laser ablation milling system removes materials from a block using millions of high-intensity laser pulses until the final shape is completed [30, 32, 33]. Each laser pulse removes a small amount of material from the block by vaporizing the excess material. The spot size of the laser pulses is very small making the resolution of this system higher than any other traditional milling system [33]. Finally, the dental restoration completes without the need for secondary crystallization steps [30, 32].

4.2.3.3 Advantages of Laser Ablation

High Precision and Quality

The laser ablation milling system is extremely precise, and it can mill crowns with high-resolution features. This is because the diameter of the laser beam is smaller than the diameter of the burs in the traditional milling systems at least by the factor of ten [30, 33]. The laser ablation milling system is also integrated with an in-process 3D scanner to achieve high-quality control during the milling process. In addition, this technique reduces some problems associated with the traditional milling systems such as chipping of thin edges [30, 32].

Cost-Effectiveness

The initial cost of the laser ablation milling equipment and materials is high. However, the overall cost of the laser ablation milling system is lower than the traditional milling systems due to low operating costs since the system does not use cutting tools, such as burs, which need to be replaced often due to breakage and wear [30, 32, 33].

High Productivity

The laser ablation milling system is fast and comparable to the traditional milling machines [33]. Dental restorations can be finished on the same day using this milling system. Also, a wide variety of dental restorations materials can be used with this system [33].

4.2.4 Potential and Future Direction of the Laser Ablation

Although this technology relatively is new, it has the potential to become a main method for fabrication of dental restorations for its advantages over previous technologies.

4.3 Additive Manufacturing

4.3.1 3D Printing

4.3.1.1 Overview of the 3D Printing

3D printing or rapid prototyping (RP), which is also known as solid freeform fabrication (SFF), is a type of additive manufacturing that builds up 3D objects in a layer-by-layer pattern by laying down successive layers of material until the final object is formed [26, 34]. 3D printing technologies are growing and developing quickly, and they are used for different applications in various fields such as aerospace, automotive, engineering, jewelry, education, arts, architecture, and medicine [34]. The first 3D printing technology was developed in the 1980s, and the first use of the 3D printing technology to treated patients in the late 1990s [3, 34]. However, 3D printing for dental applications is relatively new.

4.3.1.2 Dental Applications of 3D Printing

3D printing can be used for various dental application either directly by printing the final object in resin or metal or indirectly by printing burnout resins or waxes for subsequent casting process [34]. Direct applications of 3D printing technology in dentistry include fabrication of custom trays, temporary or definite crowns or bridges, and partial denture frameworks [10, 34–36]. Also, different orthodontic products can be fabricated by 3D printing such as positioning trays, orthodontic models, clear aligner retainers, bite splints, and night guards [34, 35]. Other application for maxillofacial surgery and dental implants include surgical guides and maxillofacial prostheses [10, 34–36]. The indirect dental applications of the 3D printing include wax or resin castable pattern for crowns or bridges, partial denture frameworks, and complete dentures [34, 37].

4.3.1.3 3D Printing Production Process

The process of 3D printing can vary depending on the technique used, but it always follows similar concepts. A 3D model is created from data generated with a 3D or CT scanners. The object to be printed is designed in a computer-aided design (CAD) software, and then using another CAD software, supports are added, and the model is sliced as multilayers [3, 34, 35]. Then, 3D object is printed, and for some 3D printing technologies, post processing such as supports removal, heat treatment, and washing or polishing apply [34, 35].

4.3.1.4 Types of 3D Printing Technology

There is a large number of 3D printing technologies available for medical and dental applications including stereolithography (SLA), digital light projection (DLP), polyjet or multijet, inkjet printing, fused deposition modeling (FDM), and powder bed fusion (PBF) [3, 9, 38]. The main differences between these techniques are in the materials used and the way the layers are deposited to create the 3D object. 3D printing technologies can be classified into three categories of liquid-based, powder-based, and solid-based depend on the form of the material used [34]. Each technique has its own advantages and drawbacks in terms of accuracy, speed, costs, choice and cost of the materials, and color capabilities (Table 4.1). The main types

Table 4.1 List of main materials, advantages, disadvantages, and dental applications with each dental 3D printing type

	Materials				
Technique	Form	Type	Advantages	Disadvantages	Dental applications
SLA	Liquid	Polymers, PLLA, PEG-DMA, PPF, PTMC, PMMA; ceramics, PLGA/TCP, alumina	High accuracy, smooth surface, high density, low-cost materials	High-cost technology, limited strength. requires support structures, and requires post-processing treatment	Dental models, surgical guides, custom trays, temporary crown and bridge, prosthesis pattern, maxillofacial prosthesis, orthodontic prosthesis, and bone
Polyjet/ multijet	Liquid	Waxes, resins, and silicone	High accuracy, variety of materials and colors, average-cost technology	High-cost materials	Dental models, custom trays, surgical guides, temporary prosthesis, mouth guards, and orthodontic appliances
Inkjet	Powder	Plaster of Paris and ceramic suspension	Low cost, and variety of materials and colors	Low accuracy, low strength, and rough surfaces	Dental models, ceramic dental restoration, bone graft materials
PBS	Powder	Metals: cobalt-chromium and titanium; ceramic; polymers	High accuracy, good strength, high productivity, low-cost materials	High-cost technology, rough surface and post-processing required	PRDP framework, crowns and bridge, and PFM coping, customized dental implants
FDM	Filament	Polymers: PLA, PC, ABS, PCL, PPSU, and waxes	Low cost, good strength, and variety of materials and colors	Low accuracy and density, rough surfaces, and limited to thermoplastic materials	Custom trays, surgical guides, and prosthesis patterns
SEBM	Powder/ filament	Metals: cobalt-chromium and titanium	Good strength, low-cost materials	High-cost technology, average accuracy and rough surface	Customized dental implants

SLA stereolithography, *FDM* fused deposition modeling, *SEBM* selective electron beam melting, *PLLA* poly(D,L-lactide), *PEG-DMA* polyethylene glycol dimethacrylate, *PPF* poly(propylene fumarate), *PTMC* poly(trimethylene carbonate), *PMMA* poly(methyl methacrylate), *PLGA/TCP* polylactic-co-glycolic acid and tricalcium phosphate, *PLA* polylactic acid, *PC* polycarbonates, *ABS* acrylonitrile butadiene styrene, *PCL* polycaprolactone, *PPSU* polyphenylsulfone, *PRDP* removable partials denture, *PFM* porcelain fused to metal, PBS Powder bed fusion of the 3D printing technology are explained underneath including production process, characteristic, materials used, and dental application.

Stereolithography (SLA)

Stereolithography (SLA) is photopolymerization process that builds up solid parts in multilayers from a liquid-based material using an ultraviolet (UV) light or laser for solidifying the materials [3, 9, 35, 36]. SLA was developed in 1986 by 3D systems, and it is considered to be the first commercially available 3D printing system [39]. SLA systems consist of a bath of photosensitive liquid polymer monomer (e.g., acrylates and epoxy monomers), an ultraviolet (UV) light or laser, and building platform (Fig. 4.7) [9, 36]. Objects are built in a layer-by-layer pattern (50–200 μm); at each layer, the UV light cures and hardens a thin layer of the polymer on specific areas defined by the CAD data, and then the platform lowers or raises depending to the technology for the next layer, while the UV light cures the next layer with previous one [3, 36]. The process continues until the completion of the full object [35, 36]. Then, the object is removed from the bath [3, 35]. The post-processing treatment is applied into the final object including support structure removal. The object can be further cured in UV light or laser, and it can also involve surface treatments with primers, paints, or sealants to change surface roughness [35]. Another approach of SLA is digital light projection (DLP) that is similar to SLA, but the object builds upside down with different light source [34]. DLP uses a projector light source that is applied to the entire surface of the photopolymer resin bath. This results in lower running costs and faster processing compared to SLA.

The accuracy of SLA is superior to other 3D printing techniques, and it can print complex geometries with fine details. A resolution of 5 μm in the *X*-/*Y*-axis and 10 μm in the *Z*-axis can be achieved by SLA [9, 34, 35]. However, this is influenced by many conditions such as the UV light parameters (wavelength, power, and

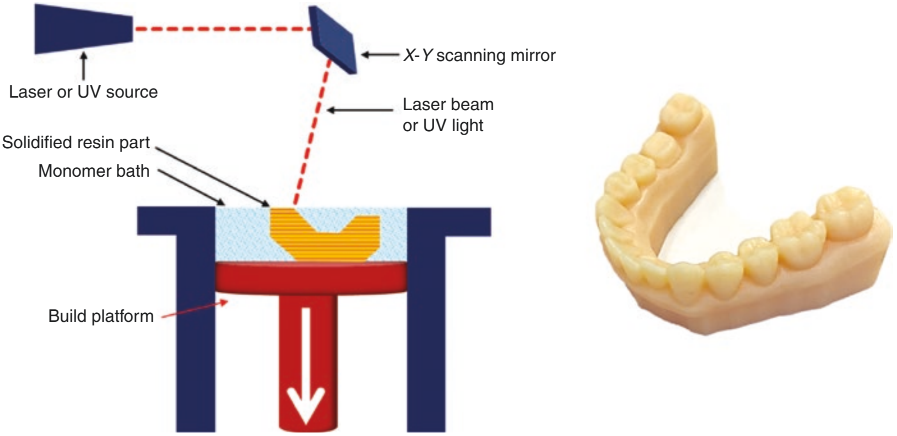

Fig. 4.7 Schematic of the SLA production process and a photograph of a dental model printed by SLA

exposure time), layer thickness, and step size [35]. Also, accuracy depends on the position of the object in the build platform that accuracy is high at the center than at the peripheral of the build platform [40]. One limitation is that SLA technology requires support structures to process objects, which increases the production time and consumes additional material [41]. In addition, SLA produces soft objects with limited mechanical strength [34, 35].

Typical dental materials used in SLA technology include acrylic resin, silicone, and epoxies [8, 9]. These materials are available in different colors and present different mechanical and physical properties [9]. These materials include poly(D,L-lactide) (PLLA), polyethylene glycol dimethacrylate (PEG-DMA), poly(propylene fumarate) (PPF), poly(trimethylene carbonate) (PTMC), and poly(methyl methacrylate) (PMMA) [8, 37]. In addition, ceramics can also be used with the SLA such as PLGA/TCP, polylactic-co-glycolic acid (PLGA)/tricalcium phosphate (TCP), and alumina ceramics [8, 9, 42, 43]. Ceramic in SLA presented some issues with shrinkage, but it may be useful to be used as scaffold for tissue regeneration [9].

One ideal dental application for SLA is for fabrication of dental models, surgical guides, and custom trays [3, 5]. Dental model that for the treatment planning or for educational purposes now can be produced by the SLA technology [3, 44]. The surgical guides that help for the placement of dental implants are commonly produced by the SLA technology [3, 45–50]. In addition, custom trays, temporary crowns and bridges, and prostheses pattern for lost-wax casting process are produced by this technology [3, 48, 49, 51–53]. Definitive complete dentures have been fabricated successfully by the SLA technology using poly(methyl methacrylate) (PMMA) with TiO_2 nanoparticles [37]. Orthodontic appliances such as removable orthodontic appliances and occlusion ties were also produced successfully by this technology [54, 55]. Moreover, maxillofacial prostheses and facial replacements have been effectively printed by the SLA technology [56, 57]. Scaffold for bone reconstruction using ceramic-based materials such as calcium phosphate hydroxyapatite and PLGA/TCP composite was also fabricated by this technology [8, 42, 43].

Polyjet or Multijet

The polyjet or multijet printing (PJP or MJP) is a type 3D printing, which is similar to the 2D inkjet printing, but it builds up the object in multilayers [3, 34, 35]. This technology is also can be referred as photopolymer jetting (PPJ) [34]. With this method, droplets of photopolymer are ejected onto a surface and then cured by UV light (Fig. 4.8). In each layer, liquid-based photopolymer materials apply only on the desired area and cured with the previous layers by the UV light [3, 34, 35]. This technique can combine multiple colors and materials in one print [3, 34, 35]. This is an important feature of the technology, for example, it can be used to print a mouth guard with hard and soft parts and with different colors [3]. This technology can print objects with complex geometry since it is possible to print objects with fine details at resolution of 16 microns [34, 35]. Another advantage of this technology is the ability of using other materials such as wax or gel for the supporting structure for easier removal from the final object [35].

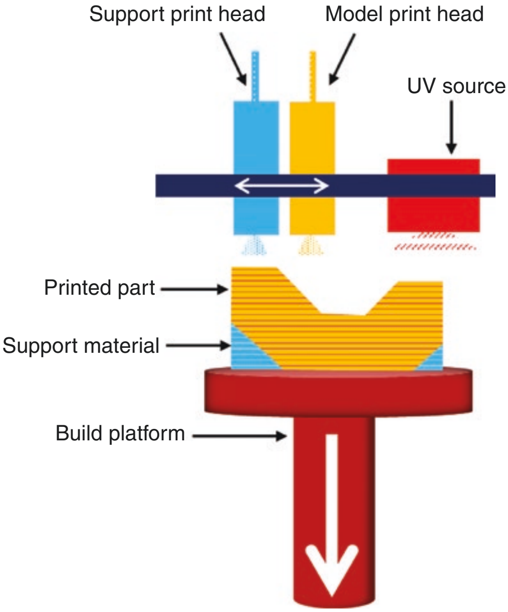

Fig. 4.8 Schematic of the polyjet/multijet production process

Different materials can be used for printing objects by polyjet or multijet technology including waxes, resins, and silicone [34]. Material jetting technologies are limited in dentistry because of their high cost compared to other less expensive 3D printing technology such as SLA [34]. This 3D printing technology can be used for processing many dental applications such as dental models, custom trays, surgical guides, temporary prosthesis, mouth guards, and orthodontic appliances [3, 34, 35, 58].

Inkjet Printing

Inkjet 3D printing or binder jetting process is a 3D printing process in which an inkjet is used to eject small ink drops of binding liquid material toward a substrate of powder (plaster, ceramic, or resins) and build up the object layer-by-layer (Fig. 4.9) [36, 38]. The term 3D printing was introduced after the inkjet printing, and then it was subsequently used for all additive manufacturing methods. The process of inkjet printing starts with spreading a thin layer of the substrate powder across the binding platform, and a liquid-binding material is applied on top of the powder; this connects together the exposed particles leaving the unexposed particles loose [35, 36]. This process is repeated with each layer until the final shape is formed [35, 36, 38]. Finally, a heat treatment is applied, and the unbound powders are removed from the building platform [38]. Different colors of the liquid-binding material can be used for printing multiple color objects. The most common material for this technology is plaster of Paris [34]. Ceramic suspension was also used in some studies to print zirconia dental restorations [3]. Inkjet printing produces a lower-resolution print with achievable accuracy of ±127 µm, which is not ideal for dental applications, but it can be used for

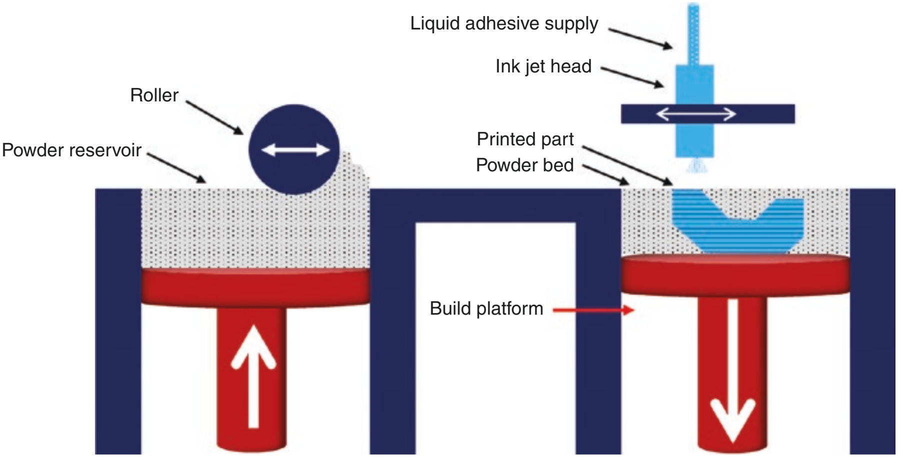

Fig. 4.9 Schematic of the 3D inkjet printing process

dental models and orthodontic diagnosis models [34–36, 38]. It has also been used experimentally to print bone graft materials [59].

Powder Bed Fusion (PBF)

Powder bed fusion (PBF) such as laser sintering and laser melting is an additive manufacturing technology used to process 3D objects in a layer-by-layer pattern using a high-power laser that melts or fuses successive layers of compacted powder [60]. To process the first layer of an object by laser sintering/melting technology, metal powders are spread onto a production platform by a counter-rotating the roller [3, 61, 62]. Then, a laser beam is focused on an area defined by the CAD data file to fuse the powders in that area, while the remaining powders remain unfused [3, 60–62]. For the subsequent layers, the production platform is lowered for one-layer thickness, a new layer of powders is applied again on top of the previous one, and the laser fuses the powders with the previous layer [3, 61, 62]. This procedure is repeated until forming the final desired shape. Laser sintering/melting technology is the newest technology in 3D printing, and it will be explained extensively in the next topic of this chapter [62].

Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) or fused filament fabrication (FFF) is a technique that builds up an object by laying down a wire of thermoplastic material onto a building platform through a heated nozzle (Fig. 4.10) [3, 34, 35]. This technique was developed in the early 1990s by Stratasys [41]. The 3D object is built from the bottom up, one layer at a time. The nozzle movement is directed by the CAM software and can be moved in both horizontal and vertical directions. The thermoplastic material is partially melted in the nozzle, and upon deposition on the building base, it solidifies immediately within 0.1 s [36]. The

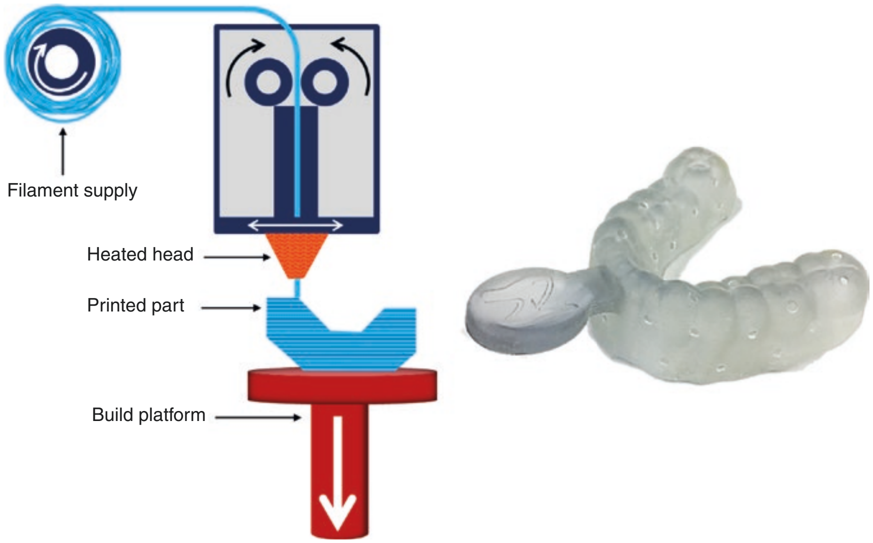

Fig. 4.10 Schematic of the FDM/FFF production process and a photograph of a dental custom tray printed by the FDM/FFF

deposition process continues for the following layers until the final object is completely formed [3, 34, 36]. The layers of the deposited materials can be bonded together by the use of chemical agents or by temperature control [41]. In addition, a new approach of FDM such as Bioplotter was recently developed, that is, the ability to print in multiple materials including ceramic pastes which can be used to print porous bone scaffolds and body parts [3].

The accuracy of FDM is lower than other 3D printing techniques such as SLA. The average accuracy of FDM is about ±127 µm [9, 36, 38]. The accuracy of FDM depends on the speed of deposition, flow of the material, material nozzle thickness, and the size of each layer [34]. One advantage of FDM is no post-processing treatment is required. However, the low-resolution, slow speed, and low surface quality, are the main disadvantages of this technique [39]. The FDM is limited to thermoplastic materials for fabrication complex shapes and geometry. Several thermoplastic materials are available for this technology such as waxes, PLA (polylactic acid), polycarbonates, ABS (acrylonitrile butadiene styrene), PCL (polycaprolactone), and PPSF or PPSU (polyphenylsulfone) [3, 9, 34, 63]. PLA is more suitable to be used in dental application since it is more biocompatible than ABS [9]. In addition, the number of FDM filament options is increasing every year [8]. The ideal dental applications for FDM are custom trays, surgical guides, and wax patterns of dental prostheses for subsequent casting or polymerization process [3, 63].

Selective Electron Beam Melting (SEBM)

Selective electron beam melting (SEBM) is similar to laser sintering and laser melting, but the processing occurs in a high vacuum and with an electron beam as the heat source to fully melt the metal powder [3]. Another approach of SEBM is to use an electron beam to melt wire of metal onto a surface to build up an object that is similar to the FDM technique but with metal rather than plastics [3]. One main advantage is the ability to produce porous objects by different alloys such as cobalt-chromium and titanium, and this technology can be used for producing customized implants for maxillofacial surgery [3, 64]. The accuracy of laser powder-forming technique such as SEBM can be about ±20–50 μm [36].

4.3.1.5 Materials

Different materials can be printed by the 3D printing technology, and these include polymers, metals, ceramics, and composites [5]. 3D printers in dentistry mainly use polymers as 3D printing material such as polypropylene, polyurethane, ABS (acrylonitrile butadiene styrene), PPSF (polyphenylsulfone), nylon, silicon, polystyrene, polylactic acid, polycarbonates, and polycaprolactone [36]. Some techniques allow the use of ceramic materials such as alumina ceramics and zirconia, while other technologies can use metals as the printing materials such as stainless steel, cobalt-chromium, and titanium [3, 34].

4.3.1.6 Equipment

Many manufactures offered 3D printing for medical and dental application such as 3D Systems, Medical Modeling, EOS, BEGO, Stratasys, Materialise, and Formlabs (Fig. 4.11) [36]. For instance, R.Pod® Desktop 3D printer (Arfona, Brooklyn, NY; arfona.com) and Perfactory Vida (EnvisionTEC, Dearborn, MI; envisiontec.com) are 3D printers based on fused deposition modeling (FDM), and they are able to print dental models, custom trays, and temporary prostheses using different materials with different colors such nylon, PLA, ABS, TPU, and polyethylene. Moreover, Formlabs Form 2 (Formlabs, Somerville, MA; formlabs.com), Objet Eden260VS Dental Advantage (Stratasys, Eden Prairie, MN; stratasys.com), and VARSEO 3D printer (Bego Medical, Bremen, Germany; bego.com) are 3D printers based on stereolithography (SLA), and they are effectively able to print dental models, surgical guides, custom trays, orthodontic appliances, and temporary prostheses. In addition, 3D Systems (3D Systems, Rock Hill, SC; 3dsystems.com) have many 3D printers for dental applications based on different technologies such as NextDent™ 5100 based on SLA technology, ProJet MJP 2500 based on polyjet/multijet technology, and ProX DMP 100 and 200 Dental based on laser sintering/melting technology.

4.3.1.7 Advantages and Limitations of 3D Printing

There are some advantages and disadvantages associated with each 3D printing technique according to their accuracy, cost, strength, speed, availability, and choice of the materials. Generally, 3D printing technology is more economical and faster than traditional methods and milling systems [13]. These advantages and disadvantages are summarized in Table 4.1 [3, 5, 8, 34–37, 42, 43, 58, 63–65]. It is important to know that 3D printing technologies are changing dramatically which it can improve their quality and eliminate their limitations.

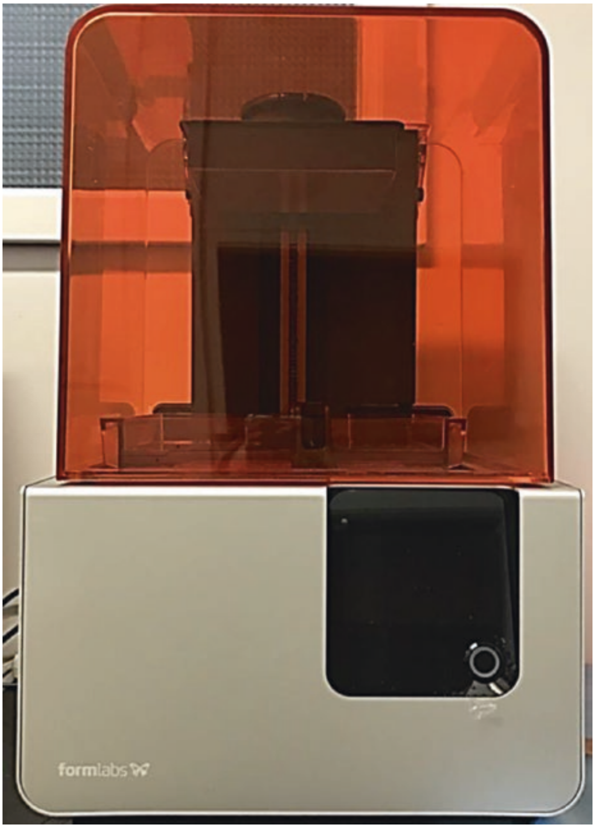

Fig. 4.11 Photograph shows a 3D printing machine

4.3.1.8 Potential and Future Direction of 3D Printing Technology

The accessibility of 3D printers has grown dramatically in the past decade [35]. Today, there are more than 300 companies selling 3D printers for general use, and some 3D printers already cost less than $1000 [35]. Indeed, 3D printing market has grown more than 33% in the last few years and was valued at $4.1billion in 2014 [35, 66]. In the next few years, the 3D printing market is expected to grow to over $8.9 billion, and the medical and dental application is comprising 21% of the market [10, 35].

4.3.2 Laser Melting

4.3.2.1 Overview of the Laser Melting Technology

Laser melting is an additive manufacturing technology used to process 3D objects in a layer-by-layer pattern using a high-power laser that melts or fuses successive layers of compacted powder [60]. Laser melting includes different technologies, such as laser melting, selective laser melting (SLM), selective laser sintering (SLS), or direct metal laser sintering (DMLS) [60]. These technologies are generally referred to as powder-bed fusion (PBF) [67]. All of these technologies rely on the same concept, but they present some differences in the physical process or in the materials used [60]. Selective laser sintering (SLS) involves partial surface melting of the powder particles, and it was initially developed and patented in the mid-1980s for processing thermoplastic polymers [68–70]. The first 3D printed metal object was done in 1990, and this method was patented as selective laser sintering (SLS) [67]. With the development of powerful high-quality lasers, selective laser melting (SLM) and direct metal laser sintering (DMLS) technologies were introduced in 1995 to process metals [68, 70, 71]. The first commercial machine for processing metals by SLM was launched in 1995 by EOS GmbH [67]. SLM involves full melting of the powder particles, while DMLS involves both full and partial melting of the powder particles [60, 71, 72]. Electron beam melting (EBM) is another PBF technology developed by Arcam in 2000 [67]. EBM is similar to SLS and SLM, but the processing occurs in a high vacuum, with a hot powder bed, and with an electron beam as the heat source to fully melt the metal powder [3].

SLS techniques often process porous and weak objects, while DMLS and SLM can produce strong and dense objects [9]. SLS is used to process polymers and ceramics while SLM and DMLS are used for processing metal [3, 60, 72].

Nowadays, the systems used to process metal objects are commonly referred to as selective laser melting (SLM) because they rely on full melting of the metal powder [67]. For this reason, the term laser melting technology will be used in this book chapter to refer to all metal powder-bed processes that use a laser as a heat source.

Laser melting technology involves the melting of powder material with a laser beam [73]. First, the building platform of laser melting machine is heated up to a temperature around ~200 °C and maintained at this temperature during the process [73]. Then, the laser beam is focused onto the powder bed to impart energy to the powder through photons and melt the metallic powder at a temperature between 500 to 1000°C [73]. Various laser parameters such as laser source, laser power, and wavelength can be adjusted to achieve an optimal powder melting [73]. The lasers used are often CO_2 lasers or fiber lasers (Nd: YAG or Yb: YAG) with a power of 200 to 300 Watt [74]. Nd: YAG crystal is a commonly used laser; while, Yb: YAG crystal is a new, and it has a larger absorption bandwidth, a lower thermal loading per unit pump power, and a longer upper-state lifetime than Nd: YAG [74]. Thus, Yb: YAG is expected to replace Nd: YAG [74].

The power of the laser, scanning speed, hatch spacing, and layer thickness are important parameters that can influence the powder melting process [73, 74]. For instance, low laser power, high scanning speed, 2 and large layer thickness can result in insufficient energy to melt the powder [74]. Whereas, high laser and low scanning speed could lead to evaporation of the melted materials. Therefore, a suitable combination of the parameters is essential for processing a successful object by this technology. Also, poor hatch spacing can result in porosity in the processed object because the adjacent melt lines do not fuse together [74]. Therefore, a suitable combination of these parameters is crucial for processing a successful object [73, 74].

4.3.2.2 Dental Applications of the Laser Melting Technology

Laser melting technology in dentistry is currently associated with processing metals since other materials such as polymers, ceramic, and composite are more effectively produced by other CAD/CAM technologies. Laser melting technology is used for different dental applications such as partial denture frameworks, dental crowns and 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

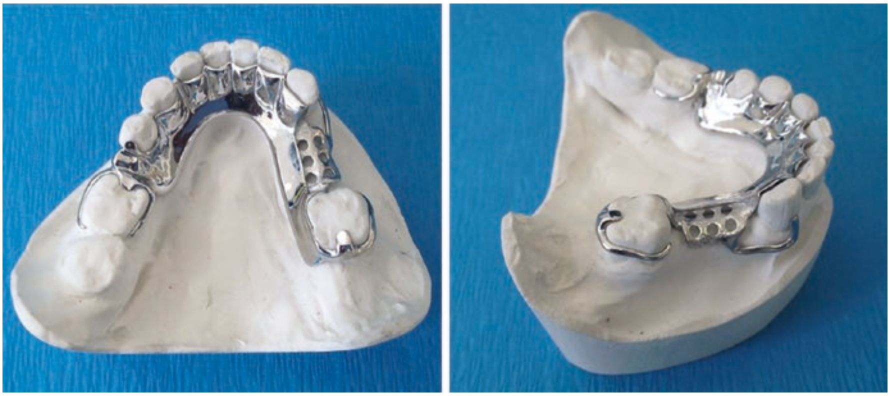

Fig. 4.12 Photographs showing the metallic framework of a partial removable dental prostheses (PRDPs) processed by the laser melting technology

implants with complex geometries opening the door for many promising clinical applications in the future [93–96]. Moreover, many studies investigated that the porous laser melting implants have improved the osseointegration [97–100]. Implant prostheses and devices such as frameworks of implant-borne fixed dental prosthesis and bone extension device were successfully fabricated using laser melting technology, and they showed comparable results with conventional one [64, 101].

4.3.2.3 Materials

A large range of materials can be used in selective laser sintering (SLS) including polymers, ceramics, and metals [3]. Different types of polymer powder can be used in SLS technology such as polyamides, PS (polystyrene), PC (polycarbonate), polypropylene, ABS (polyacrylonitrile butadiene styrene), HDP (high-density polyethylene), and PEEK (polyether ether ketone) [34, 35]. In addition, ceramic materials such as HA (hydroxyapatite), tricalcium phosphate (TCP), and alumina (Al_2O_3-SiO_2) can be used in SLS [8, 102]. However, SLS polymers, composite, and ceramic are not yet widely used for dental applications because they can be produced by other 3D printing technologies more effectively and at lower cost [60, 102]. Metals powders including cobalt-chrome (Co-Cr) alloys, titanium (Ti) alloys, and steel are the main materials used with the laser melting technique [76]. Co-Cr powders are commonly used for fabricating dental crowns and partial removable dental prostheses (PRDPs) frameworks, while titanium (Ti) powder has been used for dental implants and PRDP frameworks [77]. The quality of the powder that is used in the laser melting process determines the quality of the final product, and it is influenced by composition, size, shape, morphology, and amount of internal porosity [67]. Therefore, it is recommended to use a specified metallic powder for each laser melting system as each system is calibrated to suit its alloy. In fact, the chemical composition of the powder can affect the properties of the processed objects. Thus, it is important to measure the elemental composition of recycled powder and remove any contamination from the powder to use it within their specification [67]. Moreover, smaller powder particles can improve the surface, but they are more costly than large size particles [67]. Therefore, the use of a fine distribution of powder particles can improve the surface finish and reduce the cost [67]. In addition, smooth particle surfaces produce less porosity, while the spherical powder particles tend to improve the apparent density. Table 4.2 shows a list of the main commercially available dental alloys for processing dental prostheses by the laser sintering/melting technology [60].

4.3.2.4 Equipment

Different laser melting machines are commercially available for processing metals for dental applications [60, 103, 104]. The main laser melting vendors in the market for medical devices include Phenix Systems (Fig. 4.13), 3D Systems Corporation, EOS GmbH, GE, EnvisionTEC GmbH, Stratasys Ltd., Materialise, Renishaw, 3T RPD Ltd., Concept Laser GmbH, Arcam, Bio3D Technologies, Prodways, and Realizer. However, most of the previous studies in the past few years that tested laser-sintered metals for dental applications were done by the three commercially available systems: EOSINT M250/M270/M280 (EOS GmbH, Munich, Germany),

Table 4.2 List of commonly available laser melting equipment and materials that can be used for processing dental prostheses

Technology			Alloys	
Equipment	Type	Manufacturer	Type (brand name: composition)	Suppliers
EOSINT M250	SLM	EOS, Munich, Germany	Co-Cr (SP2, Co 52, Cr 24, Mo 6, W 6, S, Fe, Mn <2; MP1, Co 60-65, Cr 26-30, Mo 5–7, Si, Mn, Fe, C, Ni <2); Ti (TiCP: Pure titanium)	EOS, Munich, Germany
EOSINT M270	SLM	EOS, Munich, Germany	Co-Cr (SP2, Co 52, Cr 24, Mo 6, W 6, S, Fe, Mn <2; MP1, Co 60-65, Cr 26-30, Mo 5–7, Si, Mn, Fe, C, Ni <2); Ti (TiCP: Pure titanium)	EOS, Munich, Germany
PM 100 Dental System	DMLM	Phenix Systems, Clermont-Ferrand, France	Co-Cr (ST2724G: Co balance, Cr 29, Mo 6, Mn, Si, Fe <1)	Sint-Tech, Clermont-Ferrand, France
PM 200 Dental System	DMLM	Phenix Systems, Clermont-Ferrand, France	Co-Cr (ST2724G: Co balance, Cr 29, Mo 6, Mn, Si, Fe <1)	Sint-Tech, Clermont-Ferrand, France
SLM	SLM	Bego Medical, Bremen, Germany	Co-Cr (Wirobond C+: Co 64, Cr 25, W 5, Mo 5, Si 1)	Bego Medical, Bremen, Germany
Laser CUSING	SLM	Concept Laser GmbH, Lichtenfels, Germany	Co-Cr (Remanium Star: Co 60, Cr 28, W 3, Si 2; Mn, N, Nb, Fe <1)	Dentaurum, Ispringen, Germany
SLM 50	SLM	Realizer GmbH, Borchen, Germany	Co-Cr (Solibond C plus Powder: Co 63, Cr 24, W 8, Mo 3, Nb 1, Si 1)	Yeti Dental, Engen, Germany
SLM 125	SLM	SLM solution GmbH, Lubeck, Germany	Co-Cr; Ti	SLM solution GmbH, Lubeck, Germany
SLM 280	SLM	SLM solution GmbH, Lubeck, Germany	Co-Cr; Ti	SLM solution GmbH, Lubeck, Germany

SLM selective lase melting, *DMLM* direct metal laser melting

PM100/PXM (Phenix Systems, Riom, France), and Bego (Bego Medical, Bremen, Germany) [9]. PM100 dental system (Phenix Systems) is the first laser melting system that uses cobalt-chromium powders for dental applications [67]. In the past few years, there were some changes in this industry that 3D Systems bought Phenix Systems, while GM manufacturer bought two systems which are Arcam and SLM Solutions. Table 4.2 shows a list of commercially available equipment that can be used for processing dental prostheses.

4.3.2.5 Laser Melting Production Process

The first step of processing an object by the laser melting technology starts by designing the 3D object on the scanned model using a computer-aided design (CAD) system. Then, a special CAD software is used to slice the designed 3D object (STL file) into multiple layers with a defined thickness and to add supports between the model and the production platform [60]. The supports are added to

Fig. 4.13 Photograph shows a laser melting machine

prevent the collapse of the build materials [38]. After uploading the design file into the laser melting system, the production process starts with spreading a thin layer of alloy powder onto a production platform with an accurate thickness of 20–100 μm and powder particle size of 25–45 μm (Fig. 4.14) [3, 60–62]. Then, the directed laser beam fuses or melts the powder only at a specified site defined by the CAD data file, while the remaining powder particles remain unfused [3, 60–62]. For the subsequent layer, the production platform moves down a distance of one-layer thickness, and a new layer of powder is applied again on top of the previous one, and the laser fuses or melts the powder with the previous layer [3, 60–62]. This procedure continues, layer by layer, until object completion (Fig. 4.15). It should be noted that it is important to select the proper processing parameter (e.g., scanning rate, laser power, and layer thickness) for each dental material and application since these parameters can change the properties of the processed objects (e.g., accuracy, density, surface roughness, hardness, and strength) [72, 84]. Also, the build orientation can change the mechanical and physical properties of the object which should be considered during the processing [105–107].

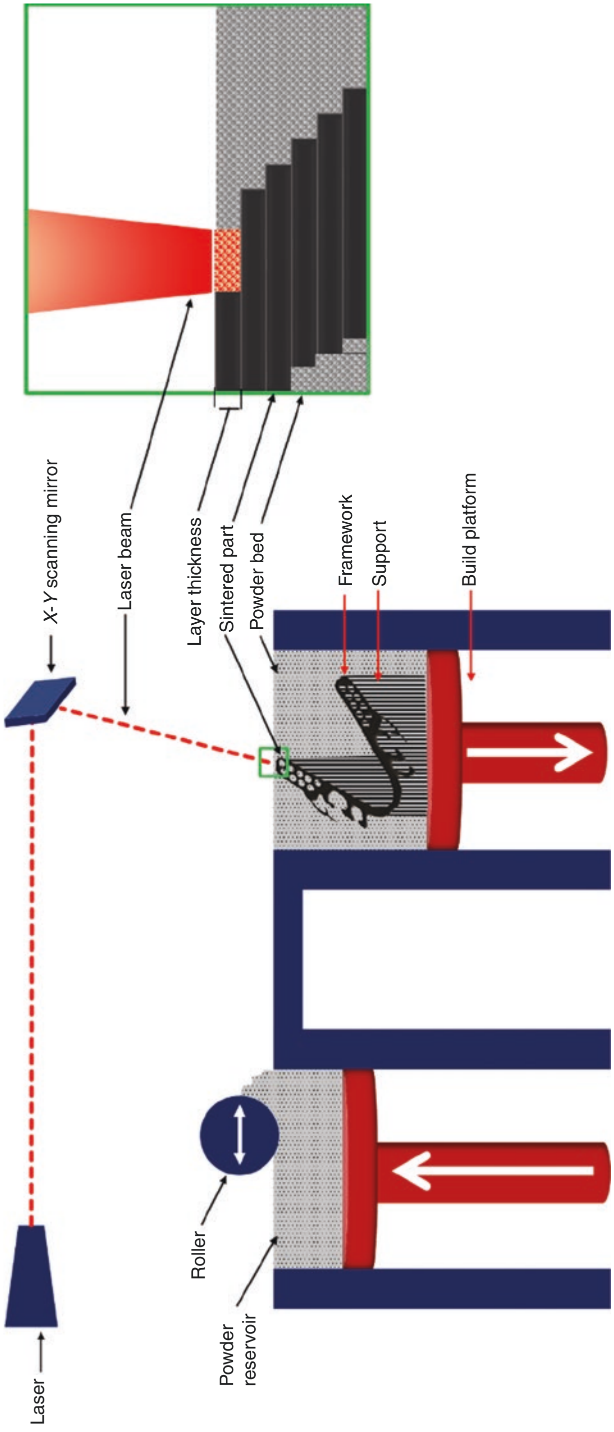

Fig. 4.14 Schematic of the laser melting production process for a PRDP framework

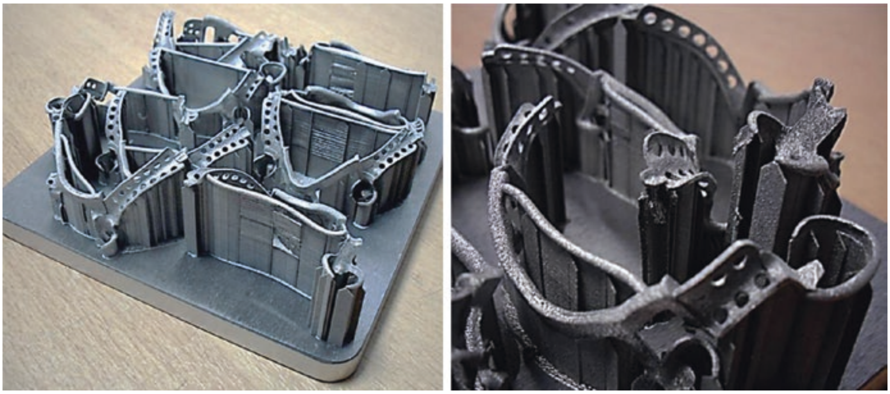

Fig. 4.15 Photographs showing the final processed frameworks of removable partial dentures (PRDPs) by laser sintering/melting technology

4.3.2.6 Post-processing Process

The post-processing process is usually required to improve the properties of the final 3D object, and this involves the following steps [60]. First, the loose powder particles are cleaned from the processed object to remove any unsintered powder sticking to the surface [67]. Next, the support structure that connects the 3D object with the production platform is removed [67]. Then, heat treatment is usually applied into the final 3D object according to the manufacturers' instructions for a period of time to enhance the mechanical and microstructural properties [60, 108]. The thermal post-processing is used to relieve residual stress and to improve the mechanical properties of the metals, and it has very important effects on the grain structure of the processed material [67]. The heat treatment for alloys is usually done at temperature of 800–450 °C for 30–60 minutes [75]. For examples, post-processing heat treatments for Co-Cr alloy is applied in 3 stages. The object is heated at 450 ºC for 45 minutes, at 750 ºC for 60 minutes, and then cooled down fast. Post-processing heat treatments for Ti alloy is applied in 3 stages, the object is heated at 750 ºC for 2 hours, at 900 ºC for 2 hours, and then cooled down fast [67]. Finally, the surface of the final metallic objects involves different finishing and polishing steps (such as electropolishing) before sending them to the clinic.

4.3.2.7 Advantages of the Laser Melting Technology

Laser melting technology is a very suitable technique for processing dental prostheses because it is accurate, fast, and cost-effective, and it can improve the quality of dental prostheses and the productivity of dental laboratories [3, 60, 71]. In addition, a vast variety of dental materials and alloys can be used for dental applications. Underneath are the main advantages of laser melting technology.

High Accuracy and Quality

The accuracy of laser melting is extremely high; this technology is able to fabricate 3D objects with an accuracy of ±20 μm [38, 75, 84, 109]. The minimum feature size

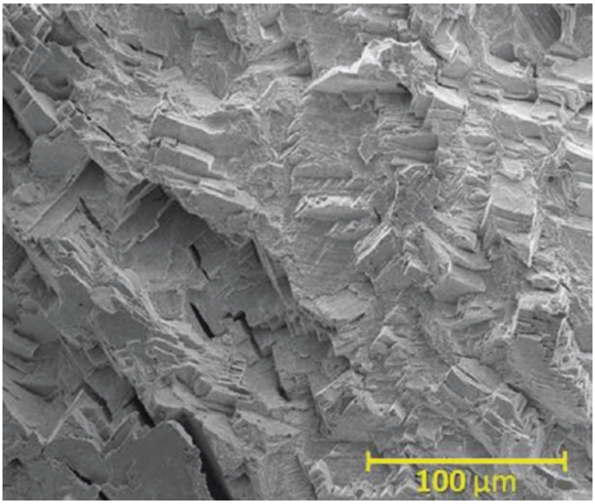

Fig. 4.16 Scanning electron microscope (SEM) images showing a homogenous and organized fracture path of the Co-Cr alloys processed by the laser melting technology

that can be printed is 75–100 µm [67]. However, the accuracy depends on the processing parameters, building direction, and the geometry of the objects [75, 84, 109]. The laser melting technology enables producing a complex 3D design and geometries, unlike the subtractive manufacture techniques. Compared to traditional casting techniques, one major advantage of laser melting is the ability to produce objects that have a more homogenous microstructure (Fig. 4.16). As a result of this, cobalt-chromium (Co-Cr) objects processed by laser melting present better fatigue resistance and physical properties than Co-Cr produced by the traditional casting method [75, 78]. Also, many studies showed that Co-Cr and Ti alloys produced by the laser melting have better or comparable biocompatibility and lower ion releases than with cast alloys [60, 75, 103, 104, 110, 111]. Clinical studies have also shown that the high precision and quality of alloys processed by this technique might improve the quality of the provided dental prostheses and therefore increase patient satisfaction with their dentures [78].

High Productivity

The production speed of laser melting devices is proportional to the size of the objects as well as other processing parameters such as scan speed, scan space, and layer thickness [112]. In the case of the fabrication of dental prostheses, laser melting usually takes less than 12 h which is much faster than the time needed to fabricate prostheses by the traditional casting technique, as it reduces the fabrication steps (e.g., waxing up, molding, firing, casting, etc.) into one step [60]. Also, during the manufacturing process, multiple dental prostheses can be processed simultaneously on the same production platform which considerably increases productivity. For instance, one laser melting system can produce around 450 units of dental crowns and bridges within a day [113]. In fact, this technique can speed up the denture delivery, as it enables to finish processing the framework within 1 day [3].

Cost-Effectiveness

The overall cost of the dental prostheses processed by the laser melting technique is lower than processing by milling or casting techniques [60]. The reduced cost is a result of low labor, time, waste materials, and cost of the materials as well as the ability to recycle the unused materials [60]. It has been estimated that fabrication of dental prostheses by laser melting technology could reduce manufacturing costs down to less than half the cost of traditional techniques [114].

4.3.2.8 Limitations of the Laser Melting Technology

There are some disadvantages of the laser melting technology. The initial cost of laser melting equipment is relatively high [11, 60]. Also, most of the laser melting methods require post-processing treatments for the objects including heat treatment to improve their mechanical properties and support structure removal which may delay the processing time [8, 34]. Other limitations are the staircase effect and surface roughness, which may appear due to the layering nature of the process; however, they can be minimized by reducing the layer thickness of the object [9, 115, 116]. Although laser melting was successful for process dental implants roots, the accuracy of laser melting is not accurate enough to process dental implants connection parts; thus, they need to be machined by the of milling techniques.

4.3.2.9 Potential and Future Direction of the Laser Melting Technology

Laser melting technology is a very promising technology, and its market is growing rapidly as the manufacturing process improves and the costs keep falling. Manufacturers are expanding rapidly to fulfill the growing demand for this technology for industrial, medical, and dental applications. For instance, in 2016, General Electric (GE) bought two 3D printing groups, Sweden's Arcam and Germany's SLM Solutions, for a total of $1.4 billion, and in 2013, 3D-Systems acquired the French company Phenix [117, 118]. As a result of this competition, the mechanical properties, precision, and production speed of laser melting technology are expected to be further improved in the future. Moreover, the price of laser melting machine is expected to decrease drastically by the market competition, especially as the patents of the technology expire in the nearby future. Besides its proven potential for PRDPs, oral and maxillofacial prostheses are also produced by this technology, and the future developments on this technology could render it more competitive over current CAD/CAM subtractive technologies for manufacturing dental crowns, bridges, and implant prosthodontics.

Beyond its impact on dentistry, this technique will also have an impact on the society in next few years. First, the reduced cost of dental prostheses processed by laser melting technology could render the treatment less expensive and more accessible to a larger portion of the population [60]. Large and small dental laboratories both can benefit economically from using this technology and through new forms of business models; however, large-scale dental laboratories are at an advantage over smaller laboratories because the initial cost of the equipment can only be amortized across the large-scale production [60]. Instead, small dental laboratories and dental offices can benefit economically if they design the dental prosthesis in CAD file, as it only requires a scanner and CAD system, and outsource the fabrication of the prosthesis framework to local processing centers.

4.4 Conclusion

CAD/CAM (computer-aided design/computer-aided manufacture) technology is rapidly growing and changing dentistry at an unprecedented pace. Dental CAD/CAM is now used for an ever-growing number of dental applications such as the fabrication custom trays, surgical guides, temporary or definite fixed or removable dental prostheses, and orthodontic and maxillofacial appliances.

CAD/CAM technologies available in dentistry can be classified as either “subtractive” or “additive” manufacturing methods. With subtractive methods such as machining and milling and laser ablation technologies, dental parts are manufactured by subtracting the undesired material from a block with the use of burs, disks, or lasers. The CAD/CAM systems for subtractive manufacturing methods can be classified into chairside systems and laboratory systems. Additive methods, such as 3D printing or rapid prototyping, manufacture dental objects in a layer-by-layer pattern by building successive layers of material until the final object is formed. There are many 3D printing technologies available for dental applications such as stereolithography (SLA), digital light projection (DLP), polyjet or multijet, inkjet printing, fused deposition modeling (FDM), selective electron beam melting (SEBM), and laser melting.

Additive manufacturing is a more recent technology and more versatile than subtractive manufacturing, but the subtractive methods are more precise and accurate. Thus, each of these technologies is used for different dental applications according to the accuracy, speed, costs, and materials required.

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Part II

Clinical Procedures

3D-Printed Removable Partial Dentures

5

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Abstract

Recently, digital techniques have revolutionized the production of partial removable dental prostheses (PRDPs). This chapter reviews current systems for PRDP production, how they are done in clinical practice, its advantages and limitations, and current literature regarding their clinical performance. Currently, several digital techniques are available in the market for PRDP production including subtractive and additive techniques. Subtractive milling technique is mainly effective for nonmetal PRDP. Digital techniques expand the range of materials that can be utilized for PRDP production, including new polymers (PEEK), and facilitate previously difficult procedure such as casting titanium PRDP, which can be produced digitally more easily. This review shows that available evidence suggests that these techniques have promising clinical results. Laser-sintering resulted in higher patient satisfaction compared to conventional technique.

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However, long-term clinical trials are recommended to explore the long-term effects of these techniques. Moreover, this review showed the lack of evidence on the clinical performance of nonmetal partial removable dental prostheses.

Although digital partial removable dental prostheses (PRDPs) have entered clinical practice only recently, they have revolutionized PRDPs production and disrupted the market. The aim of this chapter is to describe the advances in digital PRDPs, including the clinical procedures, how are they done, and their clinical performance.

5.1 Introduction

Despite the success of preventive dentistry in reducing the prevalence of edentulism, partial edentulism remains a public health issue worldwide especially among elderly people. Prevalence of partial edentulism ranges from 30% to 60% among Europeans over the age of 65, and given the increased life expectancy and the aging trend in developed countries, the prevalence of partial edentulism is expected to keep growing [1]. In Germany as well as Japan, it has been estimated that the number of partially dentate people will increase, and in the UK, 96% of adults are expected to be at least partially dentate by 2028 [1, 2].

PRDPs are noninvasive simple treatments that improve the quality of life of partially edentulous patients [3, 4]. Despite the great success of dental implant treatments lately, several factors contribute to the continuous need for PRDPs such as lower socioeconomic status, access to care, and compromised general health. It has been reported that 13–29% of European adults wear PRDPs [5], and in the USA it is projected that PRDP treatments will consume a minimum of 270 million hours of dentists' work per year by 2020 [6, 7].

5.2 History

Since their conception in the early 1930s, PRDPs have been traditionally made of cast alloys using the traditional lost-wax technique. This involves lengthy steps including manual construction of a wax pattern for the designed prostheses frameworks, investing the pattern to form a model, melting the wax to prepare the space, and then pouring the molten metal to the prepared space in the mold. This lengthy process consumes large amount of materials and is highly prone to human errors [8].

The evolution of computer-aided design and digital milling manufacturing marked a huge milestone in the fabrication of dental restorations. This technology reduces the time, cost, and human errors associated with the rehabilitation of fixed dental prostheses. However, milling manufacturing of partial removable dental prostheses is difficult to accomplish due to the spatial restriction of the complex structure of PRDP frameworks with its clasps, rests, and connectors and proven uneconomical due to the high hardness of PRDP alloys which quickly wears the milling tools. Therefore, lost-wax casting remains the standard technique for metal-based partial removable dental prostheses [9, 10], although milling wax or resin PRDP patterns are available in the market but did not gain widespread popularity.

Stereolithography have been recently used to print the resin or wax sacrificial patterns of the PRDP frameworks [11]. This processing produces frameworks with acceptable fit and reduces some of the costs and human errors associated with the manual wax-ups [12]. However, the printed resin pattern still has to be cast conventionally to get the final PRDP framework [11, 13]. In 2006, laser-sintering was introduced to produce PRDP frameworks digitally in order to eliminate the investing and casting steps [14]. Due to the lack of specialized software, selective laser-sintering originally required the use of physical sculptor to virtually build the framework [15]. The physical sculptor is a haptic device that allows the users to touch and manipulate objects in the 3D virtual environment. It helps technicians to utilize hand movements very close to the hand movements they use for conventional framework wax-up, but it increases the time, cost, and complexity of the procedures [15].

To overcome these limitations, different software solutions were tested to virtually design PRDPs without the need for a sculptor. However, these programs were not specifically developed for PRDP design and required lengthy procedures to determine the path of insertion, eliminate undesirable undercuts, and draw the framework components [16]. Specialized software for designing PRDP framework was not introduced until 2010 [17]. Surface roughness and long post-processing steps are limitations of laser-sintering technology. Recently, simultaneous technology of repeated laser-sintering with high-speed high-precision milling was introduced to fabricate PRDP with higher precision and smoother surfaces [18]. This technology integrates both laser deposition and high-speed milling on the same platform. The fabrication starts with ten layers of laser deposition followed by high-speed milling to smoothen the surface and provide extra detail precision [19]. This technique proves effective for titanium PRDP, which overcomes the casting challenges of titanium [20]. Moreover, laser-sintering followed by metal annealing was also used for titanium PRDP fabrication which increases the ductility and improves resistance to crack [21].

Digital technology has also ameliorated the fabrication of metal-free PRDPs. Metal-free acrylic PRDPs were introduced early as an interim alternative to metal-based PRDP. Around 1950, nylon-based ployamide PRDP (Valplast) was introduced in the USA and gained popularity since then. Later, with the development of denture base fabrication techniques, other thermoplastic resins (polyamide, polyester, polycarbonate, and polypropylene) were utilized to produce nonmetal PRDPs [22]. These prostheses have several advantages over metal-based PRDPs, including improved esthetics, suitability for patients allergic to metal, lightness, flexibility, and cheaper price compared to metal-based PRDPs [22]. Conventional fabrication techniques include compression molding, injection molding, and fluid resin technique. With the introduction of CAD/CAM milling in dentistry, most of these prostheses are easily produced by milling, and more recently 3D printing has been introduced to fabricate nylon-based polyamide flexible prostheses [23, 24]. Upon the success of digital production for PRDP, new materials are now introduced to the market, such as polyether ether ketone (PEEK), which is currently produced by CAD/CAM direct milling [25].

5.2.1 Digital PRDP in Today's Market

Nowadays, digital production of PRDPs is widely spread. The current procedures involve first digitization of the case with either intraoral or extraoral laboratory 3D scanners (acquisition stage) and subsequent design of the PRDP frameworks using specialized software with or without the aid of a physical sculptor (manipulation stage) [26]. Most of the available designing systems do not require physical sculptors, although the Geomatic® Touch™ X (3D systems, South Carolina, USA) still requires it. The available digital systems for producing the digital PRDPs are either direct metal production systems including laser-sintering systems or indirect production including the stereolithography systems; the special variation of it is the digital light processing (DLP) and milling (Table 5.1). For metal-free PRDP digital production, direct milling of thermoplastic resin is the most common method; however, a new 3D filament printing system is available for Valplast (Afrona, New York, USA). Table 5.2 shows current materials used for fabrication of digital nonmetal PRDPs.

Table 5.1 Currently available systems used to fabricate digital metal partial removable dental prostheses

Step	Equipment	Manufacturer
Scanning	Intraoral 3D scanners	
	Cadent iTero	Align Technology, San Jose, CA, USA
	CEREC Omnicam	Dentsply Sirona, York, PA, USA
	TRIOS	3Shape, Copenhagen, Denmark
	Extraoral 3D scanners	
	DS20 optical scanner	Reinshaw, UK
	7Series	Dental Wings, Montreal, Canada
	inEos X5	Dentsply Sirona, York, PA, USA
	E3	3Shape, Copenhagen, Denmark
Designing	Without physical sculptor:	
	3Shape CAD points	3Shape, Copenhagen, Denmark
	Partial Framework CAD	exocad GmbH, Darmstadt, Germany
	DWOS Partial Frameworks	Dental Wings, Montreal, QC, Canada
	SilaPart CAD	SilaDent, Golsar, Germany
	Digistell CAD	C4W-Digilea, Montpellier, France,
	ModelCast	imes-icore GmbH, Eiterfeld, Germany
	InLab CAD	Dentsply Sirona, York, PA, USA
	With physical sculptor:	
	Geomatic® Touch™ X	3D SYSTEMS, SC, USA

Table 5.1 (continued)

Step	Equipment	Manufacturer
Production	*Direct metal production*	
	1. Laser-sintering	
	AM 250	Reinshaw, UK
	PM100 Dental & PM100T	Phenix, Riom, France
	Farsoon FS121M	LSS GmbH, Holzwickede, Germany
	M1 cusing laser	Concept Laser GmbH, Lichtenfels, Germany
	EOSINT M270	EOS, Munich, Germany
	2. Repeated laser-sintering and milling	
	LUMEX advance-25	Matsuura, Tokyo, Japan
	Indirect production	
	1. 3D printing	
	Varseo S	Imes-icore GmbH, Eiterfeld, Germany
	Asiga PICO$_2$ HD	BEGO, Bremen, Germany
	ProJet™ DP 3000	Whipmix, Louisville, KY, USA
	2. Milling	
	Organical Desktop S8	R+K Organical CAD/CAM GmbH, Berlin, Germany

Table 5.2 Currently available materials used for fabrication of digital nonmetal PRDP

Fabrication technique	Materials	Brand name	Manufacturers
Direct milling	PEEK (polyether ether ketone)	PEEK-Optima LT1	Juvora Ltd., Lancashire, UK
		CORTiTEC medical PEEK	imes-icore GmbH, Eiterfeld, Germany
	Ultaire AKP (aryl ketone polymer)	Dentivera	Solvay Dental 360, Alpharetta, GA, USA
	Acetyl copolymer	Zirlux acetal	Zirlux, Milville, NY, USA
	Polyethylene terephthalate	Estheshot Bright disk	Nissin Ltd., Japan
	Polymethylmethacrylate (PMMA)	PMMA	Nissin Ltd., Japan
3D printing	Polyamide nylon	Valplast denture base filaments	Afrona, Brooklyn, NY, USA

5.3 Step-by-Step Procedures of Digital PRDP Fabrication

Following a thorough examination and a careful treatment planning, the clinical steps of PRDP can be started. The digital workflow consists of three steps: acquisition, manipulation, and fabrication [26].

Acquisition

1. Primary impressions are made using alginate impression, which are then poured to have the diagnostic cast. On the diagnostic cast, the case is studied carefully, and the PRDP design is planned. Necessary abutment teeth preparations are planned at this stage.

2. Abutment teeth are prepared as planned. Here, one of two options is possible; either the patient arches are scanned intraorally using an intraoral scanner, which eliminates the need for physical impression, or the final impressions are made in rubber base materials, and then either scanned directly or poured into stone master casts that are subsequently scanned using an extraoral digital scanner. The scanner produces a stereolithographic file (STL) of the master cast that is imported in the designing software (Fig. 5.1). Intraoral scanning involves multiple scans for both arches, taking around 3–17 min depending on the case. These scans are stitched by the software to provide the full-mouth image [27].

Manipulation

3. Using a specialized software, the PRDPs are designed digitally through a series of digital steps that mirror the traditional laboratory procedures. First, the path of insertion is determined automatically using a digital survey tool; the software automatically rotates the cast three dimensionally and calculates the parallelism and the depth of undercuts in all dimensions to reach to the best tilt for the path of insertion (Fig. 5.2), and survey line is then automatically made. This step saves a lot of time compared to the conventional manual step. This is followed

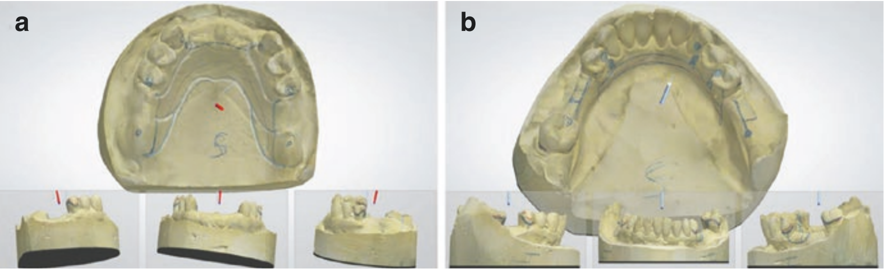

Fig. 5.1 Virtual casts (STL files) of a PRDP case scanned by extraoral 3D scanner; (**a**) maxillary arch and (**b**) mandibular arch

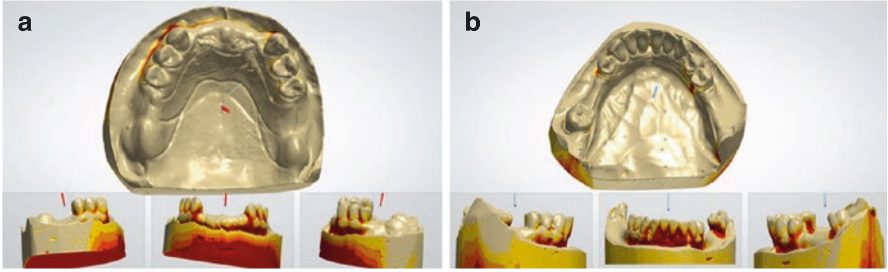

Fig. 5.2 Virtual determination of the path of insertion of a PRDP using 3Shape CAD points software; (**a**) maxillary arch and (**b**) mandibular arch

by blockout of undesirable undercuts (Fig. 5.3). After that, the retentive areas for the retentive clasp tips are determined.

4. Relief areas are marked by laying thin layers of virtual wax on relief areas such as rugae. Next, the meshwork patterns are added (Fig. 5.4), and the major connectors and rests are drawn as built (Fig. 5.5). The clasp arms and

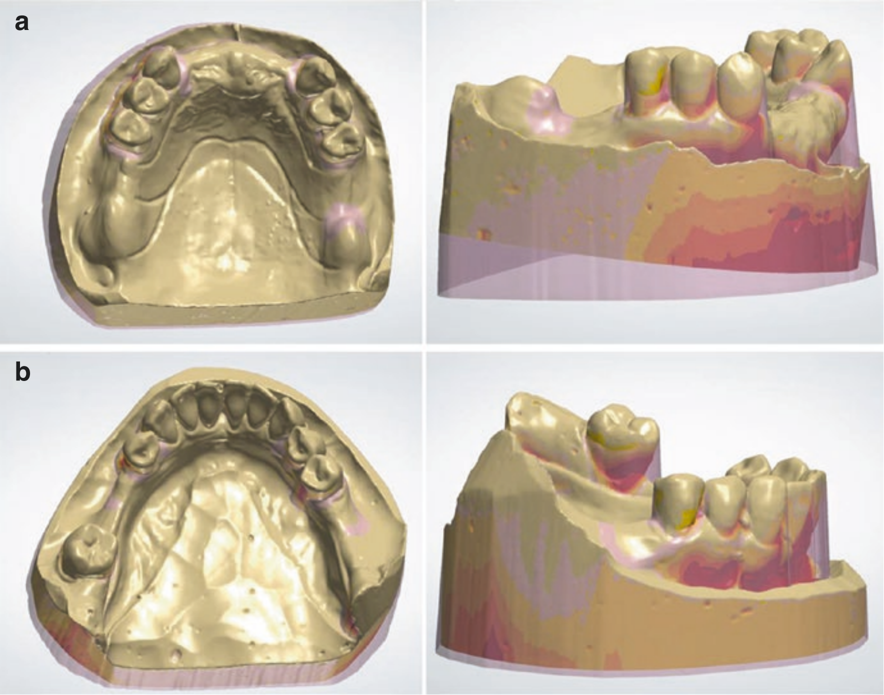

Fig. 5.3 Virtual blockout of undesirable undercuts of a PRDP case using 3Shape CAD points software; (**a**) maxillary arch and (**b**) mandibular arch

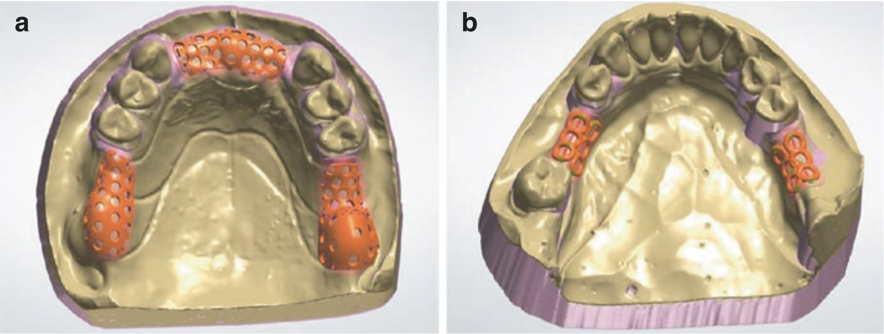

Fig. 5.4 Virtual building of the meshwork in the edentulous area of a PRDP case using 3Shape CAD points software; (**a**) maxillary arch and (**b**) mandibular arch

the clasp systems (width and thickness) are drawn three dimensionally (Fig. 5.6), and the thickness of the framework is adjusted and smoothed (Fig. 5.7). Finally, the finish lines are drawn using the curve tool which utilizes default or customized profiles (Fig. 5.8), and the designed framework is finished (Fig. 5.9).

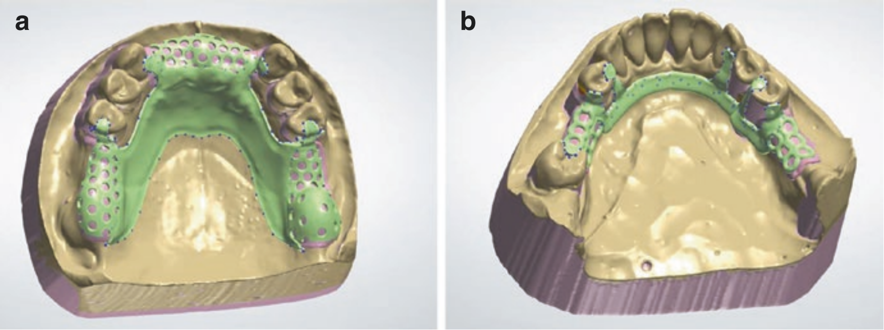

Fig. 5.5 Virtual building of the major connectors and rests for a PRDP case using 3Shape CAD points software; (**a**) maxillary arch and (**b**) mandibular arch

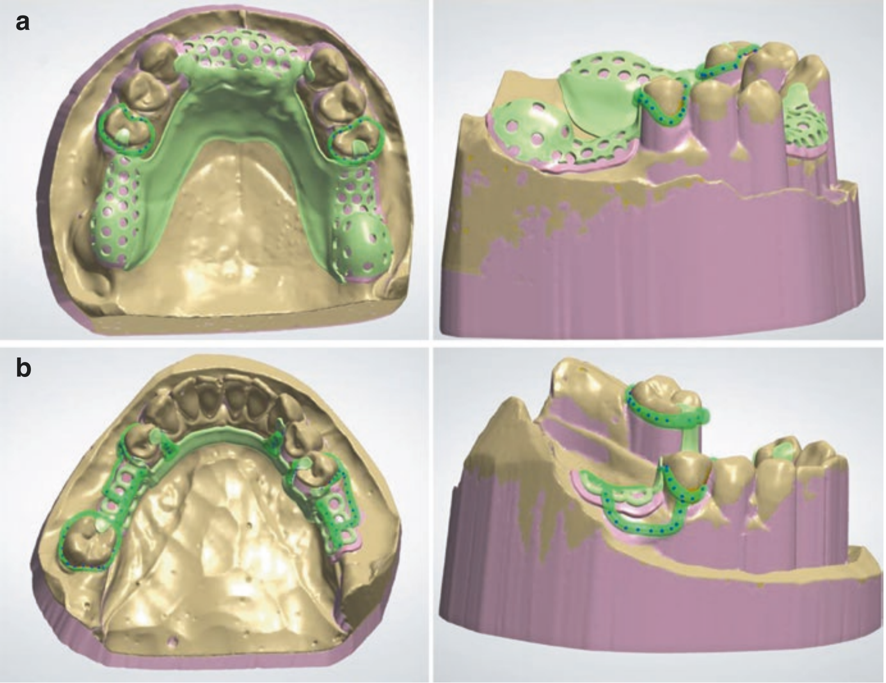

Fig. 5.6 Virtual building of the clasp arms of a PRDP case using 3Shape CAD points software; (**a**) maxillary arch and (**b**) mandibular arch

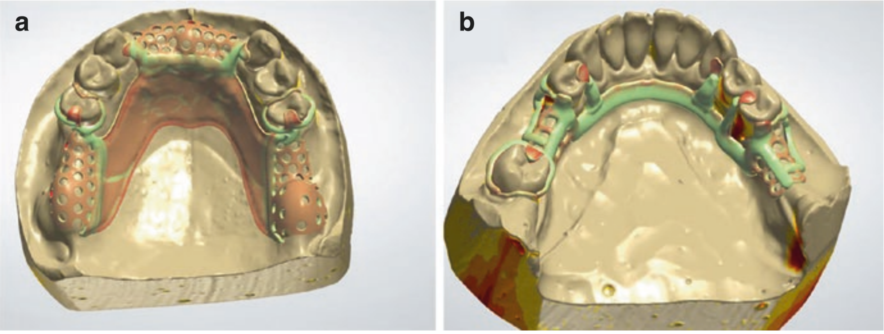

Fig. 5.7 Virtual adjusting of the thickness of the framework of a PRDP using 3Shape CAD points software; (**a**) maxillary arch and (**b**) mandibular arch

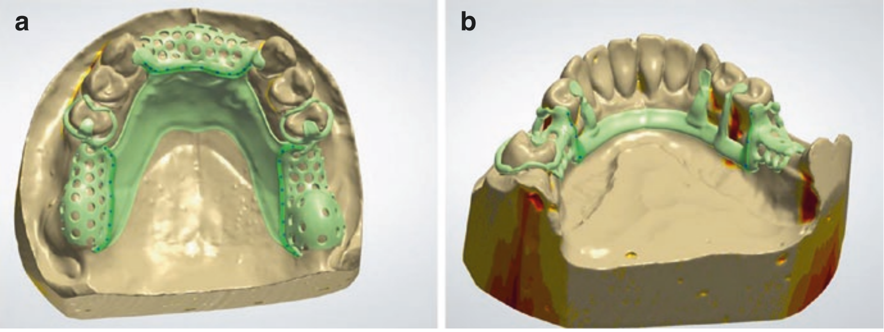

Fig. 5.8 Virtual drawing of the finish line of a PRDP case using 3Shape CAD points software; (**a**) maxillary arch and (**b**) mandibular arch

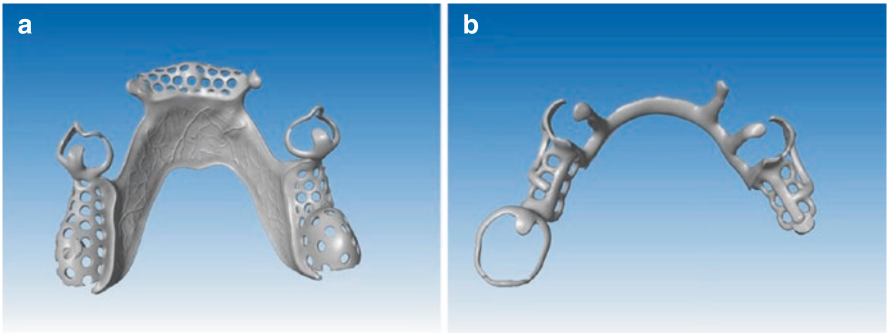

Fig. 5.9 Finalized virtual design of a PRDP case using 3Shape CAD points software; (**a**) maxillary arch and (**b**) mandibular arch

5. Sprue is designed for indirect fabrication systems (3D printing and milling) to be used in the casting process. For additive technology systems (laser-sintering and 3D printing), supports are added to the structure before submitting the finished design (Fig. 5.10). Appropriate supports of adequate strength are required to stabilize the PRDP framework layers upon their production as they are laid down in very thin layers. Also, during manufacturing it prevents movement and dissipates heat away from the finished part of framework during manufacturing [14]. The designing process takes approximately 30 min per framework (Fig. 5.11) [17].

Fabrication

6. Once the design file is complete, it is sent to the production machine. At this point, the frameworks are produced with either direct or indirect production systems.

   Direct Metal Production

   For direct metal production systems including laser-sintering and laser melting, metal powder is laser-sintered to produce PRDP frameworks. One laser-sintering machine takes up to 12 h to fabricate 12 PRDPs in one cycle. After that, the printed PRDP is retrieved (Fig. 5.12) and subjected to post-processing. Most of

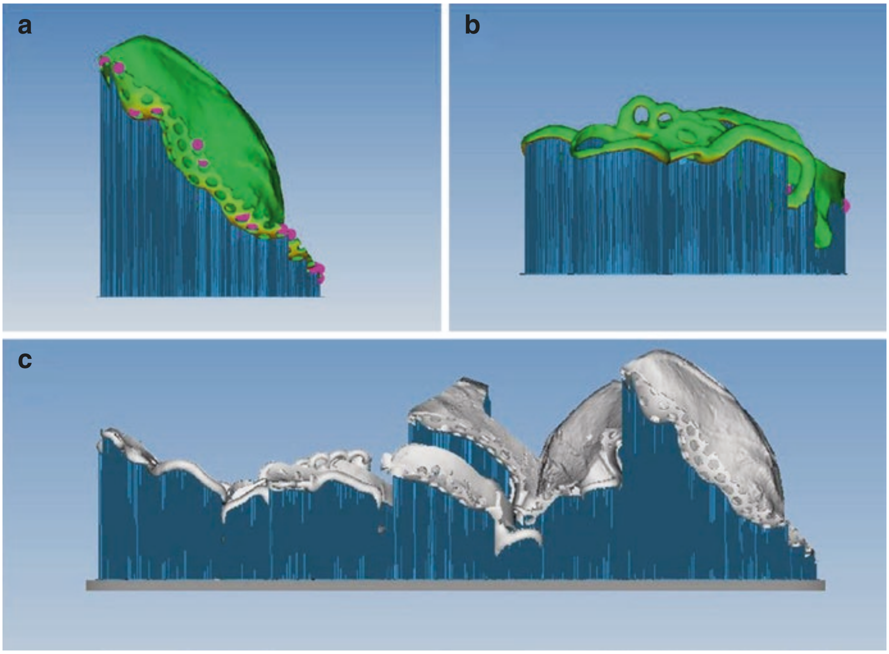

Fig. 5.10 Illustration of the supports required for successful laser-sintering of a partial removable dental prosthesis: (**a**) maxillary arch, (**b**) mandibular arch, and (**c**) PRDP frameworks in the building platform

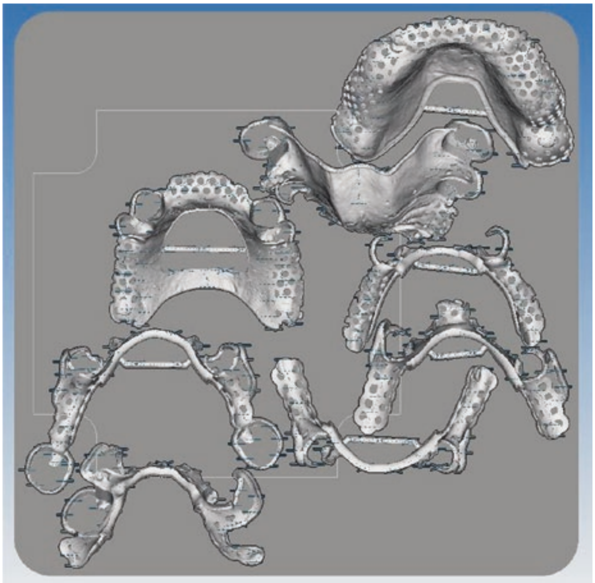

Fig. 5.11 Illustration showing the arrangement of PRDP frameworks in the building platform

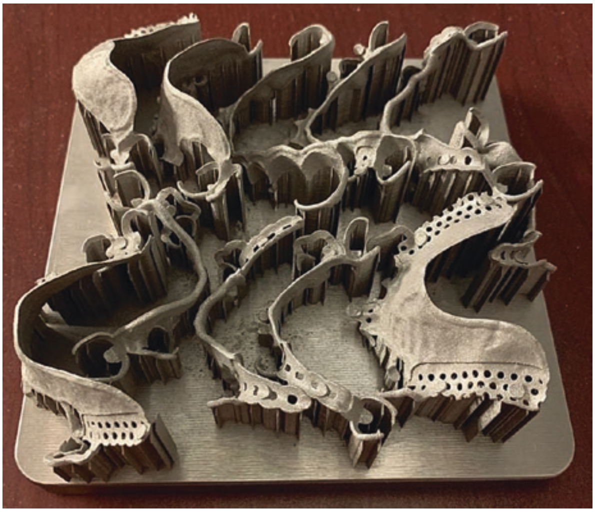

Fig. 5.12 A photograph showing the PRDP frameworks in the building platform processed by laser-sintering technology

the uncured metal powder is reused for future frameworks which reduces waste and improves efficiency. PRDP is heat-treated following manufacturer instructions and is then separated from the supporting base. Fit of the framework is checked on the cast and adjusted as necessary (Fig. 5.13).

Indirect Metal Production

For indirect metal production systems including stereolithography, direct light processing, and milling, a resin or wax framework pattern is printed or milled (Fig. 5.14). In the case of 3D printing, several post-curing steps are required

Fig. 5.13 Laser-sintered partial removable dental prosthesis framework fitted on the cast

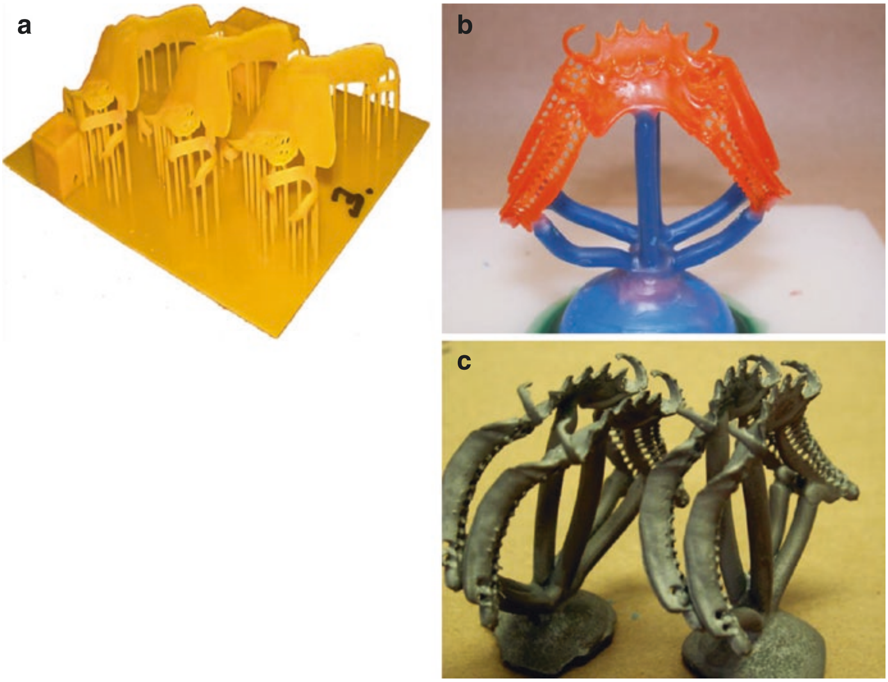

Fig. 5.14 3D printing for fabrication of partial removable dental prosthesis: (**a**) 3D-printed resin patterns of partial removable dental prostheses, (**b**) resin pattern of partial removable dental prosthesis framework with wax sprue ready for casting, and (**c**) metal frameworks of partial removable dental prosthesis cast from 3D-printed resin patterns

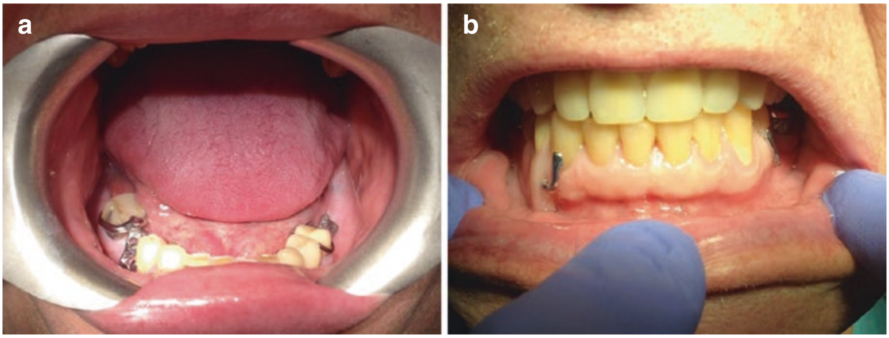

Fig. 5.15 Laser-sintered partial removable dental prosthesis in the patient mouth of a patient: (a) occlusal view, (b) frontal view

including removing any wet resin remnants by immersing the pattern in a solvent, followed by final curing in UV oven to fully harden and get its structural integrity [28]. Resin pattern can also be tried in the patient's mouth if needed. The pattern is then cast conventionally using the lost-wax technique.

7. The framework is finished and polished in several steps. First, the framework is finished by finishing burs; then the frameworks are finished under rotating barrels of ceramics, followed by barrels of corns. Finally, frameworks are electropolished in electropolishing machines.
8. PRDP framework is checked for fit and occlusion in the patient mouth (Fig. 5.15). Maxillomandibular relationship is recorded at this stage, and teeth shade and form are selected in a similar manner used for conventional PRDP.
9. The framework is returned to the lab for teeth setting, final wax-up, and acrylization.
10. PRDP is tried in the patient mouth and adjusted for fit, retention, and occlusion. Then framework is polished and delivered to the patients.

5.4 Clinical Evidence on Digital PRDP

Digital PRDPs are new products and therefore have not been studied thoroughly yet. Most of the studies in this field have been focused on testing the feasibility of the technique, and they have shown that digital direct or indirect metal fabrication can produce accurately fitting PRDPs [12, 16, 29–31].

Extraoral scanning of the master cast has been reported effective in several studies and resulted in well-fitting RPDP frameworks [12, 32]. On the other hand, intraoral scanning is effective for capturing in Kennedy class III cases [27, 33, 34], but not Kennedy class I and II as the scanning does not capture the physiologic extensions of the movable mucosa [27].

Regarding clinical performance, only few studies have been published. A clinical trial has shown the superiority of digitally produced PRDPs by laser-sintering over the traditional PRDPs in terms of patient satisfaction [35]. It also showed that most of the patients had preferred the laser-sintered PRDPs over the conventional prostheses after using both [35]. Another study showed that although digital PRDPs (produced by laser-sintering) showed statistically significantly larger gap between occlusal rests and corresponding rest seats compared to the traditional casting PRDP, it is considered clinically acceptable [36]. Similarly, digital PRDPs produced by 3D printing followed by casting showed variable fitting discrepancy but were considered clinically acceptable [37].

Laboratory studies showed that laser-sintered cobalt-chromium alloys are about eight times more accurate than casting and have better mechanical properties, higher yield strength and fatigue resistance compared to cast Co-Cr alloys [38]. Moreover, Aker clasps produced by simultaneous repeated laser-sintering and high-speed milling showed higher fitting accuracy and retention forces compared to conventional cast clasps [39]. However, when the fit of laser-sintered PRDP frameworks was compared with lost-wax technique, milled and 3D-printed frameworks, laser-sintered frameworks demonstrated significantly larger gaps than all other techniques. Technical parameters might need to be adjusted to get better fitting results [40]. Several factors can affect the final product in laser-sintering, including heat treatment, amount of relief designed, and position and angulation of the support structure [18]. Moreover, with this new technology, time is required to get to the top of the learning curve and optimize the product [41].

Currently, there is insufficient evidence regarding the metal-free PRDP although they are widely used in the market [22]. Laboratory studies showed that flexible PRDPs have lower color stability and higher risk to fracture compared to polymethyl methacrylate (PMMA) acrylic PRDPs [42]. The newly introduced PEEK high-performance polymer showed good fitting accuracy and adequate clasp retention in vitro; however, it was inferior to metal clasp retention [40, 43]. It could be an alternative to metal PRDP in cases of patients with taste sensitivity or metal allergy; however, more clinical studies are needed before this treatment can be recommended [25].

5.5 Advantages and Limitations of Digital PRDPs

Digital production of PRDP has several potential advantages. Indirect fabrication techniques benefit from the digital designing step which saves time compared with manual surveying and framework wax-up. Also, direct metal fabrication systems increase productivity and shorten the work flow while reducing manufacturing costs as several steps are omitted (cast duplication, manual wax-up, investing and casting) and reduce maintenance cost for expensive investing and casting machines.

Digital production can be environmentally friendly considering the potential reduction in environmental impact due to reduced waste of alloy, wax, and investment materials (this applies to direct metal production systems) and the recycling potential of uncured metal powder left after laser-sintering.

Moreover, virtual designs can be saved for later use which enable dentists to provide patients with extra prosthesis or replacement prosthesis with the same or modified design without the need to restart the entire process. This also permits sharing designs between technicians and clinicians via internet/e-mail, which improves communication.

Digital production opens the door for endless opportunities to enhance both the work flow and the quality of provided treatment; PRDP with optimized designs can be provided for individual patient to provide required mechanical properties needed in the different oral environment of each case [44, 45]; moreover digital PRDP can be performed for cases requiring altered cast technique and with added simplicity and shorter step [46]. Digital production may open the door for different materials to be used for PRDPs like polymer-based materials, which can overcome some of the limitations of current metal-based PRDP [47].

Utilizing intraoral scanning can provide greater success with gagger patients, patients with special needs, or anxious patients. It involves multiple section scanning so it is easier to control moisture section by section than to control moisture for the whole arch at one time. It uses multiple scans that are stitched together automatically at real time, so any defect or deficiency in the impression can be identified and corrected at the same visit [34].

5.5.1 Limitations

Digital fabrication of partial removable dental prostheses has some limitations. First, this technology only allows fabrication of the metal framework, but it does not allow for digitalized tooth setup; currently tooth setup needs to be done manually. Another limitation is the high initial cost of the machine. This technology requires time and expertise to learn the technique. Digital PRDPs currently require special supports to hold the prostheses during the 3D-printing process. This adds extra steps for planning the supports and removing them after fabrication. Another limitation is the staircase effect, which may appear due to the layering nature of the 3D-printing process. It can be significantly reduced by reducing the layer thickness which could increase the production time [26]. Moreover, currently this technique cannot be used for all patients, since some special designs cannot be produced easily because of the limitations of the available software and manufacturing procedures [35].

5.6 Potentials and Future Directions

Currently, digital technologies were used to produce PRDP frameworks; then the denture base is produced conventionally by manual waxing followed by acrylization [35, 37]. The future direction would be toward digitizing this step too. PRDP frameworks could be scanned after being clinically fitted and adjusted in the patient mouth; teeth and denture base can be designed digitally and then produced digitally. This will open the door for a wider range of materials to be utilized but might also create newer challenges regarding the bonding between the framework and denture base or denture base and denture teeth produced from different materials.

Moreover, current digital technologies can produce structures in the nanoscale, and therefore frameworks with thinner sections, and different dimensions than conventionally produced frameworks [26]. This can challenge current designing principles which were mainly set to result in successful casting and acrylization of PRDP. Meshwork design criteria, tissue stops, thickness of major connectors, minor connectors, length of clasp arms, and depth of undercut are all designed to produce successful PRDP. However, currently, these requirements may not be needed to produce accurately fitting digital PRDP. Instead, these different technologies would come up with different requirements that need to be discovered and respected.

Additionally, customized PRDP can be produced with enhanced mechanical properties tailored for individual cases utilizing finite element-based computational design optimization algorithm integrated automatically with the digital designing and the additive manufacturing, which is called bi-directional evolutionary structural optimization (BDES) techniques. BDES refers to adjustment of a structure by progressively adding materials in areas need it most (like underloaded areas in a denture base) and concurrently removing materials from other areas in excess (like pressure areas). A study showed the success of this technique in providing a denture base with optimal pressure on the supporting tissue as evaluated by finite element analysis [45]. This technique shows the potential of digital technology to overcome several clinical problems including multiple post-insertion adjustment visits and long-term residual ridge resorption. Utilizing computational shape optimization automatically with the digital workflow might change the future of PRDP.

5.7 Conclusions

Digital production of partial removable dental prostheses has revolutionized the fabrication process of both metal and nonmetal partial dental prostheses, and it is gaining increasing popularity in clinical practice. Metal partial removable dental prostheses are fabricated digitally using either direct or indirect production techniques. Direct production replaces the casting step and therefore significantly reduces cost and time, while indirect production involves producing resin patterns digitally, which subsequently are cast using traditional methods.

Digital production has several advantages: it saves time and materials while increasing productivity and reducing human errors, and current scientific evidence regarding the clinical performance of these prostheses, although limited, is very promising. Nevertheless, the digital technologies currently available fall short of finishing the whole partial removable dental prostheses, as tooth setup and acrylization are still done manually using traditional methods.

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6 Digital Removable Complete Denture (DRCD)

Hiroshi Hirayama

Abstract

Digital dentistry has evolved very rapidly in recent years. Areas of digital fixed and implant dentistry have shown a wide range of improvement from examinations to production of prostheses. Digital applications in removable prosthodontics have been initiated as two-visit techniques during the late 2000s by two commercially available companies. However, further improvements and increased number of applications in digital removable complete denture (DRCD) have been done lately since several new companies have announced new developments in this field. In this chapter, you will find background information of the evolution of DRCD with a literature review, comparison of conventional and digital workflows of denture fabrication, current concepts and different fabrication methods of DRCD, and advantages and limitations of DRCD. Wax rim impression and replication DRCD techniques are explained and illustrated in a step-by-step fashion.

6.1 Introduction

The history of dentistry, specifically prosthetic dentistry, started by replacing lost teeth with many different materials since 500 BC. Many materials such as human or animal teeth, ivory, bone, seashell, wood, etc. were carved to replace missing teeth until the nineteenth century. Removable complete dentures (RCD) were fabricated by carving wood, ivory, and other materials. The history of RCD impression started

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in the mid-eighteenth century with the use of beeswax. Charles de Loude first references impression trays in the mid-nineteenth century. Since then, many dental materials such as beeswax, gutta-percha, plaster of Paris, modeling plastic, zinc oxide eugenol paste, and elastomer impression materials have been used for making impression of the edentulous mouth which improved the quality of the RCD [1]. Many RCD base materials have been used until polymethyl methacrylate (PMMA) resin came on the market in 1936 [2]. Combining the use of elastomer impression materials and PMMA acrylic resin has significantly improved the quality of the RCD for the patient; meanwhile many of the RCD fundamentals were studied in areas of anatomy, physiology, occlusion, etc. [1]. The elastomer impression materials and PMMA resin are the materials of choice for fabricating the RCD for many decades until today. Recently, digital technology has emerged and been applied to fabricate RCDs. Yet still the elastomer final impression and PMMA resin are the impression technique of choice and the material of choice for fabricating the DRCD due to difficulty and accuracy of scanning an edentulous mouth; no other new materials have been developed for the RCD fabrication.

Nowadays, with the advent of digital technologies in dentistry, the RCD fabrication processes are gradually evolving toward digitalization. In this chapter, you will find background information on the evolution of DRCD with a literature review, comparison of conventional and digital workflows of denture fabrication, current concepts and different fabrication methods of DRCD, and advantages and limitations of DRCD. Wax rim impression and replication DRCD techniques are explained and illustrated in a step-by-step fashion.

6.1.1 History and Concept of Digital Denture: Literature Review

The first digitally fabricated RCD was reported by Maeda et al. by using 3D printing technology in 1994 [3] followed by Kawahata et al. using wax block with computerized numerical control (CNC, milling) technology [4]. Busch and Kordass described digital tooth arrangement based on anatomic measurements and averages [5]. Sun and Wang described CAD software that processes automatic teeth setup, semiautomatic esthetic designing, individualized gingival contouring, and base plate forming [6]. Kanazawa et al. and Inokoshi et al. explored use of the cone beam CT scan combined with a rapid prototyping method or a milling method, for fabrication of DRCD [7, 8]. Goodacre et al. described the use of recorded intaglio and cameo surfaces of RCD in relation with tooth position for designing DRCD and fabricated try-in and final DRCD [9].

Commercially, AvaDent™ meaning Ava (rebirth) and Dent (dentition) (Global Dental Science LLC., Scottsdale, AZ) and Dentca™, meaning Denture from California (Dentca Inc. Los Angeles, CA) now a part of Mitsui Chemicals group, came on the market in the early 2010s with two-visit DRCD fabrication concepts. Both companies promoted that their methods can cut down on clinical time, number of visits, and total cost, specifically when we consider two-visit DRCD techniques compared to the minimum of five visits when a conventional RCD fabrication technique is used [10]. Infante et al. reported a step-by-step use of the AvaDent system [11]. Kattadiyil et al. explained and compared two different systems [12].

AvaDent's concept uses a proprietary thermoplastic tray system for making final impressions. The first step is selecting a proper tray size and fitting it in the patient's mouth, and then modifying it in hot water for a more precise fit. A small amount of fast-setting occlusal registration-type polyvinyl siloxane impression material (PVS) is placed on several areas to create tissue stops, and then border molding with a heavy body PVS is performed, followed by a secondary wash impression using a light body PVS. A proprietary occlusal relator (anatomic measuring device—AMD), consisting of maxillary and mandibular partial trays, is selected by measuring the final impressions. The selected proper size of AMD is used to create positioning ridge impressions of the maxillary and mandibular arches with an occlusal registration PVS. The AMD has a built-in height adjustable intraoral tracer for registering an intra-occlusal record (IOR) and, in addition, an adjustable lip support flange. The adjustable lip support flange transfers the appropriate occlusal plane by using an AvaDent ruler, proper lip support by adjusted lip support flange. A denture teeth mold is then selected by using self-adhesive teeth selection mold tabs that are adhered to the facial surface of the lip support flange. These obtained final impressions, the IOR and anterior teeth information, are sent to AvaDent for scanning, merging scanned image files by best-fit method, and selection and positioning of denture teeth. Those data files are processed in their proprietary denture designing software. Once AvaDent creates a denture design, a proposed design would be available for review and approval of the proposed denture design by the dentist or both the dental laboratory and the dentist through AvaDent Viewer™ or AvaDent Connect™. The AvaDent Viewer™ provides the dentist with a 3D view of teeth position and gingival contour for final complete denture proposal; however, the user cannot modify any proposed factors. On the contrary, AvaDent Connect™ can function as the viewer and, further, can make any modifications on proposed tooth positions and gingival contour but cannot modify the denture border proposal. After approval of the proposed denture design by the dentist, AvaDent sends the digital denture design to production for milling denture bases with denture teeth sockets for selected denture teeth. Denture teeth are bonded into the sockets, and then final dentures are delivered to the dentist. The treating dentist delivers the final denture at the patient's second visit [10, 11]. Optionally, a milled denture try-in after the dentist's approval of a proposed teeth setup and gingival wax-up can be scheduled. Currently, AvaDent offers two different types of monolithic milled dentures with monotone teeth, a denture base, or multilayer shade teeth with denture base, which possess superior physical properties compared to the bonded denture teeth technique [13, 14].

The Dentca™ concept is similar to AvaDent's concept, except they use a proprietary impression tray that has a detachable and re-connectable two-piece maxillary tray and three-piece mandibular tray, with a built-in intraoral tracer. The tray can register a final impression and an IOR at the same time. The Dentca™ system uses one set of impression trays, while the AvaDent system requires one set of trays and one AMD.

Again, the Dentca™ concept starts with the selection of a proper size Dentca™ proprietary tray. These trays are not thermoplastic like the AvaDent trays; therefore the dentist should make sure the tray fitting and extension are acceptable prior to border molding. Proper border molding is carried out with a heavy body PVS, and then the first wash impressions are made with PVS. After thorough removal of excess PVS from the outside of both trays, maxillary and mandibular posterior areas of the impression are sectioned with a sharp blade knife, and then the trays are separated in two sections since the tray has a locking mechanism to allow separation and reconnection. After detaching both maxillary and mandibular trays, an intraoral tracing attachment needs to be inserted into the mandibular impression tray, from which the posterior areas were detached, and the treating dentist would adjust a central bearing screw to the proper occlusal vertical dimension (OVD). This way, potential interferences on the posterior part of impressions can be avoided during intraoral occlusal tracing to determine a centric position in IOR. The Dentca™ system provides two measurement devices, a jaw gauge for recording OVD and a lip ruler for measuring pose lip position and dynamic smile lip position from incisive papilla [10]. After obtaining the required measurements and the IOR using the intraoral tracing device with PVS record, impression trays are sent to Dentca™ for processing. Like the AvaDent system, the denture design step is carried out using their own denture software. An optional try-in 3D printed trial denture is available before processing by the conventional RCD processing technique or finalizing 3D printed denture. Heraeus Kulzer Pala Digital Dentures system uses the Dentca™ system and processes with their proprietary injection process system and may come up with 3D-printed bases with Pala denture teeth.

Baba et al. described several different DRCD fabrication techniques, with overviews and clinical procedures [15]. Saporano et al. conducted a cross-sectional retrospective study of two-visit protocols of CAD/CAM-fabricated RCDs. They reported an average of 2.39 visits to deliver the DRCD and common complications were lack of retention, occlusal vertical dimension inaccuracy, and incorrect centric relation record [16]. Kattadiyil et al. compared treatment outcomes on conventional RCD and two-visit DRCD in a predoctoral clinic. Significant differences were found on evaluation by faculty as better on DRCD and patients' overall satisfaction with DRCD over conventional technique [17]. DRCD use in pre- and postdoctoral education was surveyed and reported that more incorporation to the curricula was found in postdoctoral education than predoctoral education in 2014 [18]. It is safe to say that DRCD is more widely incorporated in education currently, since more DRCD techniques have been introduced and are available recently.

A common assumption that CAD/CAM-base material releases less monomer than conventionally processed denture bases could not be verified according to Steinmassl et al. [19]. Al Helal et al. demonstrated superior retention on maxillary milled denture bases compared to conventionally processed denture bases in in vivo testing [20]. Goodacre et al. investigated the accuracy and reproducibility of denture teeth positions on several different fabrication techniques and found that the monolithic technique was most accurate and reproducible [21]. Bidra et al. mentioned challenges and limitations on assessing occlusal vertical dimension, occlusal registration, plane of occlusion, determination of amount of lip support, and maxillary incisal edge position in two-visit systems [22]. The authors further mentioned challenges and limitations of try-in procedures on those systems [22]. Bidra et al. conducted a prospective cohort pilot study for two-visit CAD/CAM monolithic DRCD and implant retained overlay dentures (IOCD). They found that the patients' evaluation of satisfaction with two-visit DRCD protocol was higher than the clinicians' evaluation and found very positive outcome with the patients' overall satisfaction and evaluation of two-visit monolithic DRCD and IOCD protocols [13]. Kattadiyil and Al Helal reported a positive trend in the outcomes with computer-engineered complete dentures in their systematic literature review [23]. Schwindling and Stober reported no major differences on two different fabrication methods between milled polymethyl methacrylate (PMMA) blank method and milled wax base from same date than processed by injection mold using Wieland Dental Digital Denture system [24]. Wimmer et al. tested accuracy of denture teeth position on milled wax base and conventionally fabricated wax bases stored in water and concluded manually placing denture teeth into wax sockets can create deviations from the planned teeth arrangement [25]. This digital planning and conventional processing technique is employed in the Amann Girrbach digital denture system, which has the advantage of easily changing planned denture teeth positions based on the patient's esthetic and functional needs but with the disadvantage of aforementioned potential inaccuracy of denture teeth positions since this system is produced by milled wax denture [15]. Schweiger et al. introduced a technique of virtual evaluation of DRCD that eliminates the try-in visit by combining the wax rim impression technique with 3D photographs [26]. Yilmaz et al. described a DRCD fabrication technique that relays on conventional custom tray impressions and wax rim base IOR; this technique is an easy introduction to dentists familiar with the conventional RCD [27]. Ohkubo et al. reported recording of the neutral zone (aka the denture space), by using a piezographic mandibular tray with three different consistencies of PVS impression materials, which provide denture teeth position for advanced DRCD cases [28].

Currently all available and upcoming DRCD systems are using either cast scanning or impression scanning using a laboratory scanner. There could be some problems and limitations with the use of intraoral scanners (IOS) for acquisition of totally edentulous oral cavities due to lack of references on soft tissue for stitching (positioning and overlapping) of scanned images, mobility of soft tissue on peripheral border areas, presence of saliva, and the translucent nature of soft tissue. Additional to aforementioned limitations, it is impossible to apply different impression philosophies such as pressure or selected pressure impression techniques.

The quality of IOS can be evaluated in terms of trueness (accuracy) and precision (repeatability) [29]. Patelt et al. conducted an in vitro study comparing five IOS systems on a typodont and found a great variety of trueness and precision values among the different IOS systems. The authors could not recommend the use of four of the tested IOS systems, and they were unclear about the efficacy of one IOS which provided the best trueness and precision for in vivo use [30]. However, IOS systems tested in this article are not updated IOS systems at this time; therefore an updated study would be necessary. Gan et al. compared the trueness and precision of IOS impressions of whole dentate maxillary arch, which includes scanning of the whole palatal area, with conventional stone cast scanned images as control group in their in vivo study. They reported lager deviations among IOS images compared to controls in the palatal soft tissue areas. Nevertheless, the trueness (130.54 ± 33.95) and precision (55.26 ± 11.21) were within the acceptable range for edentulous impression accuracy when we consider the compressibility of soft tissue [31]. However, the scanning accuracy of a totally edentulous mouth is still unknown due to the presence of teeth in this study.

Several techniques have been suggested as to how to scan an edentulous mouth by using some intraoral artificial references [32, 33]. Goodacre and Goodacre described a technique that used IOS for fabrication of DRCD on two patients [34]. To date, there are no in vivo controlled studies to prove the accuracy and trueness of IOS for direct digital impression on edentulous soft tissues.

Currently, in all the available systems, both the impression or cast scan and the IOR scan, which includes OVD information, are transferred into a CAD software that merges them by using best-fit method. Once the final impression and occlusal relationship are uploaded into the design software, the anatomical landmarks are plotted, and the denture border is determined. An initial proposal of denture teeth setup is created based on average values of tooth position in relation to anatomical landmarks and acquired information such as lip support, maxillary incisal teeth position, occlusal plane, etc. The software then proposes a DRCD image or 3D preview of the design to the dentist and/or dental laboratory. If the proposed digital teeth setup position, digital gingival contour, and digital gingival wax-up are satisfactory and approved by the dentist, a final DRCD or a try-in denture would be produced. The final denture production would be done using an additive (3D printing) or a subtractive (milling) manufacturing method.

The following compares advantages and disadvantages of using conventional and digital RCD fabrication techniques [10, 22].

Advantages of digital RCD fabrication:

- Fewer visits, less chair time (less total cost and higher production) [10].
- Milled denture bases are stronger than conventionally processed denture bases [10, 35].
- Less porosity [10, 22].
- Fewer chances of microorganism contamination [10, 22].
- Easier to achieve proper occlusion.
- Better fitting [10, 36].
- Potentially less follow-up adjustments [16].
- Ease of replicating duplicate dentures [10].

Disadvantages (limitations) of digital RCD fabrication:

- Difficult to assess proper OVD, MMR, and maxillary anterior teeth incisal edge position and proper lip support [10, 22].
- Must use dimensionally and temperature-resistant impression materials such as PVS [10].

- Limitations of try-in, potential esthetic and functional problems, and cost from a generally more expensive laboratory fee [22].
- Possible necessity of clinical remounting [10].
- Presence of initial learning curve [10].
- Scarcer data and experiences compared to conventional fabrication technique.

Careful case selection is an essential factor for successful two-visit DRCD fabrication. If the below list are fulfilled, DRCD can be made successfully by the two-visit approach. Additionally, when the dentist gains enough DRCD experience, the two-visit method can be expanded to wider variety of cases.

- Prosthodontic diagnostics index (PDI) class 1 or 2 (presence of adequate volume of alveolar bone).
- Presence of stable maxillo-mandibular occlusal relationship (avoid Angle class 2 cases and wondering jaw cases, etc.).
- Nonesthetically demanding cases.
- Non-TMD patients.
- Careful patient selection (house patient's classification: such as philosophical type), etc.

Dentists and dental technicians unexperienced in DRCD are often challenged by the unconventional fabrication techniques required for DRCD treatments. However, there are no fundamental differences between traditional and digital RCD fabrication besides the fact that the DRCD technique reduces the number of clinical visits by consolidating some of the conventional clinical fabrication steps. Examination, diagnosis, treatment planning, delivery, and follow-up steps remain the same on both conventional RCD and DRCD methods; however the impression and bite registration appointments are often condensed into a single appointment.

One of the pitfalls of DRCD techniques, especially the two-visit technique, is the possibility of easily misjudging jaw relationship and space analysis due to the lack of mounted diagnostic casts with this technique. Assessment of proposed DRCD is quite different from checking mounted waxed RCD since many dentists and dental technicians are not familiar with reviewing screen shots and 3D viewer. DRCDs are also limited upon denture try-in, since this treatment does not provide the same freedom to reset denture teeth in desired positions. Many of DRCD try-in methods do not offer ability for resetting denture teeth as much as the conventional technique does. The abovementioned potential problems can be addressed by combining views of 2D or 3D photographs of static and dynamic lip position views and proposed denture views in 3D viewer to facilitate more accurate communication between the dentist, the dental laboratory, the company, and even the patient [26, 37].

Dental laboratory fabrication steps for DRCD are totally different from those of the conventional technique since it would not involve stone models, waxes, and processing. Many older technicians might feel uncomfortable working with computer screens instead of mounted casts and wax dentures, and it could take some time to get enough experienced to be comfortable with the digital workflow. However, this seems to be less problematic for the younger generation of dental technicians who are exposed earlier to digital technologies. We are currently facing a decreased number of dental laboratory schools and shortage of work force in the digital dentistry revolution era. Therefore, it would be our advantage to recruit the younger generation to the dental laboratory industry.

6.2 Traditional RCD Workflow

To better explain the DRCD workflow, we first have to revise the traditional procedure. Conventional RCD fabrication steps are as follows (Fig. 6.1):

(a) Examinations, treatment plan, and preliminary impression: *clinical visit 1*
(b) Fabrication of diagnostic cast and custom tray: laboratory
(c) Final impression with custom tray: *clinical visit 2*
(d) Fabrication of master cast and trial base and wax rims: laboratory
(e) Evaluation of wax rim, lip support, incisal edge position, OVD, and IOR and selection of shade and denture teeth mold: *clinical visit 3*
(f) Setup maxillary and mandibular anterior teeth: laboratory
(g) Try-in anterior teeth and evaluation and confirmation of esthetic, function, OVD, and IOR: *clinical visit 4*
(h) Conventional denture processing, finishing, and polishing: laboratory
(i) Delivery: *clinical visit 5*

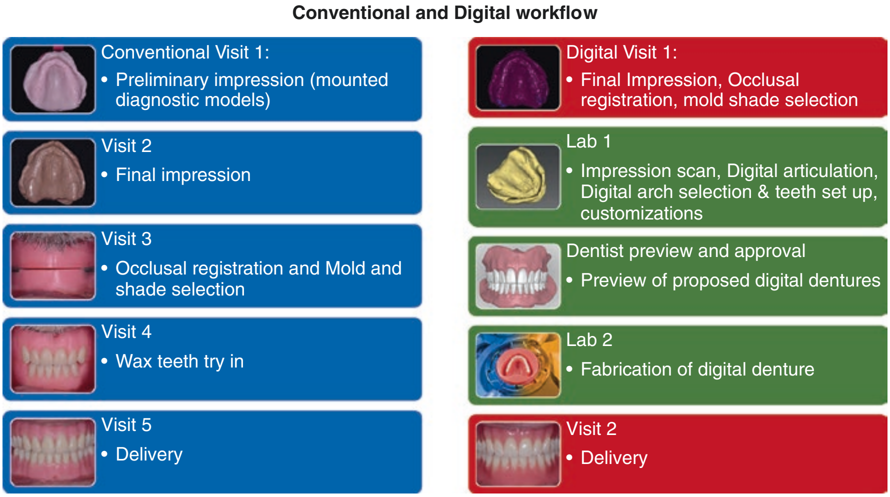

Fig. 6.1 The flowchart above explains the conventional and digital workflow of RCP

6.3 DRCD Workflow and Methods

Unlike conventional RCD, the digital RCD workflow follows a different set of steps that can be summarized in the following steps (Fig. 6.1):

1. Scan of final impressions or casts.
2. Scan of IOR with occlusal wax rims or existing or duplicate dentures.
3. Create best-fitting between impression/cast scan and IOR scan.
4. Select required anatomical landmarks and base outlines.
5. Set occlusal plane/articulator settings if applicable.
6. Model analysis for teeth positioning.
7. Customization of teeth arrangement and gingival design.
8. Send for viewing to the lab/dentist for approval/try-in (optional).
9. Rearrangement if necessary/final approval.
10. Manufacturing DRCD by milling or 3D printing including tooth sockets and position and bonding of denture teeth, DRCD, or milling monolithic.

DRCD fabrication steps range from the traditional five to six appointments of conventional dentures to as little as two appointments. Some methods require users to have a preliminary impression and a secondary final impression, while with other methods final impressions can be taken without diagnostic impression by using their proprietary tray systems, although purchasing these trays can increase the initial cost of the treatment.

Since the late 2000s to early 2010s, AvaDent™ and Dentca™ were the only two companies in the dental market claiming “two-visits to complete construction of complete denture” by using their proprietary manufacturing process. Over the years they have developed additional steps to overcome some difficulties and limitations of their two-visit denture concept. Currently, several upcoming DRCD systems are being launched and soon to be available, and many software companies have been developing digital complete denture software. Therefore, dental laboratories would soon have many options for fabricating DRCD that would include the entire fabrication process onsite without having to rely on fabrication centers such as AvaDent or Dentca.

Currently dentists have two main options to fabricate DRCD:

1. Direct center system: direct account with AvaDent or Dentca [10]
2. Laboratory system: through a dental laboratory
    (a) AvaDent or Dentca through the dental laboratory
    (b) Combination of software and material companies: Dentsply Sirona, AvaDent, Kulzer, Dentca, Ivoclar, 3Shape, Mertz Baltic denture system, Amman Girrbach, etc.
    (c) In laboratory software system: 3Shape, Dental Wing, Exocad, Stoneglass Industries [38]

Currently several DRCD fabrication methods are available:

1. Use of proprietary tray to make final impression and proprietary intraoral tracing device for IOR: direct center technique (2–3 visits)—AvaDent AMD, Dentca
2. Custom tray impression + record base and wax rim technique (3–4 visits)
3. Wax rim base final impression technique (3–4 visits)
4. Replication technique using either existing RCD or copied existing RCDs (3–4 visits)
5. AvaDent Wagner EZ guide technique (3–4 visits)
6. Preset denture teeth disk technique: Merz Baltic denture system (2 visits)

Possible DRCD fabrication techniques and steps are listed and explained below along with the expected number of clinical visits.

1. Use of proprietary trays to make the final impression and proprietary intraoral tracing device for occlusal registration (2–3 clinical visits) [10]: This approach is very common for the direct center method, although lately these methods are shifting toward working with registered/certified dental laboratories.
   Steps for DRCD fabrication using proprietary trays:
   (a) Examination, diagnosis, treatment plan, final impressions, and IOR with an intraoral tracing device: *clinical visit 1.*
      This step could vary depending on the method used
      - AvaDent AMD: final impressions and occlusal registrations are done using different trays and AMD occlusal recorders.
      - Dentca: final impressions and occlusal registrations are done using the same trays.

   (b) Impressions are scanned and digitally mounted, and the data is sent to the manufacturing facility (company): laboratory
   (c) Digital teeth setups and wax-ups are created with proprietary software: company/laboratory
   (d) Preview and approval process: dentist/laboratory
   (e) After approval of the try-in denture, the final DRCD is submitted for production: company/laboratory
   (f) Optional denture try-in: *optional clinical visit 2*
   (g) Delivery: *clinical visit 2 or 3*
2. Custom tray impression and wax rim base IOR technique (3–4 clinical visits) [27]. This method involves the following steps:
   (a) Examinations, diagnosis, treatment plan, and preliminary impression: *clinical visit 1*
   (b) Fabrication of custom tray and wax rims: laboratory
   (c) Final impression with custom tray and wax rim IOR with PVS: *clinical visit 2*
   (d) Impression scan and IOR scan, design denture base and digital mounting by using the best-fit method, digitally setup teeth and wax-up, and customization: laboratory
   (e) Preview and approval process: dentist/laboratory

  - (f) After approval try-in denture production or final DRCD production: laboratory
  - (g) Optional denture try-in: *optional clinical visit 3*
  - (h) Delivery: *clinical visit 3 or 4*
3. Wax rim impression technique (3–4 clinical visits)
  - (a) Examinations, diagnosis, treatment plan, and preliminary impression: *clinical visit 1*
  - (b) Fabrication of denture outline designed wax rims: laboratory
  - (c) Final impressions with wax rims and IOR with PVS: *clinical visit 2*
  - (d) Impression scan and IOR scan, design denture base and digital mounting by using the best-fit method, digitally setup teeth and wax-up, and customization: laboratory
  - (e) Digital preview and approval process: dentist/laboratory
  - (f) Production of try-in denture or final DRCD: laboratory
  - (g) Optional denture try-in: *optional clinical visit 3*
  - (h) Delivery: *clinical visit 3 or 4*
4. Replication technique by using copied existing RCDs (2–4 clinical visits)
  - (a) Examinations, diagnosis, treatment plan, and coping existing RCDs: *clinical visit 1*
  - (b) Final impressions and IOR by using either existing RCDs or copied RCDs with PVS: *clinical visit 1 or 2* (existing RCDs can be used at this stage as per *clinical visit 1*)
  - (c) Impression scan, IOR scan, design denture base and digital mounting by using the best-fit method, digital teeth setup and wax-up, and customization: laboratory
  - (d) Preview and approval process: dentist/laboratory
  - (e) Production of try-in denture or final DRCD: laboratory
  - (f) Optional denture try-in: *clinical visit 2 or 3*
  - (g) Delivery: *clinical visit 2, 3, or 4*
5. AvaDent Wagner EZ Guide technique (3–4 clinical visits)
  - (a) Use of proprietary tray to make final impression and record required measurements with lip gauge: *clinical visit 1*
  - (b) Use WTI (Wagner Try-In) for try-in and IOR with PVS: *clinical visit 2*
  - (c) Optional teeth setup try-in: *optional clinical visit 3*
  - (d) Delivery: *clinical visit 3 or 4*
6. Merz Baltic denture system (preset denture teeth disk) (two clinical visits).
  - (a) Impression and IOR using the ^{BD}KEY Set: *clinical visit 1*
  - (b) Scan impression, design denture using ^{BD}Creator software, CAM processing and milling using ^{BD}Load (Proprietary Milling blank)
  - (c) Delivery: *clinical visit 2*

The DRCD technique was limited to a set of maxillary and mandibular complete denture in the beginning, but now it can be applied for other indications such as single RCD, immediate RCD [32, 39], overlay RCD [40], implant overlay RCD [13, 14, 41], and a conversion denture for fixed implant provisional restorations [42].

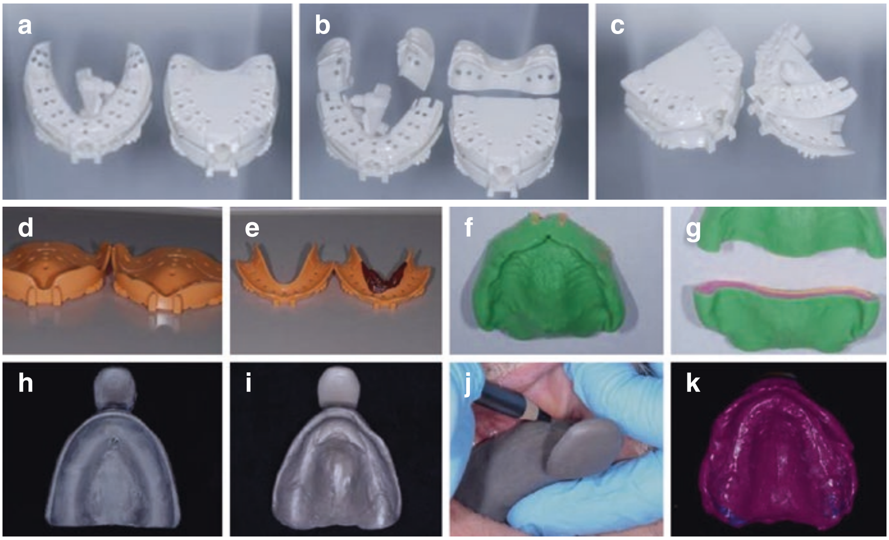

Fig. 6.2 (**a**) Dentca trays, (**b**) detached Dentca trays, (**c**) assembled Dentca trays with a tracing gothic arch, (**d**) unadjusted and adjusted maxillary Dentca trays, (**e**) unadjusted and adjusted mandibular Dentca trays, (**f**) Dentca tray maxillary impression, (**g**) sectioned and detached Dentca maxillary impression, (**h**) unmodified Wagner maxillary EZ tray, (**i**) modified Wagner maxillary EZ tray, (**j**) checking overextended modified EZ tray, (**k**) maxillary Wagner EZ tray PVS impression

The DRCD workflow can be introduced at any stage of the denture fabrication process, such as the final impression step, in which company proprietary trays can be used to eliminate the need for preliminary impressions (Dentca tray in Fig. 6.2a–g, Wagner EZ tray in Fig. 6.2h–k), the custom tray impression stage (Fig. 6.3a, b), the final cast stage (Fig. 6.3c), the wax rim stage (custom tray impression and wax rim base IOR technique) (Fig. 6.3a–n) [27], and even teeth setup try-in wax denture stage.

Since custom tray impression and wax rim base IOR techniques are the same procedure as conventional RCD fabrication steps, these steps would be the easiest way to introduce to the DRCD workflow [27] especially for dental students or dentists who have less experience with conventional RCD fabrication. DRCD fabrication can combine multiple denture fabrication steps, such as taking impression and IOR together with wax rim bases using the wax rim impression technique. When the patient has a reasonable existing denture that needs to be replaced, the DRCD can be fabricated using the existing dentures or duplicated dentures using the replication technique. Both the wax rim impression technique and the replication technique have the advantage of reducing the number of clinical visits, as long as the cases are well evaluated and adjusted for proper impression making and IOR registration.

The custom tray impression and wax rim base IOR technique will be concisely explained below. Also, the clinical and digital steps of the wax rim impression

Fig. 6.3 (**a**) Maxillary custom tray, (**b**) maxillary custom tray PVS impression, (**c**) scanned maxillary cast, (**d**) scanned wax rim IOR, (**e**) front overlap view of wax rim scan and proposed DRCD teeth setup, (**f**) front view of proposed DRCD, (**g**) maxillary intaglio view of proposed DRCD, (**h**) overlap intaglio view of maxillary wax rim and proposed DRCD, (**i**) mandibular intaglio view of proposed DRCD (**j**) overlap intaglio view of mandibular wax rim and proposed DRCD, (**k**) Biofunctional Try-In (BTI) front view, (**l**) new proposed BTI overlapped with old BTI view, (**m**) smile view of final DRCD, (**n**) front view of final DRCD

technique and the replication technique are explained step-by-step in this chapter. The use of proprietary trays to make final impressions and proprietary intraoral tracing devices for occlusal registrations, otherwise known as direct center techniques, is not covered in this chapter since both AvaDent AMD technique and Dentca technique were described in detail in elsewhere [10].

6.3.1 Custom Tray Impression and Wax Rim Base IOR Technique

This technique follows the conventional RCD fabrication steps up until the second clinical visit 2 (Fig. 6.3a) in which both the final impression and the IOR are taking in the same appointment. This appointment involves try-in and adjustment of the custom tray and border molding with suitable materials, such as modeling compound or a heavy body PVS (i.e., putty), followed by initial and final wash impressions with either a light, medium, and/or heavy body PVS. The impressions are

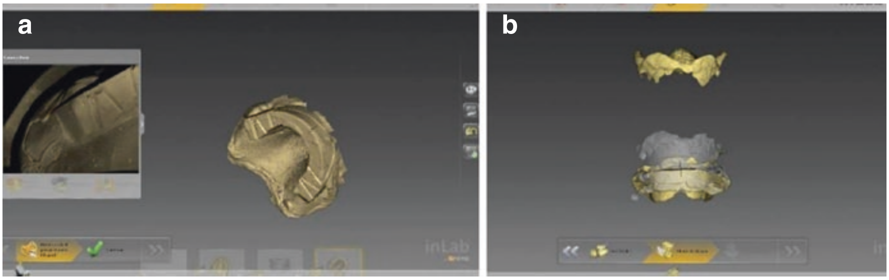

Fig. 6.4 (**a**) Maxillary wax rim scan, (**b**) best-fitting of intaglio surface of impression scan and wax rim IOR scan

evaluated, and if needed the exposed tray areas are adjusted, and secondary wash impressions for final impression are carried out (Fig. 6.3b). Conventional wax rim evaluations and adjustments are used to determine the position of maxillary anterior teeth, amount of lip support and esthetics, phonetic performance, and the posterior occlusal plane. IOR is then recorded using the wax rims and PVS occlusal registration material. After the second clinical visit, both the final impression/casts and the wax rim IOR are scanned (Fig. 6.4).

Then, both scanned files are merged using the best-fit method. In this approach the best-fitting condition of the intaglio surfaces of the master cast scan and the wax rim occlusal registration scan are digitally determined (Fig. 6.3a–d). To achieve the best-fit result, the wax rim recording bases should be relined on the master casts with a light body PVS. After scanning and merging the files, the DRCD fabrication process follows ordinal DRCD fabrication steps (Fig. 6.3e–n).

The Dentsply Sirona AvaDent wax rim impression technique and replication technique are covered step-by-step as follows:

6.3.2 Wax Rim Impression Technique

The wax rim impression technique must start with impression making followed by wax rim evaluation and adjustments and IOR registration with PVS as the conventional RCD fabrication technique (Fig. 6.5a–e). This technique can be applied for the conventional RCD fabrication technique for reducing the number of clinical appointments.

Step a: After preliminary impressions and fabrication of diagnostic casts, an outline of wax rim base on the diagnostic casts should be designed, similar to the conventional custom tray outline, for fabrication of proper recoding bases. Wax rims are then fabricated on the bases by following average dimension of wax rims according to the conventional RCD fabrication technique (Fig. 6.5a).

Step b: Try in the wax rim bases; particularly check the extension of the wax rim base to avoid overextension. If gross overextensions are present, correct them before the border molding procedure. Border molding with desired materials such

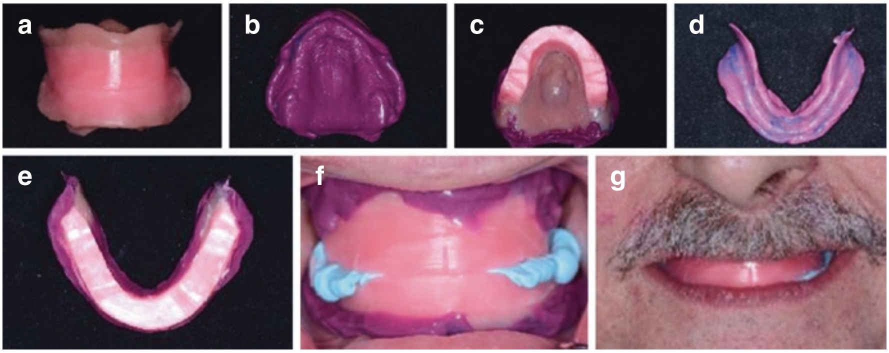

Fig. 6.5 (**a**) Wax rim impression trays, (**b**) intaglio view of maxillary wax rim PVS impression, (**c**) occlusal view of maxillary wax rim PVS impression, (**d**) intaglio view of mandibular wax rim PVS impression, (**e**) occlusal view of mandibular wax rim PVS impression, (**f**) front view of PVS wax rim tray impression IOR, (**g**) smile view of PVS wax rim tray impression IOR

as modeling compound, PVS putty, and heavy body PVS impression materials is performed. Then the final impression is taken with either a light, medium, or heavy body PVS material. Evaluate and adjust any exposed tray areas, and then perform a secondary wash for final impression if needed. The conventional method of determining maxillary anterior teeth position, amount of lip support and esthetic evaluation, phonetic evaluation, and determining anterior and posterior occlusal plane wax rim evaluations and adjustments would then be done. Finally, an IOR with wax rim and PVS occlusal registration materials would be made (Fig. 6.5b–g).

Step c: Send the wax rim impression and IOR to the laboratory. Both the intaglio and cameo surfaces of the wax rim impressions as well as the buccal surface of the occluded wax rims are scanned. The acquired files are merged using the best-matching procedure for relating the impression scan and IOR scan in the dental laboratory. All scanned files are either sent to a milling center, such as AvaDent, or kept in the laboratory for plotting the required anatomical landmarks, outlining the denture base digitally, digital teeth setup and wax-up, and customization. After completion of designing the DRCD, a preview of the proposed DRCD would be sent to the treating dentist and/or the dental laboratory for an approval of the design. After approval, a try-in denture or a final DRCD would be produced. Either a milled or a 3D printed try-in denture is delivered to the dentist if desired. If the dentist is happy with the proposed DRCD design and not wishing to have a try-in, a final DRCD would be produced and delivered to the dentist's office (Fig. 6.6a–k).

Step d: Optionally, prior to final DRCD delivery, anterior teeth waxed setup with Wagner Try-In (WTI) or 3D printed or milled digital denture try-in (BTI) could be done at the dentist's office. If the try-in procedure is acceptable for the dentist and the patient, the final DRCD would be produced and delivered to the dentist's office. If the try-in process is not successful, this process will be repeated until the patient is satisfied with the try-in DRCD.

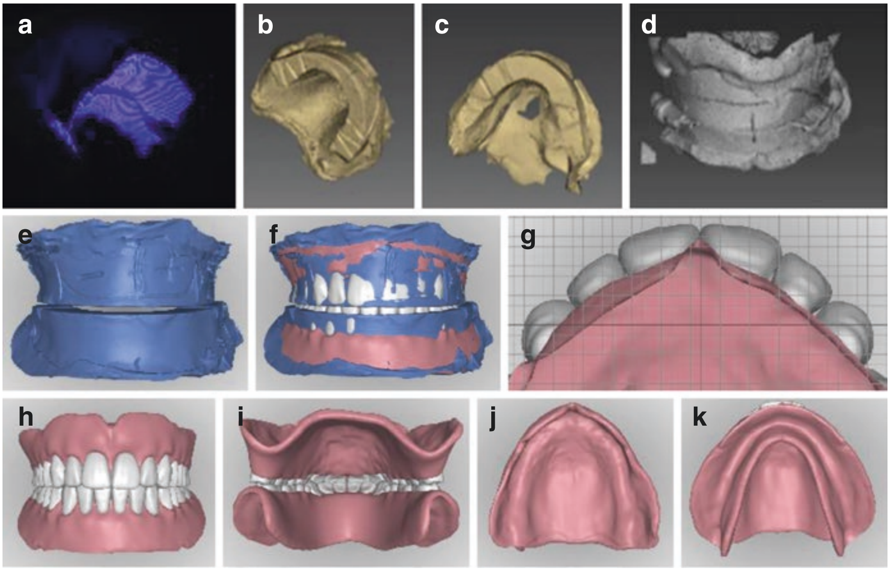

Fig. 6.6 (**a**) Scanning wax rim IOR, (**b**) scanned maxillary wax rim, (**c**) scanned mandibular wax rim, (**d**) best-fitted merged view of wax rims and IOR, (**e**) scanned wax rims IOR, (**f**) frontal overlap view of proposed teeth setup and scanned wax rims, (**g**) anterior teeth position view,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

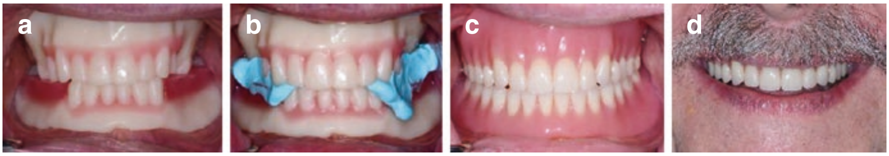

Fig. 6.7 (**a**, **b**) WTI frontal view and smile view of the final DRCD with wax rim impression technique, (**c**) front view of wax rim technique final DRCD, (**d**) smile view of wax rim technique final DRCD

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).

6.3.3 Replication Technique by Copying Existing RCDs

This technique can be used for both DRCP and conventional RCD as well, to reduce the number of clinical appointments. The replication technique starts with the evaluation and adjustment of the existing dentures, in order to allow for adequate space for border molding and impression materials. Occlusion is also be adjusted into centric relation in proper OVD.

Step a: Evaluation of existing dentures. If the existing dentures are reasonable to duplicate, do so with a duplication flask with PVS. Duplicated dentures are polished and finished in preparation for next appointment (Fig. 6.8a, b).

Step b: Try in the duplicated dentures to make sure they are satisfactory for the replication technique. Check denture overextensions, and adjust them before border molding with desired materials, such as a modeling compound, PVS putty materials, and PVS heavy body impression materials. The first wash impression would be made using a light, medium, or heavy body PVS material. The impressions should be evaluated and the exposed resin base areas adjusted. Then, a secondary wash impression for the final impression is done. The esthetics, function, teeth position, occlusion, and OVD are then evaluated following conventional methods, and adjustment of the dentures is performed necessarily. Once all are satisfied, an IOR with PVS is taken (Fig. 6.8c).

Step c: Send the duplicated denture impressions and the IOR to the laboratory. Impression scans and IOR scan would be made on both intaglio and cameo surfaces of the duplicated denture impressions and the buccal surface of the occluded dentures (Fig. 6.8d, e). The acquired files are then merged using the best-fit procedure for relating the impression scans and the IOR scan (Fig. 6.8f, g). All scanned files are either sent to the milling center or kept in the laboratory. Plotting required anatomical landmarks, outlining the denture base digitally, digitally setup teeth and wax-up, and customization would be carried out to create a DRCD proposal. After completion of designing the DRCD, a preview of the proposed DRCD would be sent to the treating dentist and/or the dental laboratory for approval of the design (Fig. 6.8h–m). After approval, a try-in denture or a final DRCD would be produced. Either a milled or 3D printed try-in denture is delivered to the dentist if desired. If the dentist is happy with the proposed DRCD design and not wishing to have a try-in, a final DRCD would be produced and delivered to the dentist's office.

Step d: Optionally, the milled Biofunctional Try-In (BTI), 3D printed (Dentca), or WTI try-in would be done at the dentist's office. If the try-in procedure is fine with the dentist and the patient, the final DRCD would be produced and delivered to the dentist's office. If the try-in process is not successful, this process will be repeated until the patient is satisfied with the try-in DRCD (Fig. 6.8n–r).

Step e: Delivery of the final DRCDs would follow the same delivery protocol as the conventional RCDs. However, since the DRCD technique does not have any mounted cast, a clinical remount may be necessary (Fig. 6.9a–c).

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

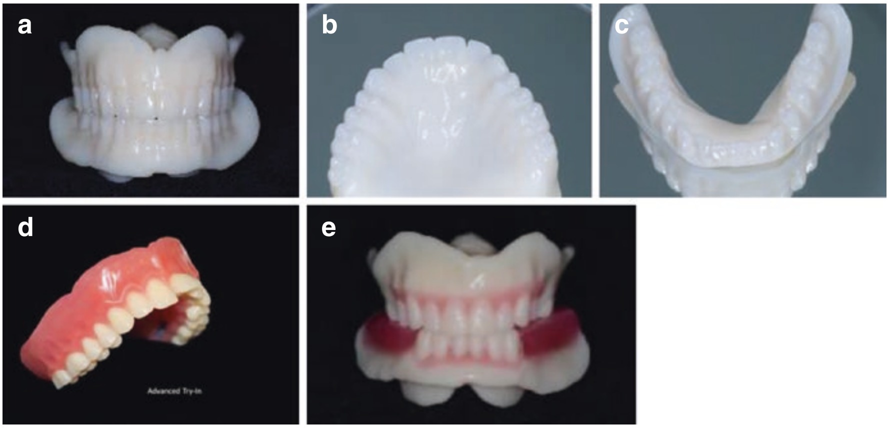

Fig. 6.10 (**a**) Functional BTI (Biofunctional Try-In), (**b**, **c**) Dentca try-in dentures, (**d**) ATI (AvaDent Try-In), (**e**) WTI (Wagner Try-In) frontal view

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 experience and data on the DRCD. It has very good potential to replace conventional RCD applications with faster and better-quality outcomes.

The same fundamentals of RCD should be applied for fabrication of the DRCD. Digital technology only cannot provide the best care to our patients; this can only be achieved by applying the sound fundamentals of RCD concepts and knowing the limitations and understanding of digital technologies.

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Fixed Restorations in Digital Dentistry

7

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and Hesham Nouh

Abstract

The area of digital fixed prosthodontics has seen many developments in software and hardware as well as Computer-Aided Design and Manufacturing (CAD/CAM) materials experience, and these has resulted in a wide range of improvements spanning from examinations to production of prostheses. This chapter will explain in-office systems, laboratory systems, and digital workflows related to fixed restorations.

7.1 Introduction

Today's CAD/CAM concepts have continued to evolve since François Duret published his thesis of Emprinte Optique (Optical Impression) in 1973 [1]. Duret treated his wife's lower premolar crown by digitally scanning, designing, and milling a DICOR block in 50 minutes in early 1985. In 1980, the CEREC (computer-assisted

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ceramic reconstruction) method was developed by W. H. Mörmann and M. Brandestini at the University of Zurich [2, 3]. The first patient was treated using CEREC and VITA block Mark I, in 1985. The CEREC 1 system, by Siemens, was the world's first commercialized CAD/CAM system for dentistry in 1987. Since then, evolution of the in-office or chairside CAD/CAM technology has been steady [2, 3]. In 1983, M. Andersson developed the Procera system which is the beginning of the dental laboratory CAD/CAM system [4].

However, exponential growth in CAD/CAM dentistry took off in the early 2000s. In 2007, the International Dental Show (IDS) in Cologne Germany, the largest dental show in the world, had only 37 CAD/CAM and digital dentistry-related exhibiters, but in only a few years, that increased to over 240 CAD/CAM and digital dentistry exhibitors at the 2011 meeting. Since then, new software, hardware, and materials for CAD/CAM dentistry have been continuously released. To date, there have been many improvements in CAD/CAM dentistry. Early stages of developments were focused on areas of fixed prosthodontics CAD/CAM production especially design and production of inlays, onlays, and fixed dental prostheses (FDP). Today, focus has shifted to development and improvement of CAD/CAM systems for in-office use, such as the CEREC system and development of the Laboratory CAD/CAM system that is compatible with dental laboratory scanners, milling machines (CNC machine), and software. Currently many of the laboratory CAD software can design almost all aspects of FDP designs including implant restorations. The use of additive manufacturing technology (3D printing technology) was very limited due to slow production time, taking up to 6–8 h, large equipment footprints, and high cost of 3D printers. Today, the latest dental 3D printers are marketed as inexpensive, smaller in size, high-speed printing capabilities that could be used with a wide variety of new FDA-approved 3D printing materials. Currently, the commercial production of 3D-printed metal restorations such as metal frameworks for porcelain fused to metal (PFM) restorations and removable partial denture frameworks is available by using the selective laser melting (SLM) or direct metal laser sintering (DMLS) technology [5–7]. However, this chapter will focus on the digital application on FDP from the CAD/CAM system to materials.

7.2 Background Literature Review

7.2.1 Impressions

The fundamental theory of intraoral scanning was very well described in a review article based on different technologies currently used (light projection, distance object determination, and reconstruction) and the clinical considerations (handling, learning curve, powdering, scanning paths, tracking, and mesh quality). [8]. Accuracy of the IOS and the laboratory scanner is very well studied in the dental literatures [9–29].

In vitro comparisons between conventional impressions for single restorations and three different IOS systems have shown that all IOS systems provided better time efficiency than conventional impression techniques [22–24]. A clinical study evaluating patients' perception and clinical efficiency of polyether conventional and CEREC Omnicam digital impressions showed that patients preferred digital impressions over conventional ones probably because they were more efficient and faster [30]. Nevertheless, patients are more comfortable with the digital impression technique when scans are performed by an experienced operator. Comparisons between different IOS systems showed that independently of the clinical experience of the operator, the Trios IOS system has a faster scan time and learning curve than the iTero IOS system [31, 32].

Rau et al. evaluated 1157 impressions at commercial dental laboratories; at least one detectable error was found out of 86% of the impressions, and the finish line related critical errors were 55% of the noted errors. Soft tissue above the finish line was the largest single error category (49.09%), followed by missing unprepared stops in dual-arch impressions (25.63%), soft tissue pressure caused by the tray (25.06%), and finish line void (24.38%). Bleeding and tray type were two main causes of finish line errors [33]. These impression errors would affect the quality of both conventional and digital impressions. These obstacles are common issues with the IOS impression; since the current IOS uses an optical impression technique, blood and tissue fluid can appear on the finishing line. Possible new applications of ultrasound technology may arise for resolving these issues [6, 34–36].

Patzelt et al. conducted an in vitro study comparing five IOS systems on a typodont and found great variety of trueness and precision values among the different IOS systems [22–24]. The accuracy of images obtained from an IOS, and a cone beam computed tomography (CBCT) on 60 dry skulls was evaluated for orthodontic evaluation measurements. The authors found that the IOS provided a near perfect match from digital calipers' measurements [9]. Using a new measurement method to evaluate trueness and precision accuracy of full arch impressions, Ender and Mehl reported that the stereolithography (STL) file from the conventional full arch model was more accurate than the STL file from the digital impression [11, 12]. These findings are in disagreement with the finding by Akyalcin et al. This might be due to a measurement method of manual digital calipers used by Akyalcin et al. Three different methods of obtaining digital images were evaluated and found that the digital image from the stone scan from a laboratory scanner was the most accurate, followed by the stone model scan from an IOS, and lastly the direct mouth scan by the same IOS [14]. Digital images from an IOS, impression scan and model scan by a laboratory scanner were compared for accuracy. Results showed that the IOS images were the most accurate, followed by impression scanned images, and then model scanned images [16]. The mean differences in this study were within 20 μm; therefore, all scan methods should be clinically acceptable. Bohner et al. conducted an in vitro study that compared two IOS and two laboratory scanners on trueness of scans and reported that the two IOS and EOS showed similar trueness in scanning prepared teeth [37]. Theoretically, since the IOS uses a stitching technology, the laboratory scanner would have better accuracy than the IOS, but there is no major difference in accuracy on the die and short distance level. The influence of different restorative materials and powder coating thicknesses were studied on four IOS. Powder coating had a positive effect on the accuracy of scans, while materials with translucent nature affected one IOS with a non-coating scanner [38]. The nature of the IOS is limited in its ability to recognize and stitch together a 3D image on plane, homogeneous, and nonreflective translucent surfaces. Therefore, application of a reflective material on the scan surface leads to better recognition and stitching of aforementioned surface images.

7.2.2 Fabrication of the Restorations

A systematic review on marginal adaptation of fixed restoration has concluded that CAD/CAM produced restorations and substructures are clinically acceptable or better those obtain with other methods [39]. The fit of digitally fabricated crowns compared to conventionally fabricated crowns using various impression methods has been well investigated in vitro and in vivo, and although there were existing statistical differences, all are within clinically acceptable levels [18, 37, 40–48]. In vitro analysis of Lithium Disilicate (LD) crowns revealed that crowns produced using IOS scanning-, digitally design-, and milling had significantly better fit than crowns produced by conventional impression, manual wax up, and pressing [41]. However, the combination of digital impression methods (IOS impression) with analog crown fabrication methods (press) showed the least accurate internal crown fit [41]. An in vivo study comparing the fit of zirconia crowns prepared with either IOS impressions or polyvinyl siloxane (PVS) impressions concluded that, even though all resulting crowns had clinically acceptable marginal gaps and occlusion, crowns from IOS impressions had better marginal fit and interproximal contact area than crowns from PVS impressions [47]. A clinical study on zirconia crowns in 24 patients also found digitally fabricated crowns had a better fitting than the conventionally fabricated crowns, though both methods are clinically acceptable [40].

In vivo comparisons between the Lava™ Chairside Oral Scanner (Lava C.O.S.) and CEREC AC systems showed that both produced zirconia restorations with clinically acceptable fitting, even though three out of four measurement points had statistically significant differences [43]. Long-term clinical studies showed that CEREC restorations have a 5-year survival rate of 97% and 10-year survival rate of 90% [49].

7.2.3 Tooth Preparation

Principles of tooth preparation for conventional and CAD/CAM crowns have been explained in the literature [50–54]. Tooth preparation principles are almost same on both conventional and CAD/CAM crowns. However, the CAD/CAM crown preparation design must accommodate a minimal milling bur tip size. Ideal occlusal preparation of either flat or anatomic occlusal preparation design is not conclusive [50, 53]. Realistic clinical total occlusal convergence (TOC) would be about 17° range (10–20°) rather than an ideal 2–7° TOC could apply both conventional and CAD CAM crown preparation design. Mejía et al. tested trueness and precision of various TOC angle models scanned by an IOS, conventional PVS impression scan, and type 4 dental stone models scan by a laboratory scanner for comparison. The IOS scan was significantly better in trueness and precision compared to the two other groups. They found that the closer the TOC angle was to 0°, both impression and stone scans had increased inaccuracy [51].

Fusing CAD/CAM-fabricated lithium disilicate crown to zirconia copings (e-Max CAD on technique Ivoclar Vivadent AG, Liechtenstein) results in restorations with superior mechanical properties compared to those prepared by layering or pressing veneering porcelain onto zirconia copings [55, 56].

7.2.4 Models

Regarding dental models, digitally fabricated polyurethane milled models made from IOS can be compatible with conventionally fabricated models [57], and models prepared by stereolithography (SLA) have now been found to be even superior to the milled ones [22–24] (an example of 3D-printed SLA model is shown in Fig. 7.1a–c).

Nevertheless, comparisons between scan images of stone models with the scanned image of 3D-printed model (rapid prototyping RP) reveal that the stone model cannot be replaced by the RP model at this time [58].

Currently, dental milling technology is a mature standard production method that has seen many improvements over the years. Milling machines used for the fabrication of prosthetic restorations can operate with five or four milling axes. Comparisons between these two milling modalities have shown that inlay and onlay restorations prepared with five-axis milling machines yield higher trueness than the restorations prepared with most four-axis milling machines [59]. Also, smaller diameter cutting bur produced better trueness than thicker burs [60]. More recently, burs are being replaced by Nd/YVO4 nanosecond lasers for fabrication of zirconia copings [61]. This could be a promising method in the future for fabrication of CAD/CAM restorations with great precision.

Unlike subtractive methods, additive manufacturing in dentistry is less mature, but this technology is rapidly expanding lately. It is predicted that many applications produced by the subtractive technology (milling) would be replaced with the additive manufacturing technology in the nearby future. For instance, direct inkjet printing is already being tested for producing dental ceramics [62], and laser sintering is used to produce metal crown copings.

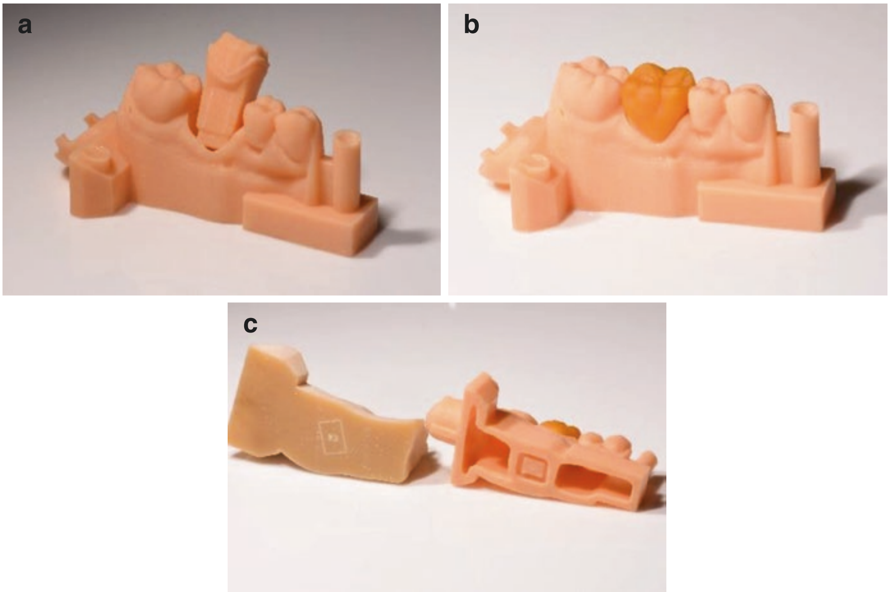

Fig. 7.1 (**a**) 3D-printed model with removable die; (**b**) 3D-printed model with removable die and restoration; (**c**) 3D-printed model, solid and hollow

7.3 Digital Workflow

Currently, there are digital several workflows for fixed restoration. Two main workflows are categorized as image acquiring methods including (1) direct image acquiring, through scanning of the patient mouth using an intraoral scanner (IOS), and (2) indirect image acquiring, scanning a master cast or impression using a laboratory scanner. The direct image acquiring method is further divided by manufacturing methods. In-office systems such as the CEREC AC system (Dentsply Sirona, York, PA, USA), has a closed file system (rst file and dxd file) for better quality control, while the Planmeca FIT® system (Planmeca Helsinki Finland) has an open file for wider range of compatibilities (Fig. 7.2a, b). The in-office systems consist of an IOS, a proprietary CAD/CAM software with computer, and a milling machine. Applications of the chairside CAD/CAM unit are expanded from ordinal types of restorations to advanced applications such as thin veneer fabrications [63, 64]. The in-office method is a true stoneless method (no physical models). However, to overcome some milling limitations such as chipping of thin margins, the clinician can use a quick physical model fabrication to finalize very delicate margin finishing areas. This method can be applied to the stand-alone open IOS method.

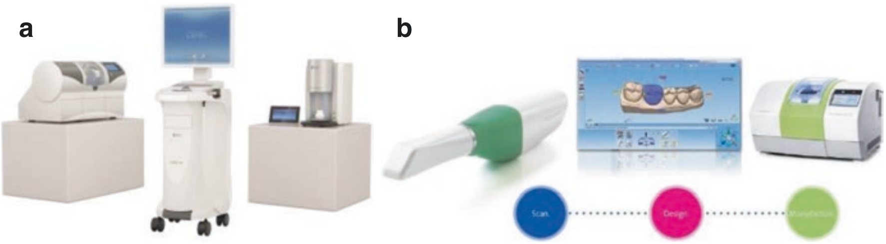

Fig. 7.2 (**a**) CEREC AC system, Rapid fire by Dentsply Sirona (copyright Dentsply Sirona); (**b**) Planmeca FIT® system by Planmeca (courtesy of © Planmeca OY)

One of the most common reasons to introduce the in-office system is to reduce the cost of laboratory fees. However, chair time should also be considered as part of the cost calculation, though it is difficult to translate as this varies depending on office size and number of staff members. One of the best settings is to have a group practice with an in-office unit, or a stand-alone IOS, and a CAM unit with a dedicated dental assistant to manage the CAD/CAM system and a dental technician to produce the final CAD/CAM restorations. This way the dentist can have more chair time to treat a greater number of patients while being able to deliver high-quality customized CAD/CAM final restorations to the patient on same day.

There are many stand-alone open IOS systems currently on the market, including 3M™ True Definition (3M, St. Paul, MN, USA), TRIOS® 3 (3Shape A/S Copenhagen, Denmark), DWIS (Dental Wings Inc., Montréal, Québec, Canada), iTero Element 2 (Align Technology, Inc., San Jose, CA, USA), CS 3600 (Carestream Dental LLC, Atlanta, GA, USA), CEREC AF or AI with software CEREC SW4.5 which can export the STL file format to outside laboratories that accept the STL file (Dentsply Sirona, York, PA, USA), and Planmeca PlanScan® (Planmeca/E4D Technologies, Richardson, TX, USA), as depicted in Fig. 7.3a–g. The stand-alone open IOS system is comprised of an IOS and a computer unit that operates the CAD software. The IOS can be connected to the computer unit using a wireless connection, or through a wire, using USB or types of connections. In addition, having CAD and CAM software in the office as well as a milling machine or 3D printer allows in-office design and production of the restoration otherwise, the scanned images could be sent to a dental laboratory or production center (milling or 3D printing) for offsite design and fabrication.

Besides the fabrication of restorations, in-office CAM units (software, 3D printer, and/or milling machines) can also be used for case designing, producing mock provisional, provisional restorations, and more. Currently many CAM machine production companies offer connection to compatible IOSs to create an in-office full production system.

Fig. 7.3 (**a**) 3M™ True Definition by 3M (The photograph is reproduced herein with permission © 3M 2018 All rights reserved); (**b**) TRIOS® 3 MOVE by 3Shape (courtesy of 3 Shape, Inc.); (**c**) DWIS by Dental Wings (courtesy of Dental Wings); (**d**) iTero Element® by Align Technology (iTero element 2 by Align Technology. Courtesy Align Technology. Inc., San Jose, CA); (**e**) CS 3600 by Carestream Dental (courtesy of Carestream Dental LLC); (**f**) CEREC AF by Dentsply Sirona (copyright Dentsply Sirona); (**g**) PlanScan® by Planmeca/E4D Technologies (courtesy of © Planmeca OY)

The dental laboratory scanning (indirect image acquiring) method is a part of our everyday dentistry now, since the majority of our dental restorations are produced already this way. Many dental laboratory scanners are currently on the market, as depicted in Fig. 7.4a–d. Zirconia restoration is entirely digitally processed. The number and type of materials are not limited since we can handle all types of restorations and cases with this method [65]. The dentist sends out a final impression to a dental laboratory, and the laboratory scans either the poured master cast or final impression from the dental office. Scanning powder is not needed to scan stone models when scanned by a laboratory scanner (3Shape D900) [66]. The dental laboratory designs the final restoration using specialized CAD software and

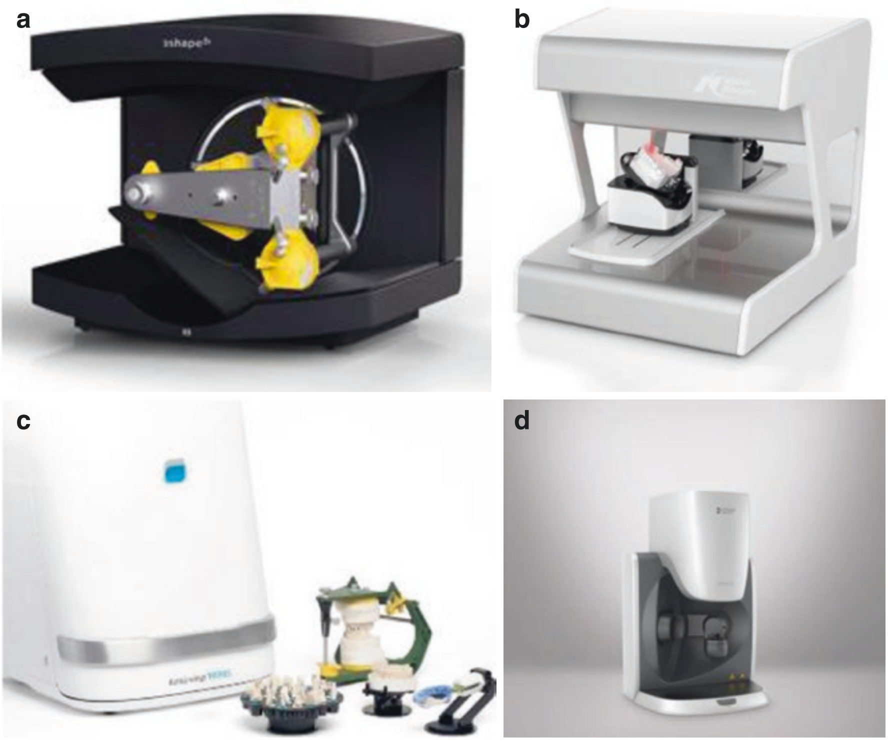

Fig. 7.4 (**a**) E3 3Shape (courtesy of 3 Shape, Inc.); (**b**) NobelProcera 2G Nobel Biocare (courtesy of Nobel Biocare Service AG); (**c**) 7Series Dental Wings (courtesy of Dental Wings); (**d**) inEos X5 SIRONA (copyright Dentsply Sirona)

then either produces the final restoration in-house, using milling machine or 3D printer, or outsources the fabrication to a production center with large industrial milling machines or 3D printers. The use of fabrication centers is becoming very popular among small laboratories because it minimizes their equipment requirements and costs since they only need to have a laboratory scanner and CAD software. Once the laboratory receives a restoration from the production center, the laboratory goes through a quality control process and customization to finalize the restoration. Then the final restoration is sent to the dental office for delivering to the patient.

Virtual facebow techniques are still not fully developed. And the two IOS methods cannot deliver dynamic jaw motions to a virtual articulator. Therefore, a virtual articulator often relies on the average value of occlusal movements unless it is combined with facebow-transferred information or cone beam CT scan data, which seems to have problems with accuracy, repeatability, and exposure to radiation at this point in time [67–69].

7.4 In-Office Method

Comparison of workflows between conventional technique and in-office system is depicted in Fig. 7.5a, b. The CEREC system is the first commercially available in-office system, since its introduction in 1987, and the most popular one in the world. The CEREC system comes with a cart system that consists of an IOS (Omnicam), built-in screen, built-in keypad a mouse, and a built-in computer with CEREC CAD/CAM software. In addition to the CEREC cart, the dentist must have a CEREC milling machine for in-office production of the restorations, which is limited to ceramic or polymer ceramic materials unless the dentist purchases an additional fast zirconia sintering oven for processing of zirconia.

After proper examinations, diagnosis, treatment planning and agreement, and informed consent, tooth shade selection, removal of existing restoration, caries control, and/or tooth preparation should be carried out. Evaluating prepared tooth condition such as healthy pulpal condition, linear margin, margin placement (supragingival, equigingival, or slightly subgingival), health gingival condition, etc., and confirming proper resistance form, retention forms, and suitable preparation form (10–20° TOC, the presence of 4-mm axial wall height, rounded angled preparation corners, etc.) for CAD/CAM restoration are critical steps for successful treatment outcome.

Step-by-step procedure phases for the in-office method are described below:

1. Administration phase: Patient information and case information input
2. Acquisition phase:

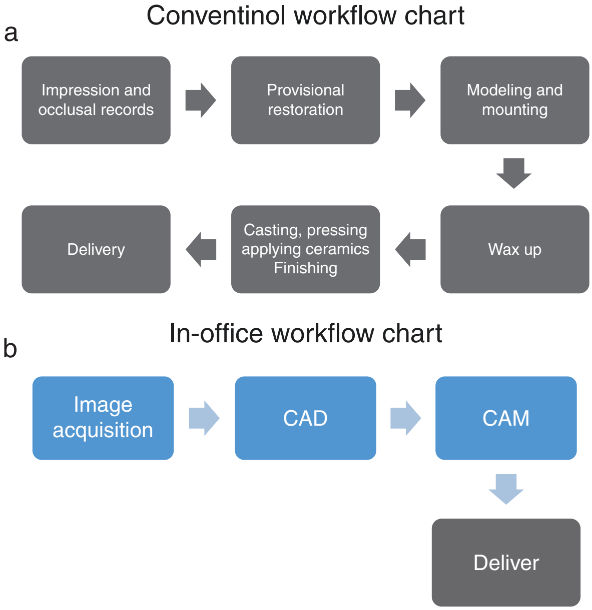

Fig. 7.5 (**a**) Conventional workflow chart; (**b**) in-office workflow chart

   (a) Start scanning at least one tooth posterior to the prepared tooth/teeth, and continue until at least one tooth anterior to the prepared tooth
   (b) Scan opposing segment
   (c) Scan buccal/labial occlusal record (buccal bite)
3. Edit model phase: Remove, smooth, and add tools, crop out unnecessary parts of scan (trim area)
4. Default-automatic alignment (auto buccal bite) of maxilla and mandible scans using buccal/labial occlusal record scan in occlusion. Manual alignment is optional
5. Set model axis on the screen template
6. Model analysis phase:
   (a) Draw margin
   (b) Define insertion axis of each restorations
   (c) Preparation analysis:
      - Distance to antagonist
      - Undercut evaluation
      - Margin evaluation (identify margin problem-sharp margin)
      - Surface evaluation (identify preparation surface problem-sharp internal angle)
7. Set restoration parameter phase
8. Design phase
   (a) Calculation of the restoration-auto designing
   (b) Edit restorations: tools, analyzing tools, and display objects boxes for facilitating proper designing process
      - Form tool
      - Move tool
      - Shape tool
      - Biogenic variation tool
      - Recalculation tool
      - Contacts
9. Milling phase: tools, block sizes, display objects, and device/export boxes
   (a) Select block size
   (b) Select milling mode
   (c) Adjust mill position
   (d) Sprue
   (e) Send to milling
10. Di-sprue, adjusting, sintering, staining, and grazing
11. Delivery

For more information please watch video Tutorials, which are available as below for CEREC Software:

- CEREC SW 4.4: Tutorial 1—Start Phase. Dentsply Sirona: https://www.youtube.com/watch?v=wN5_VgSOwgs&t=113s
- CEREC SW 4.4: Tutorial 2—Administration Phase. Dentsply Sirona: https://www.youtube.com/watch?v=y4qWEZXE68E&t=105s

- CEREC SW 4.4: Tutorial 3—Model Phase #1. Dentsply Sirona: https://www.youtube.com/watch?v=Bh4LvXjotXw&t=52s
- CEREC SW 4.4: Tutorial 4—Model Phase #2. Dentsply Sirona: https://www.youtube.com/watch?v=d5-toaF8BUg&t=119s
- CEREC SW 4.4: Tutorial 5—Design Phase. Dentsply Sirona: https://www.youtube.com/watch?v=67t7ydl8B10&t=73s
- CEREC SW 4.4: Tutorial 6—Mill Phase. Dentsply Sirona: https://www.youtube.com/watch?v=4PszW9f0BIw
- Dentsply Sirona Tutorials for CEREC software: CEREC Premium SW 4.4 Basic, CEREC SW 4.5 Basic, CEREC SW 4.6.
- https://my.cerec.com/en/tutorials.html

Advantages of the in-office method:

1. Same day delivery
2. Reduced number of visits
3. Reduced total chair time
4. No provisional restorations necessary
5. Positive patient experiences (the patient's comfort level and preference)
6. No need for block out undercuts
7. No removal of existing restorations or loose teeth by making an impression
8. Reduced potential gagging reflexes
9. No aspiration and/or swallowing loose impression materials
10. Potentially increased referrals from the patient or from the office website
11. Laboratory cost saving
12. Easy reproduction of the restoration or easy production of a new modified restoration

Disadvantages of the in-office method:

1. Large initial investment and continuous yearly membership or maintenance contracts
2. Very fast technological change—equipment can become obsolete in a few years and requires hardware updates
3. Need of continuous training for software updates
4. Need of training for staff members who operate the in-office system or hiring new staff trained in CAD/CAM
5. Need of additional spaces to place the CAD/CAM units: IOS CAD cart, milling machine/3D printer, ceramic oven, laboratory space
6. Maintenance/calibration of CAD/CAM system: IOS, milling unit and ceramic oven calibration, milling unit cleaning, and maintenance
7. Stocking of milling blocks (different shades, sizes, and materials), ceramic powder, glaze and staining materials, firing pins, firing support paste, milling burs, and coolant

8. May not achieve proper esthetics and functional results and should avoid highly esthetic and functional demanding cases
9. Limited case selection: margin position, material, and cement use (all ceramics/polymer ceramics, resin adhesive cement only)
10. No dynamic occlusal movements possible: average setting

The in-office method case-selection criteria:

1. Presence of proper anterior guidance
2. Presence of stable occlusal condition
3. Presence of healthy gingival condition
4. Small number of units (2–3 units)
5. Preferably having a supragingival or an equigingival margin
6. All ceramics/polymer ceramics restorations only (can use only a resin adhesive cement)
7. Not highly esthetically demanding cases
8. No active TMD cases

7.5 Stand-Alone Open IOS Method

The stand-alone open IOS method is very popular (Fig. 7.3a–e, g) and currently two in-office systems (Fig. 7.2a, b) can be used for this option. The stand-alone open IOS workflow is depicted in Fig. 7.6. However, closed file systems such as Sirona Connect is only managed at registered Sirona dental laboratory. On the other hand, the new version of CEREC SW 4.5 software can send out open STL file formats for wide applications of the scan data by any dental laboratory with software to handle the open STL file. This open STL file is sent to a laboratory equipped with CAD software and production machines for designing and production of the final restoration.

Procedural steps are very similar to the traditional methods up to completion of image acquisition (scanning). After proper examinations, diagnosis, treatment planning and agreement, and informed consent, tooth shade selection, removal of

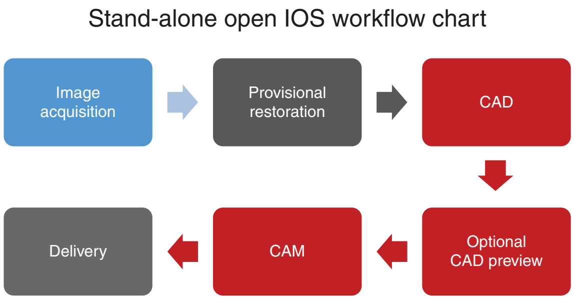

Fig. 7.6 Stand-alone open IOS workflow chart

existing restoration, caries control and/or tooth preparation would be carried out. Evaluating prepared tooth condition (pulpal condition, margin position and gingival condition, etc.) and confirming proper resistance form, retention forms, and suitable preparation form for CAD/CAM restoration are a critical step for a successful treatment outcome.

After image acquisition with an IOS, the scanned data is shared with the selected dental laboratory for designing and production. Laboratory CAD software often have 3D preview functions to share the proposed designed for the restoration with the dentist. The laboratory can also provide a digitally produced model to the dentist. These models have acceptable levels of accuracy [22–24], with finish lines as good as conventional models. However, these models can still present some problems of reproducibility and accuracy on the entire model area specially the distal areas [70].

With careful case selection, the *stand-alone open IOS method* can handle large scale restoration cases and esthetically challenging cases [71]. A case report was published that used an IOS (iTero) to scan final digital impression of a complex case which involved 20 units, all premolars and anterior teeth, to fabricate provisional restorations and final lithium disilicate restorations with a company's milling center [72].

Step-by-step procedure phases for the stand-alone open IOS method are below:

1. Administration phase: Patient information and case information input
2. Acquisition phase:
   (a) Start scanning at least one tooth posterior to prepared tooth/teeth until at least one tooth anterior to the prepared tooth or full arch scanning
   (b) Scan opposing segment either segment or full arch
   (c) Scan buccal/labial occlusal record (Buccal bite)
   (d) Fill electronic laboratory prescription send acquired scanning STL files through internet. This must meet HIPPA (Health Insurance Portability and Accountability Act of 1996) regulations
   (e) Fabrication of provisional restorations and cementation
3. CAD phase
   (a) Modeling, occluding, designing the final restoration
   (b) 3D preview of the designed restoration if this function is available in the laboratory software
4. CAM phase: Subtractive (Milling) or additive (3D printer) production
   (a) Milling
      - Ceramics, polymer ceramics
      - Wax for casting or pressing
      - Polymer for provisional restorations, occlusal guard
   (b) 3D printing
      - Polymer for metal framework pattern, pressed ceramics patterns, dental model, provisional restorations, occlusal guard, orthodontics appliance (Invisalign Align Technology, San Jose, CA, USA)

   - Porcelain fused metal framework (selective laser melting printer to print in a choice of metal)
   - Wax patterns for metal framework and pressed ceramics
5. Delivery

Advantages of the stand-alone IOS method:

1. Possibly a minor reduction of total chair time
2. Positive patient experience (the patient's comfort level and preference)
3. No need for block out undercuts
4. No risk of removal of existing restorations or loose teeth by making an impression
5. Reduce risk of gagging reflex
6. No aspiration and swallowing of loose impression materials
7. Potentially increased referrals from the patient or from the office website
8. Easy reproduction of the restoration or easy production of a new modified restoration

Disadvantages of the stand-alone open IOS method:

1. Need for provisional restorations
2. A moderate initial investment and continuous yearly membership or maintenance contracts
3. Very fast technological change—need for hardware updates
4. Need of training for updated software
5. No physical model available unless digitally created the model
6. No dynamic occlusal movements possible: average setting

The stand-alone open IOS method case-selection criteria:

1. Presence of proper anterior guidance
2. Presence of stable occlusal condition
3. Presence of healthy gingival condition
4. Limited number of units (not for full mouth case yet)
5. Preferably having a supragingival or an equigingival margin

7.6 Indirect Laboratory Scanning Method

The indirect laboratory scanning method is very popular among dentists because it does not require any substantial upgrading of the clinical setup. In this approach, the dentist takes regular impression and occlusal records and sends out the case to a dental laboratory equipped with a CAD/CAM system.

The laboratory scans the impression or model and proceeds with the digital designing and fabrication process of the restoration (Fig. 7.7).

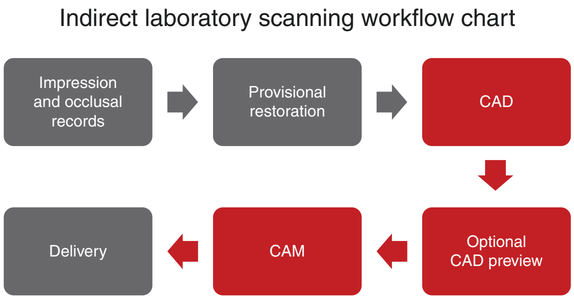

Fig. 7.7 Indirect laboratory scanning workflow chart

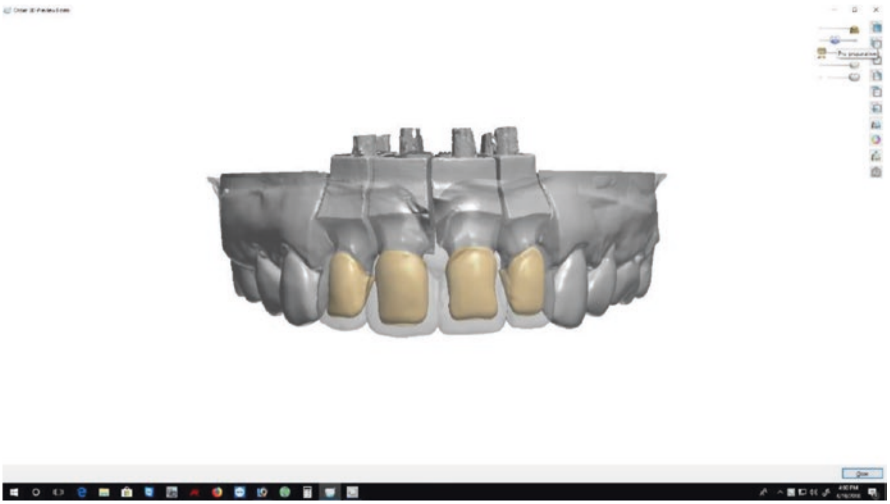

Fig. 7.8 Zirconia layered crown framework designs and full contour overlay views on teeth #7, 8, 9, 10

This method also allows adjustable articulation of the case using a facebow transfer. This is done by mounting the case in an adjustable articulator using standard manual procedures and then scan the case using a specific mounting jig and mounting base in the scanner. The laboratory can adjust the articulator setting to achieve dynamic occlusal movements in the CAD software (Figs. 7.8, 7.9, and 7.10); this is not an option with direct IOS methods. Once completed, the laboratory can share the treatment design with the dentist using 3D preview software.

Step-by-step procedure phases for indirect laboratory scanning method are below:

1. Acquisition phase
   (a) Conventional impression and occlusal records registration
   (b) Fill a laboratory prescription with the necessary case information
   (c) Fabrication of provisional restorations and cementation

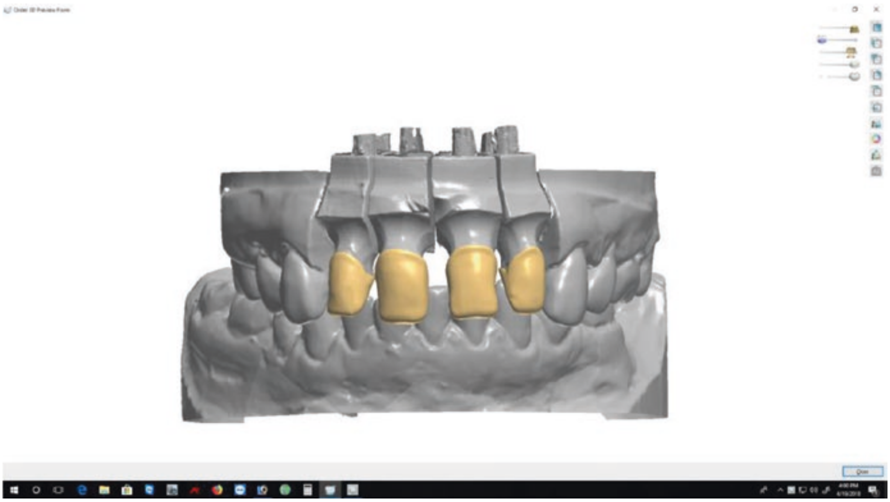

Fig. 7.9 Zirconia layered crown framework designs on teeth #7, 8, 9, 10

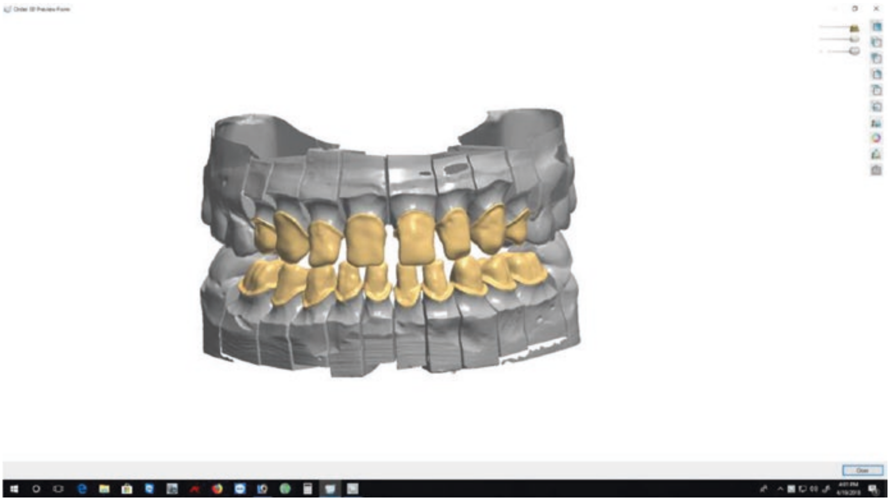

Fig. 7.10 Maxillary 8 units and mandibular 10 units crowns framework designs for reviewing

2. Dental laboratory phase
   (a) Scanning of the occlusal records and impression (or poured model)
   (b) Modeling and digital mounting
   (c) Designing the final restoration
   (d) 3D preview of the designed restoration

3. Production phase: Subtractive (milling) or additive (3D printer) production
    (a) Milling
        - Ceramics, polymer ceramics
        - Wax for casting or pressing
        - Polymer for provisional restorations, occlusal guard
    (b) 3D printing
        - Polymer for metal framework pattern, pressed ceramics patterns, dental model, provisional restorations, occlusal guard, and orthodontics appliance (Invisalign Align Technology, San Jose, CA, USA)
        - Porcelain fused metal framework (selective laser melting printer to print in a choice of metal)
        - Wax patterns for metal framework and pressed ceramics
4. Delivery to the dentist

Advantages of the indirect laboratory scanning method:

1. Dentist does not need to make any investment on CAD/CAM technology
2. No changes to the office organization and workflow
3. No additional trainings necessary for the CAD/CAM technology
4. No additional maintenances necessary for the CAD/CAM technology
5. It is possible to set up condylar information: can produce dynamic occlusal border movements
6. Final restoration comes back with a master cast and die, so the dentist can inspect the quality of restorations
7. The best total direct cost-effectiveness

Disadvantage of the indirect laboratory scanning method:

1. Need to fit and adjust impression trays
2. Provisional restorations are necessary
3. No reductions of chair time or number of office visits compared to conventional methods
4. Potential negative patient experiences with conventional impression procedures
5. Need for block out undercuts for the impression
6. Risk of removal of existing restorations or loose teeth by making an impression
7. Potential gagging reflex
8. Possible aspiration and/or swallowing of loose impression materials
9. Higher laboratory cost
10. Longer total chair time

The indirect laboratory scanning method case-selection criteria:

1. No particular limitations: same as the conventional method
2. No limitations to number of restored teeth

7.7 Clinical Case: In-Office CEREC Crown Workflow

The in-office CEREC process enables the practitioner to construct, produce, and insert ceramic restorations directly at the point of treatment (chairside) in a single appointment, rather than over multiple appointments with laboratory work in between. The duration of the appointment may vary due to the experience of the user, the ability to achieve good isolation during the scan, and the position of the tooth within the dental arch.

The following clinical case involves a patient presented with a failing crown on tooth #30 (Fig. 7.11a) with an existing root canal. CEREC AC Omnicam with CEREC SW v. 4.4.4 was utilized for this case. This example illustrates the full procedure from pre-scanning the patient prior to the procedure, to the final delivery of the restoration.

In the administration phase, the biocopy option was chosen. This option allows the practitioner to take a preoperative scan that provides the software with a baseline dental morphology that can be used later to design the digital crown based on the preexisting condition.

Pre-scan of the tooth to be restored was made alongside the adjacent teeth. Existing defective porcelain fused to metal on tooth #30 was then sectioned and removed due to an open margin. The tooth preparation was finalized, and gingival retraction cords were placed (Fig. 7.11b) before scanning the prepared tooth #30 along with the opposing arch and the buccal bite.

Once the virtual model was developed, the clinician marked the margins, selected the insertion axis, and evaluated the preparation by analyzing undercuts, surface roughness, clearance, degree of taper, and margins. The software provides a color scale to better understand the analysis of the preparations (Fig. 7.12a, b).

A proposed design can then be generated by the software. The user may use multiple tools to modify and optimize the crown. This includes tools to control the minimal thickness, position, shape, proximal, and occlusal contacts of the restoration.

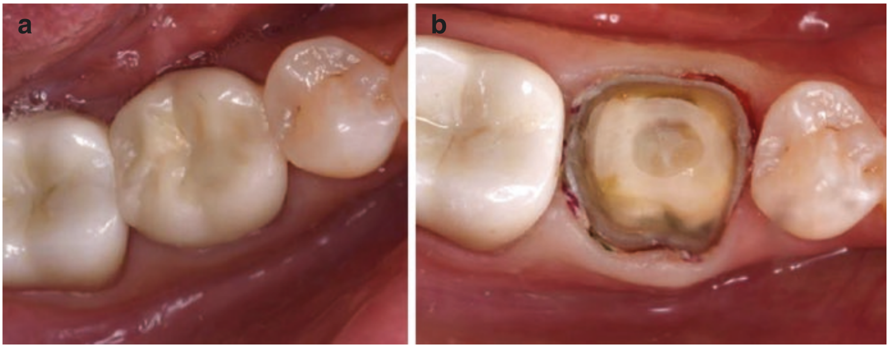

Fig. 7.11 (**a**) Existing crown on tooth #30; (**b**) tissue retraction after tooth preparation

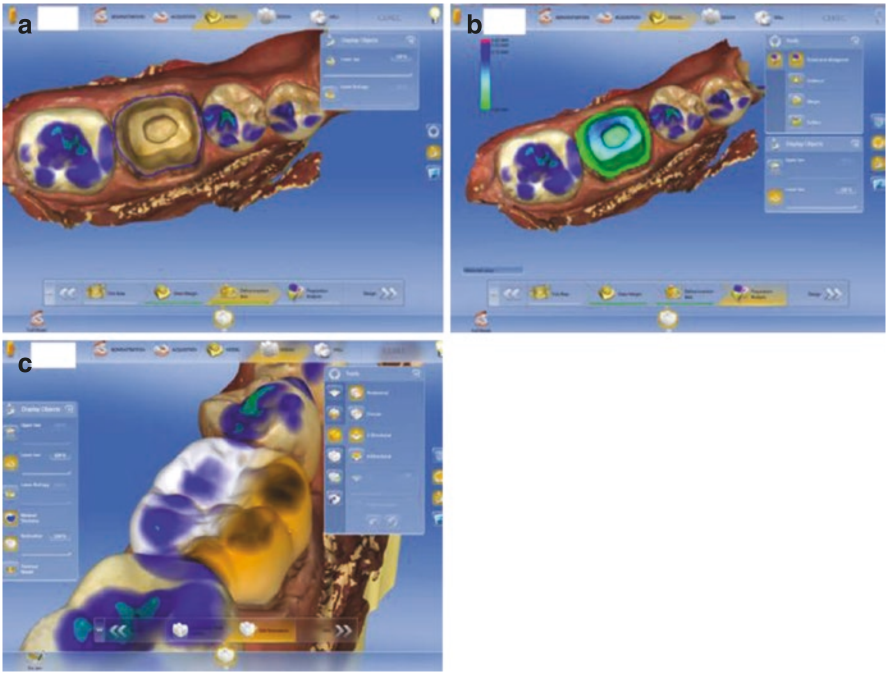

Fig. 7.12 (**a**) Margin placement; (**b**) prep-check; (**c**) designing phase

After the restoration is designed (Fig. 7.12c), the milling module of the software allows the clinician to position the crown within the milling block selected. This allows the crown to be rotated and place the sprue on the buccal or lingual wall to avoid interfering with the contact area (Fig. 7.13).

After the milling process is completed, the crown is rinsed and washed with soap and water, and the sprue is removed using a fine diamond with a high speed under copious water irrigation to avoid craze lines in the ceramic.

The crown is then tried intraorally in the green (purple) stage to verify the fit and contours (Fig. 7.14a, b). The ceramic (IPS e.max) is fairly brittle during this stage; hence heavy occlusal forces should be avoided at this point. Adjustments to contacts and occlusion should always be completed using irrigation or slow speed porcelain wheels designed for this purpose. The crown is then cleaned with Ivoclean to remove any phosphate contamination.

7.7.1 Crystallization and Characterization

The milled IPS e.max crown was crystalized using the Programat CS2 Porcelain oven (Ivoclar Vivadent Inc., Amherst, NY, USA) with the speed crystallization program. IPS Empress Universal Stains and IPS e.max CAD Crystall Glaze Spray (Ivoclar Vivadent Inc., Amherst, NY, USA) were applied to the restoration and then

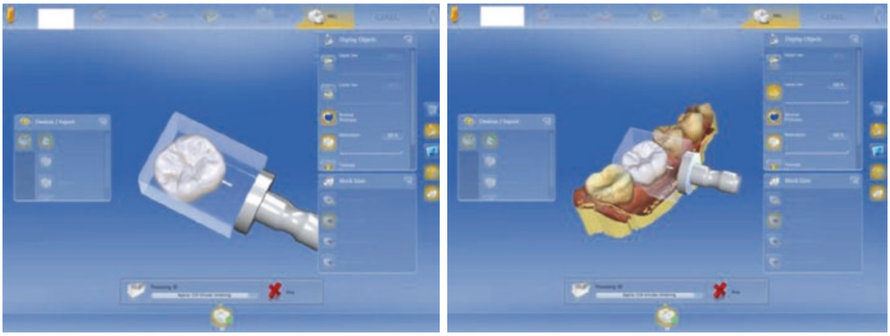

Fig. 7.13 Sprue positioning

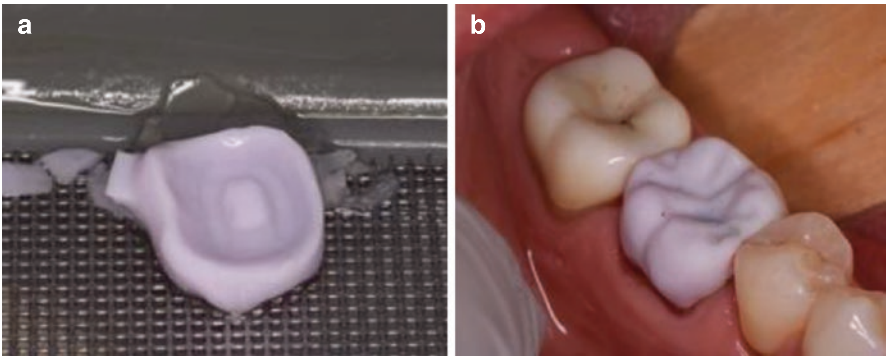

Fig. 7.14 (**a**) Milled e Max CAD crown; (**b**) clinical try in

placed on a crystallization pin and tray using the Object Fix (Ivoclar Vivadent Inc., Amherst, NY, USA). Once the crystallization process was completed, the crown was removed from the pin and the excess Object Fix, and it was steamed and cleaned.

In preparation for cementation, the intaglio surface of the restoration was etched with an aqueous solution of 5% hydrofluoric acid for 60 s and then rinsed and dried before applying a silane coupling agent (Monobond Plus, Ivoclar Vivadent Inc., Amherst, NY, USA) that was left to air-dry for 60 s. The prepared tooth was etched with 32% phosphoric acid (Scotchbond™ Universal Etchant, 3M, St. Paul, MN, USA) for 15 s and rinsed and dried for 30 s before applying a primer (Multilink Primer A+B, Ivoclar Vivadent Inc., Amherst, NY, USA) that was air-dried for 10 s and cured, following manufacturer's recommendations.

Ivoclar Multilink Automix Dual Cure resin cement (Ivoclar Vivadent Inc., Amherst, NY, USA) was used for the bonding of this restoration. The cement was applied to the crown and placed on the tooth; excess cement was removed. The cement was then light cured while using the Liquid Strip Glycerin barrier (Ivoclar Vivadent Inc., Amherst, NY, USA) to avoid oxygen exposure and formation of inhibition layer. Final cemented restoration is shown in Fig. 7.15a, b.

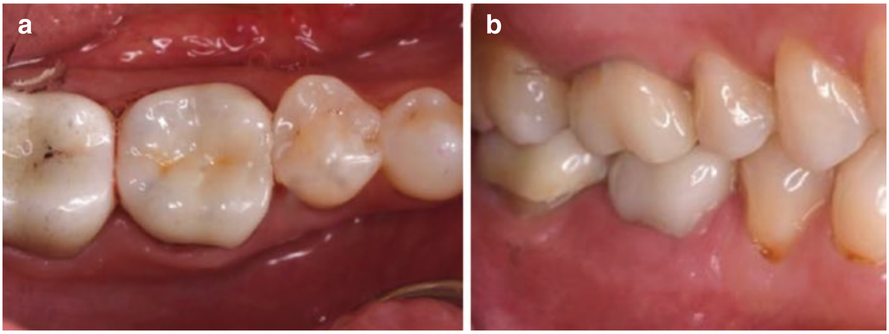

Fig. 7.15 (**a**) Occlusal view of final restoration on tooth #30; (**b**) lateral view of the final restoration on tooth #30

7.8 Conclusions

The concept of CAD/CAM started back in the early 1980s, and the technology has not looked back. The in-office CAD/CAM system is very popular in today's dental practice especially many selections of materials and very well-established user-friendly office software for single and small numbers of crowns. Today the focus has shifted to development and improvement of CAD/CAM systems for in-office use, such as the CEREC system and development of laboratory CAD/CAM systems compatible with dental laboratory scanners, milling machines (CNC machine), and software. New software and hardware continue to be developed, creating new workflows. Currently, many laboratory CAD software can design almost all aspects of crown and FDP designs including implant restorations.

3D printing has evolved from being a time-consuming and less accurate process to being time efficient with high accuracy, high throughput, and a smooth surface finish. As the technology continues to grow, so have its applications. 3D printers can deliver well-fitting crowns and orthodontic models. Once considered strictly a laboratory procedure due to cost and footprint of the machine, today desktop printers have emerged, providing dentists the opportunity to learn and integrate the newest technology into their practice.

Dental materials are one of the fastest-growing areas of dental research and development from ceramics to zirconia and even provisional materials such as PMMA give clinicians and patients many options for different indications and uses.

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CAD-CAM Fixed Dental Prostheses (FDPs)

8

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Abstract

Fixed dental prostheses are a common and predictable option for the replacement of missing teeth. These restorations require the preparation of the abutment teeth in order to allow adequate space for the materials used to fabricate the prosthesis. Once the preparation is completed, the three-dimensional information relative to the oral hard and soft tissues is captured through a digital or an analog impression to allow the design and fabrication of the prosthesis using CAD-CAM technology. Clinical evidence has shown the predictable long-term survival of fixed dental prostheses, which varies depending on the length of the edentulous span, the abutment status, and prosthetic materials.

8.1 Introduction

In the past decades, the prevalence of complete edentulism has decreased mainly due to socioeconomic factors, better recall programs, improved oral hygiene, and preventive approaches. This resulted in a shift toward more partial edentulism that can be treated with fixed tooth or implant-supported reconstructions [1, 2].

Traditionally, metal-based fixed dental prostheses, fully or partially veneered with feldspathic porcelain, have been the gold standard for decades. However, the

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advent of CAD-CAM technology and new prosthetic materials with adequate esthetics and mechanical properties has led to the addition of monolithic restorations to the clinician's treatment planning options [1]. In this chapter we explain the different steps and procedures involved in the fabrication of an FDP using digital technologies.

8.2 Clinical Process

8.2.1 Tooth Preparation

Tooth preparation for CAD-CAM fixed dental prosthesis is based on principles designed to facilitate the fabrication process of the prosthesis (i.e., impression making, interim prosthesis fabrication, die and cast fabrication (digital or analog), and waxing/designing) and ensure its long-term success [3–5].

General guidelines of tooth preparation:

1. Total occlusal convergence (TOC), which is the angle formed by two opposing axial walls of the abutment teeth, should range between 10° and 20° (Fig. 8.1) [3, 4]. Studies assessing preparation TOC in daily practice reported mean values between 18.2° and 23.9° [5].
2. The occlusal-gingival height of the preparation should be at least 3 mm for incisors and premolars and 4 mm for molars [3, 4]. This value should take into consideration the TOC and width of the preparation. The greater the buccolingual dimension of a preparation, the lower its resistance to dislodgment by lateral axial forces for a given TOC and taper; thus a height to base ratio of 0.4 will ensure proper resistance (Fig. 8.2) [5].
3. Maintaining the morphology of the line angle between buccal or lingual and proximal walls will increase the resistance form. The resistance form is defined as the features of a tooth preparation that enhance the stability of a restoration and resist dislodgment along an axis other than the path of placement [6].

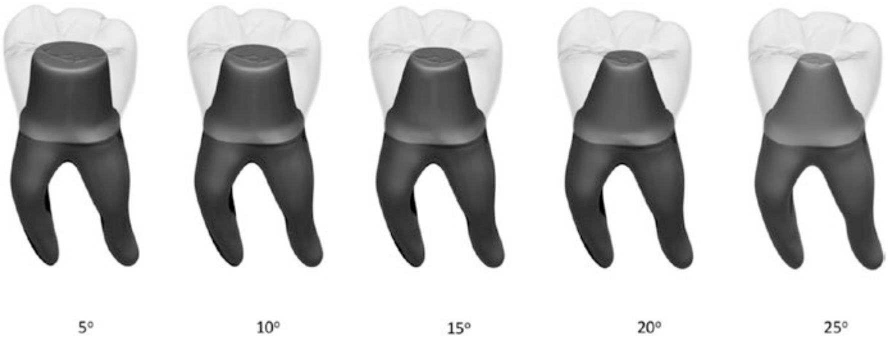

Fig. 8.1 Various total occlusal convergence representations

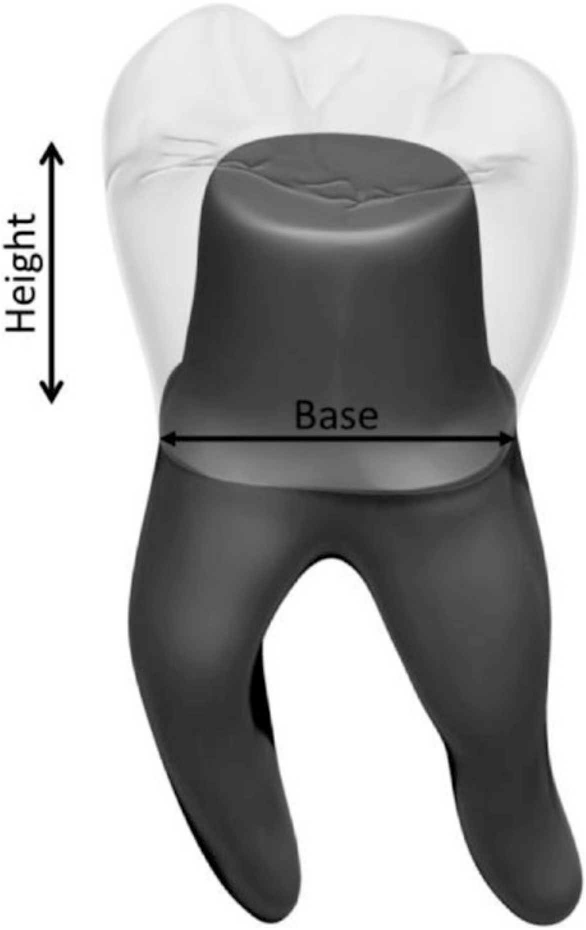

Fig. 8.2 The height-to-base ratio of a preparation will affect the resistance form for a given TOC

4. Adding proximal grooves/boxes to molar tooth preparation is recommended whenever the occlusal-gingival height is inadequate. Also, in situations where the prepared tooth lacks proximal morphology (round horizontal cross section of the tooth), it is advantageous to add grooves/boxes in order to increase resistance form (Fig. 8.3) [3, 4].
5. Place supra-gingival finish line margins whenever esthetics and remaining tooth structure permit. If a subgingival finish line is required, care should be used to avoid or minimize trauma to the gingival margin.
6. Line angles should be rounded on preparations for all-ceramic prostheses to reduce stress in the prosthetic material (Figs. 8.4 and 8.5). It is also recommended to round the line angles for metal-based restorations to facilitate the laboratory process and seating of the prosthesis. Furthermore, finishing the preparation margins with either extra fine/fine diamond burs reduces surface or

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

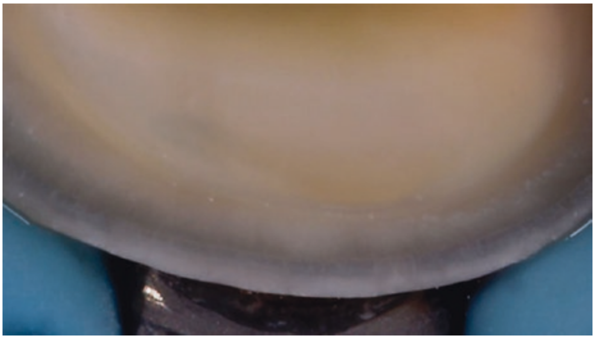

Fig. 8.6 A close-up showing a marginal finish line prepared with extra fine/fine diamond burs

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.

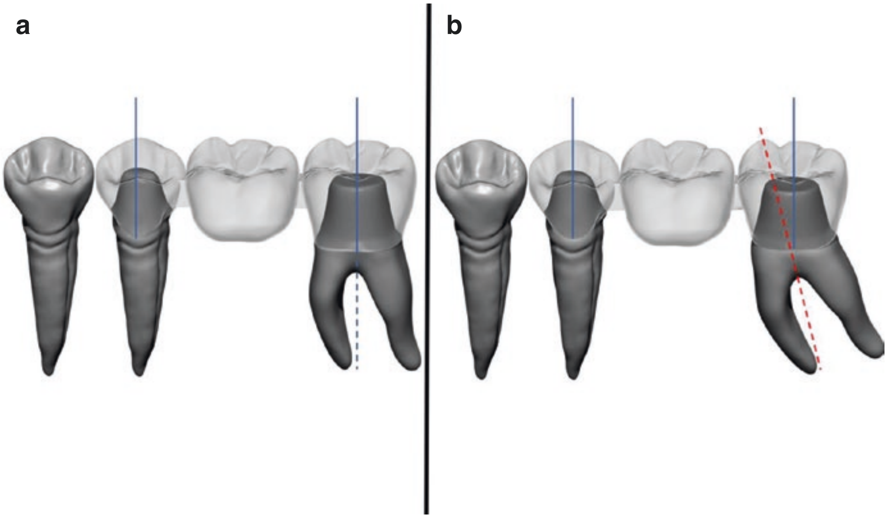

Fig. 8.7 The preparation design on the abutment teeth should create a single path of insertion. (**a**) The roots of both abutment teeth are parallel. (**b**) The preparation design on the molar compensates the mesially tipped tooth in order to respect the path of insertion

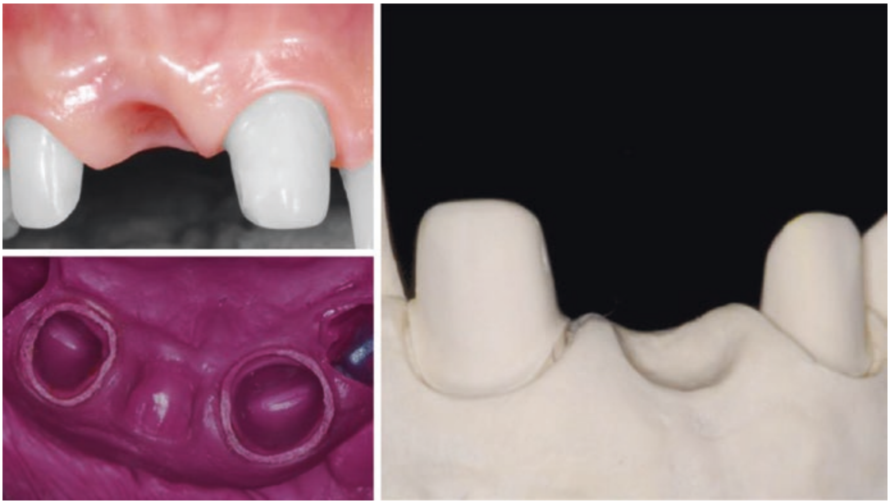

Fig. 8.8 Analog impression and master cast

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 techniques with intraoral scanners (IOSs) are gaining popularity over the traditional impression methods. Conventional impressions and stone casts can also be digitized using laboratory scanners that enable subsequent digital manufacturing using either additive or subtractive techniques (Fig. 8.9). Conversely, in fully digital CAD-CAM fixed prosthodontic workflows, intraoral data acquisition is done with an IOS, eliminating the need for conventional impressions altogether (Fig. 8.10).

In regards to the accuracy of fit of prostheses fabricated after digital impressions, a recent meta-analysis reported that the digital impression technique provided better marginal and internal fit of fixed restorations than conventional techniques [8]. On the other hand, Örtorp et al. compared the fit of cobalt-chromium three-unit FDPs

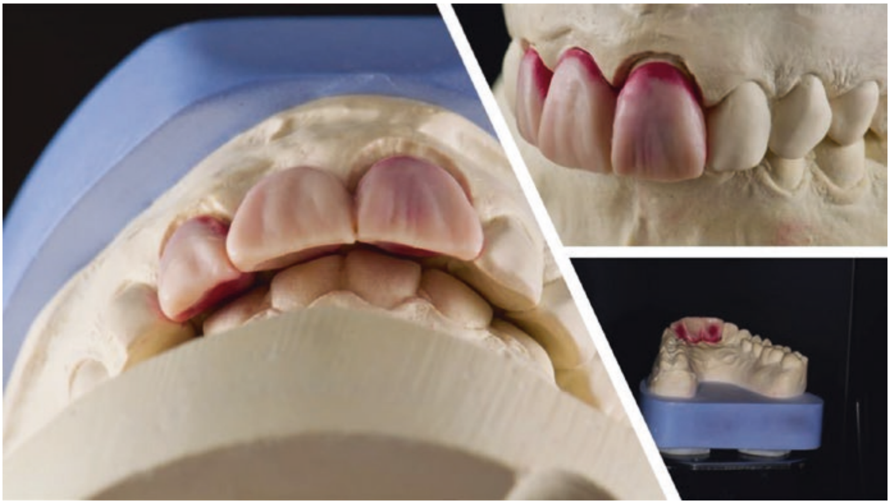

Fig. 8.9 Fixed dental prosthesis conventional wax-up scanned for computer-assisted manufacturing

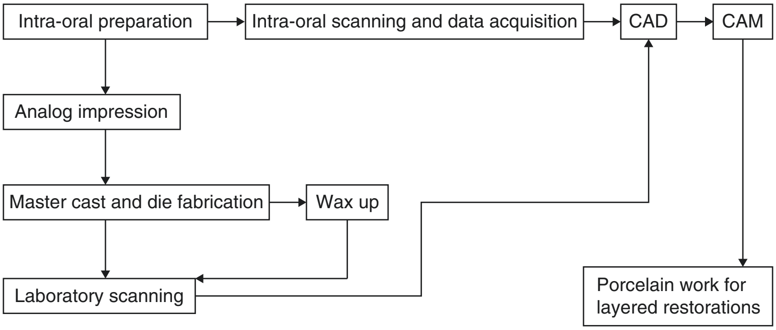

Fig. 8.10 Digital workflow for fixed dental prosthesis (FDP) fabrication

fabricated with four different techniques: conventional lost-wax method, milled wax (with subtractive milling unit) with lost-wax method, milled Co-Cr (with subtractive milling unit), and direct laser metal sintering (with additive manufacturing unit). In this in vitro study, best fit was observed with direct laser metal sintering followed by milled wax with lost-wax method, conventional lost-wax method, and milled Co-Cr [9]. These improvements and rapid changes in the fabrication techniques will continue to make the newer technologies more cost effective and more precise. Conversely this will command flexibility from clinicians and laboratory technicians and will require adjustments of clinical and laboratory steps in order to refine and perfect the process.

8.3 Conventional Impression Materials

Notwithstanding the emergence of CAD-CAM technology and the accessibility of IOSs, the reproduction of the intraoral preparation is currently predominantly done with conventional impression materials. Polyvinylsiloxane and polyether are the most commonly used impression materials.

Polyvinylsiloxane is very popular in dental practices due to its favorable handling properties, good patient acceptance, and advantageous physical properties. The set material is less rigid than polyether but stiffer than polysulfide [3]. Polyvinylsiloxanes deform at much slower rates and tear at permanent deformation values lower than other elastomeric materials. Polyvinylsiloxanes are reported to be the most ideal elastic impression materials because they exhibit better elastic recovery and less permanent deformation than the other elastomers. They can absorb over three times more energy up to the point of permanent deformation than other elastomers, and if elongated to over 100% (strain at tear), they rebound to only 0.6% permanent deformation [10].

Polyether impression material exhibits accuracy similar or somewhat superior to that of other elastomers [3]. With excellent dimensional stability, polyethers are accurate even when poured 1 week after setting. Unlike polyvinylsiloxanes, polyethers are hydrophilic which makes their storage in a moist environment contraindicated. The material is stiff, and undercuts must be blocked out during impression making to ensure ease of removal and avoid unwanted tear of the material. Its resistance to tearing upon removal is roughly equal to that of silicone and less than that of polysulfide. It is somewhat brittle [11].

8.4 Intraoral and Laboratory Scanners

A dental scanner is a data-collection instrument that measures oral hard and soft structures in three dimensions and converts the images into digital data. There are two basic digitization methods [12]: optical scanners and tactile mechanical scanners.

8.4.1 Mechanical Scanners

Mechanical scanners use a ball, which, through a series of micro-palpations, measures the three-dimensional structures line by line. *Mechanical or tactile scanners can be used to scan cast models of partially edentulous patients; however even though they are very precise, they are very slow and they cannot be used intraorally*. Mechanical scanners were used in the 2000s, but their popularity dropped with the rise of laboratory and intraoral optical scanners [13].

8.4.2 Optical Scanners

Optical scanners (Figs. 8.11 and 8.12) *can be based on various technologies such as triangulation, parallel confocal, and active wavefront sampling technologies. Triangulation* scanner scans three-dimensional structures using a process, whereby the light source and the collecting unit (camera) are at an angle to one another. Based on this angle, the computer calculates the digital data for images formed on the collecting unit [14]. Some systems require titanium dioxide powder in order to reflect light homogeneously from the surface of the object so that the line profiles projected can be captured by the camera with sufficient contrast [15]. Triangulation optical scanners fall into four categories:

- Projection of a single beam (i.e., laser pointer)
- Projection of a line of beams (i.e., laser line)
- Projection of a multitude of beam lines (frame)
- Projection of more complex beams (Moiré pattern)

Fig. 8.11 Example of laboratory scanner scanning a master cast

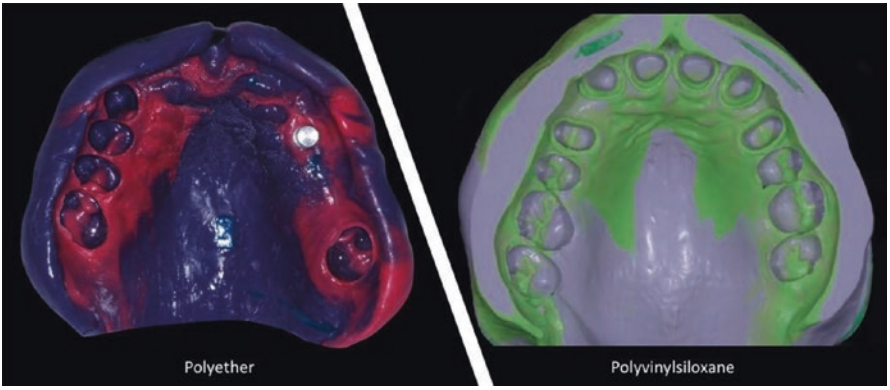

Fig. 8.12 Examples of final impressions taken with conventional materials

Parallel confocal imaging scanners use a laser beam to sweep the surface of the oral cavity. Parallel confocal imaging allows for fast data acquisition, and a full-arch scan can be performed in under a minute.

Active wavefront sampling is based on the 3D surface imaging technique, known as depth-from-defocus measurements [15]. This technique provides a reconstitution model of instant video sequences in real time [15].

8.5 Intraoral Scanners and the Full Digital Workflow

Intraoral scanners (IOSs) are essential for the application of a fully digital workflow. During the digital workflow, intraoral images along with occlusal registrations are captured with an IOS, and then the STL data are imported into CAD software for the restorative design including marginal description, thickness of die spacer, restorative contours, and proximal and occlusal contacts. The CAD data are forwarded to CAM facility in-office or in-laboratory, and the restorations are fabricated directly with subtractive or additive technology by the milling or printing machine [12]. Many factors can affect the outcome in the digital workflow, including the use of different IOSs and use of physical working casts and quadrant or complete-arch scans. Therefore, clinicians should choose an adequate IOS and scanning strategy for a specific clinical situation. It is worth mentioning that nowadays most intraoral scanners (IOSs) do not require the use of powder for data acquisition, and the only system that may still require powder are those based on active wavefront sampling technology.

Clinician's experience is a key variable that may affect successful treatment outcomes using either digital or conventional workflow. It has been reported that when comparing efficiency between dental students and clinicians, it was found that 76% of the students preferred digital impressions, while 48% of the dentists were favoring conventional impressions [12]. Therefore, besides the clinical situation and scanning equipment, the operators' experience is also one of the factors affecting the scanning accuracy and operators' perception.

8.6 Design

Digital technology is gaining popularity, and its applications translate into the so-called digital workflow. This workflow includes digital three-dimensional (3D) imaging, digital planning and computer-guided implant placement, digital impressions with intraoral scanner (IOS) systems, and CAD-CAM prosthodontics [16].

Digital workflows are available in fixed prosthodontics from impression to digital design and fabrication of the definitive prosthesis. A time-efficient result with improved patient satisfaction can be obtained by the digital workflow to fabricate tooth- or implant-supported SCs. In summary, clinical benefits of digital workflow include:

1. Reduced laboratory and clinical treatment time
2. Simplified laboratory production to reduce the possibility of human errors
3. Accurate marginal and internal fit
4. Electronic storage and transfer of the digital files
5. Expensive manpower resources reduced
6. Higher patients' preference with reduced discomfort generally caused by conventional impressions
7. Potential for in-office milling of the restorations

There are also some limitations, including the additional cost for purchasing an IOS and related equipment, the learning curve for the new technology, and the need of frequent updates [16–18]. In regard to the accuracy of fit of the prostheses fabricated after digital impressions, a recent meta-analysis reported that digital impressions provided better marginal and internal fit of fixed restorations than conventional impressions [8]. Also, studies have reported that irrespective of the CAD-CAM system used, the overall laboratory time for the dental technician is significantly reduced by the digital workflow compared to the conventional workflow (Fig. 8.13) [17, 18].

Each company provides specific software with its system. The software is used to design frameworks for crowns and fixed dental prostheses, as well as fabricate crowns, inlays, veneers, metal frames for removable partial prostheses, bars for implant-supported restorations, and many other types of prostheses.

The software currently on the market are constantly evolving. Digital data are saved in several different formats, although the basic format is STL. These software have many features that make the CAD processes generally easy to learn and efficient in terms of production. Options such as tooth anatomy library, pre-calibrated minimal safe thickness (which varies based on the material being used), automatic cement spacer application (which can be controlled and modified precisely), interproximal and occlusal contact intensity adjustment, preparation margin identification tools, and other features facilitate the design and fabrication processes of the prosthesis (Fig. 8.14).

When designing fixed dental prostheses, the digital workflow allows easy and fast communication between the dental laboratory technologist and the clinician. Once the designing process is completed, the technician can forward the plan to the

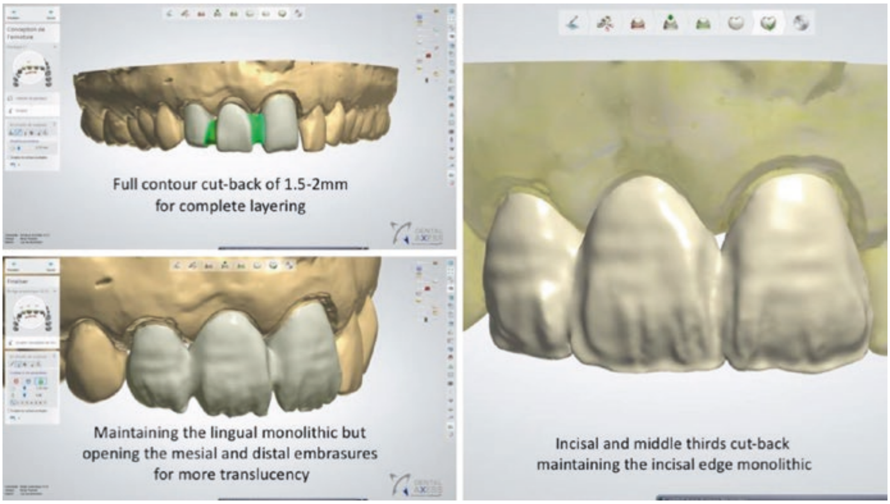

Fig. 8.13 Example of different FDP framework designs done using the digital workflow. The time required to achieve this is considerably less than with conventional manual techniques

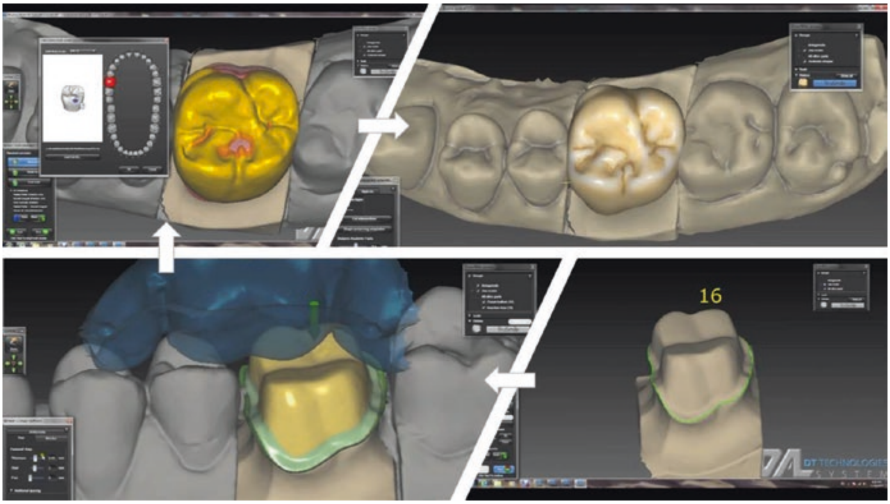

Fig. 8.14 Example of different steps during the designing process

dentist for review with a 3D representation file (Fig. 8.15). This allows for effective communication and the ability to easily correct the design before initiating the fabrication process.

While it has been shown that the digital workflow leads to time efficiency and clinically satisfactory results for single-tooth crowns or implants, further studies are necessary to elucidate its benefits for the fabrication of definitive short- and long-span FDPs, while a financial analysis is also warranted.

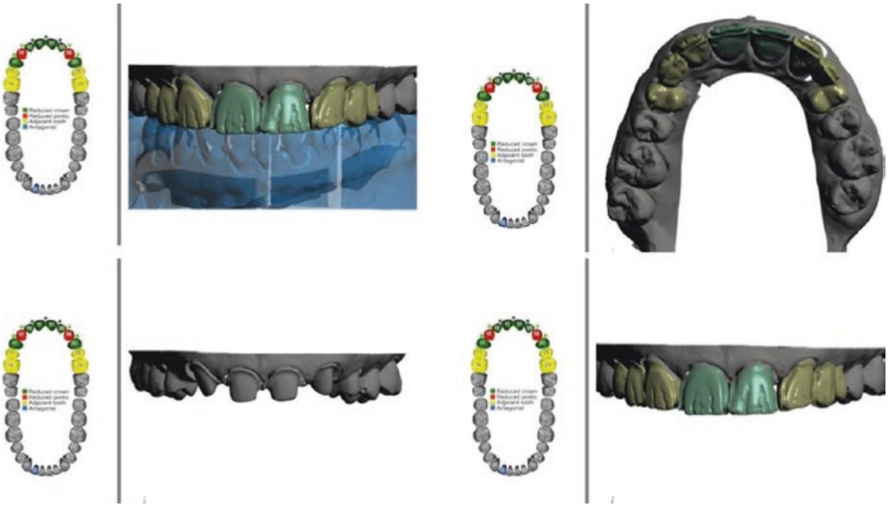

Fig. 8.15 3D Representation of the designed restorations allowing communication between the technician and the clinician

8.7 Materials and Fabrication Techniques

With the advancement of dental technology, dentists today are confronted with many different options when it comes to choosing a material for fixed dental prostheses (FDPs). CAD-CAM technology has been mainly used to fabricate modern ceramics; nonetheless a wide array of materials ranged from monolithic to multilayered systems can be used.

Monolithic methods include:

1. Full metal restorations
2. Full contour zirconia restorations
3. Full contour lithium disilicate restorations (i.e., e.max)

Multilayered methods include:

1. Metal-ceramic restorations
2. Zirconia-ceramic restorations
3. Layered lithium disilicate restorations (i.e., e.max)
4. Alumina-based restorations (i.e., In-Ceram, Procera)

The computer-assisted design is completed first followed by the computer-assisted manufacturing (CAM) process. Fabrication of fixed dental prostheses can be achieved through either subtractive or additive manufacturing. Milling represents the current standard for prosthesis fabrication [14]. Three-dimensional (3D) printing achieves more complex geometries but may be less accurate than milling [14].

When considering subtractive manufacturing, it is important to consider the complexity of the design in order to choose the appropriate milling unit. For complex designs four or more axis milling units should be considered. With subtractive manufacturing technology, the following materials can be chosen to fabricate fixed dental prostheses:

- Lithium disilicate
- Zirconium dioxide
- Aluminum dioxide
- Metal (titanium alloy, chromium-cobalt, gold alloy)

With additive manufacturing technology, the following materials can be chosen:

- Metal (titanium alloy, chromium-cobalt, gold alloy)

8.8 Clinical Evidence

The most common systems in the market today are metal-ceramic, zirconia-ceramic, full contour or layered lithium disilicate, and more recently monolithic zirconia restorations. Unfortunately, no system is adequate for every application, which underlines the importance of clinical judgment in material selection.

8.8.1 Survival Rates

The traditional gold standard material for FDPs is porcelain fused to metal with long-term survival rates ranging from 94.6% at year 5 to 70.8% at year 20 [19].

The number of studies published on zirconia-ceramic FDPs is limited because of the relatively short time zirconia has been introduced to dentistry. These studies have follow-up times ranging from 2 to 10 years and small sample sizes. Early 10-year follow-up studies reported a survival rate of zirconia-ceramic FDPs of 91.3% (95% CI, 69.5–97.8), compared to a 100% survival rate for metal-ceramic FDPs [20]. A more recent meta-analysis reported an estimated 5-year survival rate of densely sintered zirconia FDPs of 90.4% (95% CI, 84.8–94.0%), while the survival rate of metal-ceramic FDPs was 94.4% (95% CI, 91.2–96.5%) [1]. The difference was not statistically significant, indicating similar survival rates with both materials. It has to be highlighted that this meta-analysis included studies up to 2013, and several studies have been published since indicating further improvements in the survival rates of zirconia FDPs [21].

For lithium disilicate (LDS) fixed dental prostheses, Makarouna et al. found survival rates of 63% for 6 years [22], while Teichmann et al. reported 5- and 10-year survival rates for LDS FDPs of 63.0% and 51.9%, respectively [23]. Also, a systematic review by Pieger et al. showed a 2-year cumulative survival rate of 83.3% and a

5-year cumulative survival rate of 78.1% [24]. They concluded that the evidence for short-term survival is fair, while the evidence for medium-term survival is not promising [24]. However, in a more recent study, a 9% failure rate for LDS FDPs after a mean observation period of up to 5 years was reported [25]. Moreover, monolithic lithium disilicate (no layering ceramic) has shown even better survival rates, as high as 93% at 8 years [26].

8.8.2 Long-Span vs Short-Span FDPs

When we take into consideration the length of the prosthesis span, clinical evidence has shown that the survival of short- and long-span metal-ceramic FDPs over a 20-year period was favorable. The overall survival estimation for short-span FDPs was statistically significantly better than for long-span FDPs at year 20. The use of abutments with root canal treatments can significantly undermine the survival of fixed prosthetic restorations specially those with four or more units [19].

The survival rates for long-span zirconia FDPs have been found to be approximately 82% at 5 years [27]. Additionally, it was shown that long-span FDPs in the molar region are at greater risk of failure than FDPs in the anterior region. In summary, chipping is a major problem with these restorations, and the length and location of the FDP affect the incidence of complications [27].

8.8.3 Anterior vs Posterior FDPs

The location of the fixed dental prosthesis may also affect the clinical outcomes. Three-unit posterior metal-ceramic and all-ceramic FDPs showed similar high survival rates and acceptable success rates after 3 years of function. Ceramic veneer chipping fracture was the most frequent complication for both types of restorations [28]. Similar outcomes were reported in another randomized clinical trial by Sailer et al. [29]. A prospective study showed that anterior and posterior three-unit FDPs made out of a lithium disilicate glass-ceramic had a cumulative survival rate of 93% after 8 years. The type of cementation (conventionally versus adhesively) showed no significant differences in the failure or complication rates, respectively [26]. However, another study has shown that the majority of failures for lithium disilicate FDPs were mainly reported in the posterior region rather than in the anterior [24].

8.8.4 Complications

The most common technical complication with zirconia FDPs is chipping of the veneering ceramic. Recent studies have shown that this may be due to a difference in the coefficient of thermal expansion (CTE) between the layering ceramic and the zirconia core or the too rapid cooling of the restoration when removing it from the porcelain furnace. Development of veneering ceramic with a CTE similar to zirconia and better understanding of proper cooling rates is needed. Anatomically designed frameworks also lower the proportion of chipping [20]. Monolithic design without cutback or with mild cutback in non-functional load bearing surfaces has significantly reduced/eliminated the risk of chipping failures. A recent randomized trial has also shown that using pressed zirconia instead of layered zirconia can also reduce the risk of chipping in three-unit FDPs [30]. Nonetheless, a previous systematic review has shown that minor chipping of the veneering ceramic and occlusal wear of zirconia-ceramic FDPs is comparable to that observed with metal-ceramic FDPs [20].

Lithium disilicate FDPs have been reported in even fewer studies, so conclusions on their complications are more difficult to be drawn. In an earlier study, it was found that as much as 20% of layered lithium disilicate FDPs would present framework fractures in the connector [22]. On the other hand, monolithic lithium disilicate (no layering ceramic) has a much higher survival rate of up to 93% at 8 years [26]. Such survival rate of monolithic lithium disilicate FDPs was achieved following a set of specific design guidelines:

1. An occlusal ceramic thickness of at least of 1.5 mm on the abutments
2. Proximal connectors for posterior teeth at least 4 mm in height and 4 mm in width (16 mm^2)
3. Proximal connectors for anterior teeth at least 4 mm in height and 3 mm in width (12 mm^2)

8.8.5 Material Selection

In general, the selection for the correct material would be based in part on the following factors:

- Location of missing tooth: Occlusal forces are higher in the posterior area, especially in the second molar area.
- Interocclusal space: All ceramic materials require larger connector size to avoid catastrophic failures; therefore they necessitate larger interocclusal space.
- Parafunctional habits: Patients presenting with obvious signs of bruxism and/or clenching should not receive all-ceramic fixed dental prostheses.
- Esthetic demands: All ceramic materials offer more esthetic restorations.
- Allergies: Patients who present with certain allergies to metal might benefit from all ceramic materials.

It is imperative to decide which material to use based on clinical factors related to each patient. This decision needs to be made during the planning phase because each material behaves differently and might require specific preparation design that will enhance and ensure a predictable long-term survival.

8.9 Summary

CAD-CAM technology has improved the fabrication process of tooth-supported fixed dental prostheses, in terms of accuracy of fit, speed, cost of fabrication, and efficiency. When coupled with other digital technology tools such as IOSs, a complete digital workflow may be attainable for additional cost reduction, improvement of time efficiency, and treatment overall.

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Digital Implant Surgery

9

Arthur Rodriguez Gonzalez Cortes, Otavio Henrique Pinhata Baptista, and Nataly Rabelo Mina Zambrana

Abstract

The digital workflow for surgical rehabilitation with dental implants can help prevent complications, achieve more predictable outcomes, and render implant surgery more accessible for dentists and patients alike. The digital workflow for implant surgery consists of three steps, image acquisition, virtual planning, and implant placement using surgical guides. Digital images acquired by cone beam computerized tomography (CBCT) and intraoral scanning can help recreate the patient's condition in the computer. This information is then used to plan for optimized implant placement. The digital plan is then executed clinically with the aid of a digital surgical guide, a template that help the clinician place the implants at the exact site as planned in the computer. This chapter explains in details how implant surgery is planned and executed using a digital workflow.

9.1 Introduction

The advent of dental implant therapy was one of the most important advancements in the field of dentistry in the last 40 years. Since its conception, dental implant therapy has become one of the most predictable ways to replace missing

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teeth. However, as a result of its increased popularity, the number of problems related to lack of proper three-dimensional positioning of the implants installed by professionals has also largely increased. To manage this issue, implant dentistry has recently seen an emergence of the digital workflow for virtual surgical planning. This includes digital impressions and models, the advent of CAD/CAM (computer-assisted design and computer-assisted manufacturing) technology, and imaging software to diagnose and plan surgeries for different dental implant systems. As a result of these developments, dental implant surgeries have become more predictable, safer, faster, and more comfortable for the patients. Digital implant impressions and image-guided surgery have revolutionized implant placement surgeries and bone graft procedures and have led to the possibility of customizing prosthetic abutments and restorations by using specific digital design computer software.

9.2 Radiographic Analysis

9.2.1 The Advent of CBCT for Dental Implant Planning

In the early days, radiographic images were used solely to perform linear measurements of the implant site and to identify vital anatomical structures that need to be avoided during implant site drilling such as the incisive canal, maxillary sinus and nasal floor in the maxillae, as well as the mandibular canal, the mental foramina, and the fossa, in the mandible. A safety margin of 1–2 mm should be left between the implant hole and these structures.

Upon its introduction to implant dentistry, the CBCT was initially used to generate images, which were printed on film or paper, for chairside assessment. Such method involved the use of schematic templates prepared by oral and maxillofacial radiologists, to show surgeons optimal implant positions on cross-sectional images. Nowadays, such templates are also available as 2D digital images (Fig. 9.1). However, this type of images does not allow navigation and true 3D analysis of entire volumes.

Basically, the CBCT scan should be used to determine the three-dimensional location of the abovementioned anatomical structures, as well as the amount of alveolar bone available. For this purpose, two linear measurements are required to be displayed in the parasagittal images (i.e., cross-sectional cuts along the alveolar ridge) for each edentulous site planned to be rehabilitated with dental implants. Such measurements are (a) the alveolar ridge height, extending from the alveolar crest to the closest anatomical structure to be avoided, used to determine implant length, and (b) the alveolar ridge buccal-lingual width, which should be done in the level planned to insert the implant body (i.e., the level where the implant platform should start). Such measurement will be used in the choice of the most appropriate diameter of the implant, considering that a minimum buccal plate width should always be left in order to prevent buccal bone resorption after implant placement.

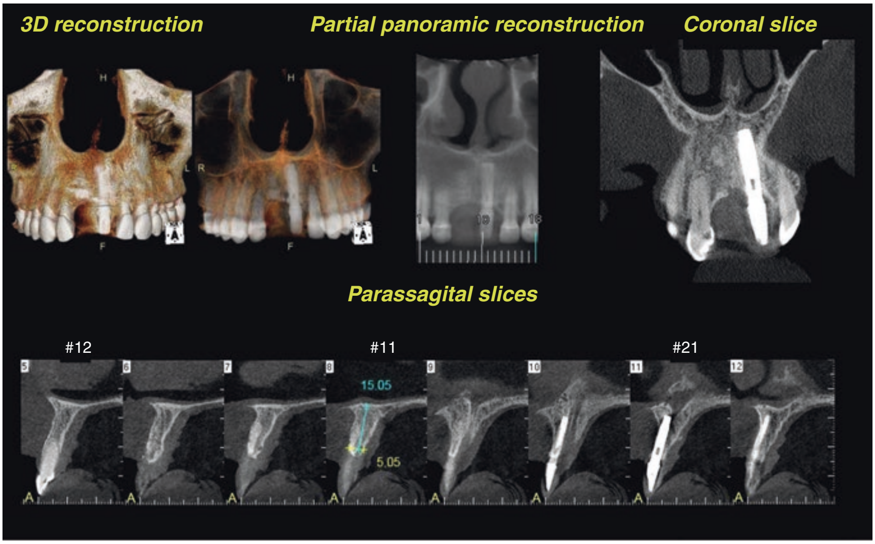


Fig. 9.1 Example of a CBCT 2D template used for implant planning

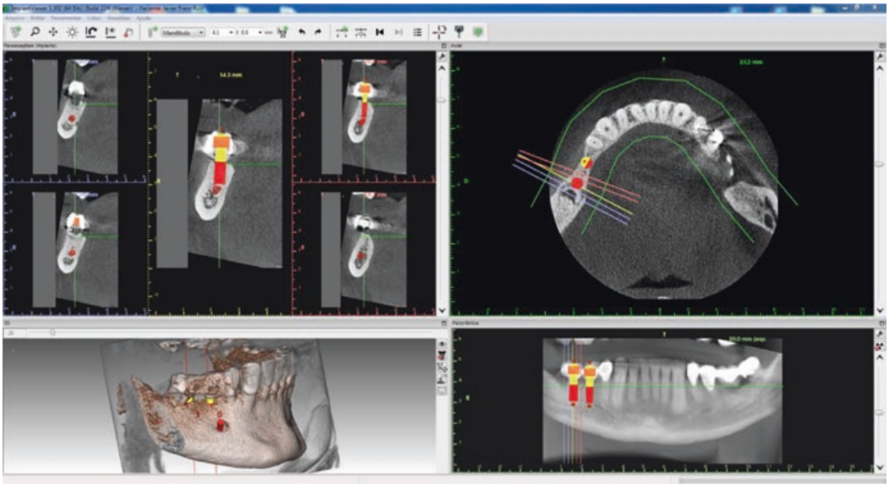


Fig. 9.2 Virtual implant planning using CBCT data only (ImplantViewer software, Anne Solutions, Sao Paulo, Brazil)

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

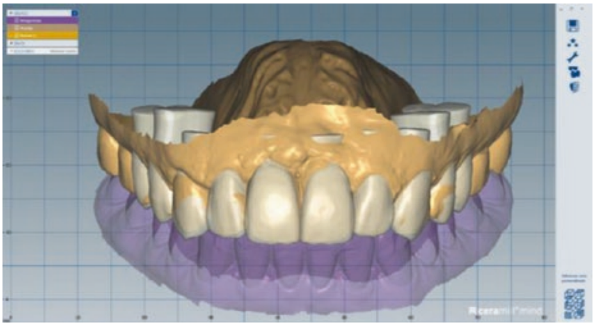


Fig. 9.3 Digital diagnostic wax-up of the case depicted in Fig. 9.1 (Exocad software, DentalCAD, Darmstadt, Germany)

a series of cross-sectional images of the alveolar ridge (named parasagittal images). Although some implant planning software can read original DICOM images, most of them require conversion of the DICOM file into a specific file extension. Images from each plane are shown in different windows containing axes that indicate the location of the current images on the other planes. With such imaging setup, the surgeon is able to perform an entire 3D assessment of the implant site. Implant planning software usually include tools for virtual implant placement in the planned site within the alveolar bone. The 3D position of the implant can then be optimized and refined in both multiplanar images and 3D reconstructed models.

Implant position should always be determined according to a prosthetic rehabilitation plan developed beforehand. Currently, this can be done with a conventional workflow (i.e., using a diagnostic wax-up) or with a digital workflow (i.e., using a digital prosthetic planning performed on STL files from intraoral scanners—Fig. 9.3). At the same time, similarly to the use of printed CBCT, virtual dental implant surgical planning must take into consideration the 3D dimensions of the underlying bone, such as vertical and buccal-lingual dimensions measured in the cross-sectional images of the implant site. As a rule of thumb, bone volume should allow for a safety distance of at least 1.5 mm between implants and adjacent teeth, 3 mm between adjacent implants, and 1–2 mm between implant and buccal and lingual plates and other surrounding vital structures.

9.3 Digital Impression

9.3.1 Intraoral Scanning

One of the main technologies that has increased accuracy and precision of image-guided surgeries is intraoral scanning. As previously discussed in this book, the process of intraoral scanning allows for a digital impression of the patient's dental arches. This procedure recreates a virtual 3D model of the patient's dental arch that includes both teeth and soft tissue.

Intraoral scanners (IOS) are devices that project a light source (either laser or structured light) onto the object to be scanned in order to capture direct optical impressions of the oral cavity [1, 2]. IOS devices are composed of a computer and a handheld camera. All images captured by IOS imaging sensors are processed by a specific scanning software resulting in 3D surface models (i.e., triangulated mesh, presented as STL files).

The first dental scanner for intraoral use was introduced in the early 1980s. Today, there is a wide range of models and brands of intraoral scanners available in the market. Intraoral scanning devices such as 3M™Mobile True Definition Scanner, Carestream Dental CS3500® and CS3600®, Dental Wings® DWIO, Sirona CEREC® Omnicam, Planmeca PlanScan®, and 3Shape Trios® are among the most popular on the current world market.

In the field of digital implant dentistry, IOS can be used prior to implant placement to enable digital implant planning and image-guided surgery or after implant osseointegration to enable digital implant impression. Digital implant planning requires integration of IOS STL images with CBCT original DICOM images. Digital implant impression requires the use of implant scanbodies for transferring the 3D implant position.

Using IOS for digital optical impression has many advantages and disadvantages (see Table 9.1). The digital impression technique is more comfortable, patient friendly, and faster than conventional impressions [1, 2]. It is also a more efficient technique requiring shorter preparation and retake time, as compared with conventional implant impressions [2–4]. The most widely used file format by IOS devices is the open STL or STL-like locked file. The STL file format encodes only the surface geometry of a 3D object.

Table 9.1 IOS advantages and disadvantages for digital implant surgery

Advantages	Simplified clinical procedures	Simplified impression for complex cases such as multiple implants No need to repeat the entire procedure for recapturing impression
	Higher time efficiency	Capturing a full-arch scan takes less than 3 min. No need to pour stone casts and obtain physical plaster models. All 3D data can be emailed
	Less patient discomfort	No more inconvenience and hardship stemming from impression materials
	Improved communication with dental technicians	Clinician and the dental technician can assess impression quality in real time. Files can be easily transferred
	Improved communication with patients	With 3D images it is easier to explain procedures to the patients. Higher patient acceptance
Disadvantages	Difficult to detect shape of edentulous alveolar ridges precisely	Stitching process may be complicated, especially in atrophic edentulous ridges
	Learning curve	Proper knowledge on the technology is required. Procedure outcomes depend on professional experience and the scanning strategy
	Purchasing and managing costs	High costs of IOS hardware and software license

Dental tissues present many reflective surfaces, such as enamel or polished prosthetic surfaces, that could cause light overexposure and disrupt scanning. To prevent this issue, practitioners could change the orientation of the camera to increase light diffusion. Another strategy employed by some systems would be the use of cameras with polarizing filters [5] or applying a 20–40 μm powder coating during the digitizing process to reduce reflectivity. Theoretically, the powder thickness could vary between operators and reduce file accuracy, although the software of the IOS is capable of taking an average thickness into consideration [6]. On the other hand, the use of powder could be relatively uncomfortable for patients, and it complicates scanning when it gets contaminated with saliva [4]. Indeed, powder-free IOS are recommended for full-arch impressions to avoid the issue of maintaining powder coating on all teeth for the whole scan duration [7].

According to the ISO 5725, accuracy is assessed by two measurement methods: trueness and precision [8, 9]. Trueness refers to the closeness of agreement between the arithmetic mean after obtaining a large number of test results and the true or accepted value of reference. Precision, in turn, refers to the closeness of agreement between all test results. In this context, the trueness and precision of IOS technologies for partial impressions range between 20 and 48 μm and between 4 and 16 μm, respectively [1, 10–14]. Thus, current IOS devices are well adapted for clinical practice, with at least similar accuracy to conventional impression methods [7, 13, 14]. Nevertheless, intraoral scanning accuracy also depends on operator handling during execution of the procedure. In this context, more training and adherence scanning protocols can also help obtaining more accurate 3D digital models. Also, the accuracy of digital implant impressions with IOS is comparable to conventional impression for both single and multiple implant cases; however, when it comes to fully edentulous cases, the accuracy is lower and may vary across devices.

9.3.2 Extraoral Scanners (EOS)

Extraoral scanners are dental scanning equipments that use an optical technology similar to intraoral scanners to digitize a gypsum model obtained by a conventional impression. Such methodology can also be considered an effective alternative to conventional dental impressions [15]. Nevertheless, alterations suffered by the gypsum models obtained by the conventional impressions may interfere in the accuracy of the digital models obtained by the scanning process. When compared, intraoral and extraoral scans do not show significant differences in quality and accuracy of the digital models obtained. Therefore, intraoral scans are the preferred option to obtain digital models, since the reduced number of steps minimizes the risk of acquisition errors.

9.3.3 Bite and Occlusal Relationship Registration

Prosthetic rehabilitation procedures commonly require registration of the intermaxillary relationship. However, this clinical step may be complex and has been described as a common source of error due to inadequate behavior of bite registration materials. In contrast, intermaxillary registration for digital impressions using IOS only requires an additional vestibular acquisition of the occluding teeth [16]. Only one left and one right lateral occlusal registration are required [16, 17]. Such acquisitions enable alignment of images of both maxillary and mandibular arches by means of an image matching process. For this purpose, the software algorithm recognizes coincident areas positioned in multiple planes.

9.4 Design

Digital surgical guides are templates designed for guided drilling, which are custom-made for each patient's prosthetic and surgical plan to ensure highly accurate drilling and implant placement [18]. This enables reliable transfer of the surgical plan from digital images to the actual surgical field, which translates to optimal implant positioning and highly predictable prosthetic outcomes. This also allows for better soft tissue management, emergence profile, and final prosthetic morphology [19]. In certain cases, implants can be loaded in the same appointment of surgical placement by using immediate loading systems such as the "Immediate Smile" or "All-on-4" protocols [20, 21].

In order to design accurate surgical guides, 3D images from STL files obtained from intraoral scanning are merged with CBCT DICOM files. The intraoral scanning and tomographic data allows for virtual planning of the prosthetic replacement and implant surgery, respectively. As a result of this process, an optimal surgical guide is created (Fig. 9.4).

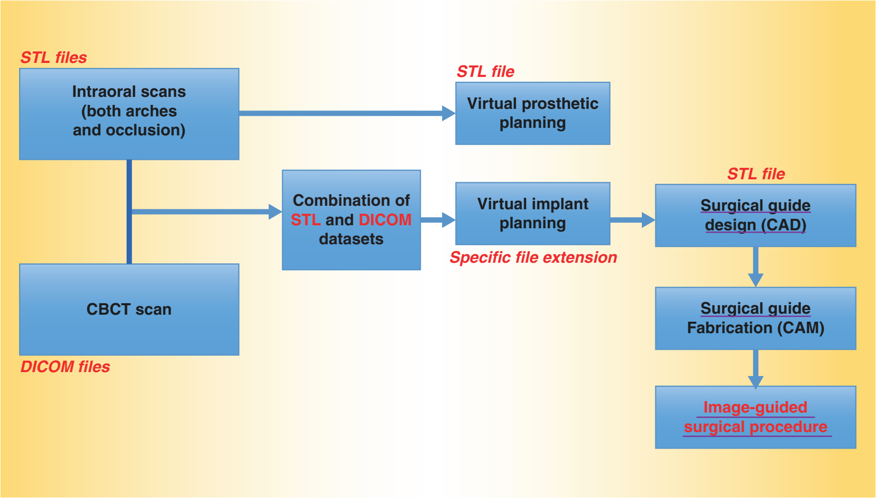


Fig. 9.4 Digital workflow chart for image-guided implant surgeries

9.4.1 Image-Guided Surgery Planning Software

In the current market, there are several different software dedicated for image-guided surgical planning. Each of them has specific strengths and weaknesses. Most of these software programs are not developed by the CBCT manufacturers, such as Simplant (Materialise Dental Inc., Glen Burnie, MD, USA), Invivo5 (Anatomage, San Jose, CA, USA), NobelClinician (Nobel Biocare, Goteborg, Sweden), OnDemand3D (Cybermed Inc., Seoul, Korea), Virtual Implant Placement software (BioHorizons, Inc., Birmingham, AL, USA), coDiagnostiX (Dental Wings Inc., Montreal, CA, USA), Blue Sky Plan (Blue Sky Bio, LLC, Grayslake, IL, USA), and Implant Studio® (3Shape, Copenhagen, Denmark), among others.

Most of these software allow access to a library of various dental implant brands and types enabling appropriate choices based on each professional's clinical experience and preferences.

In general, there seems to be no significant differences in accuracy among the different software systems, although just a few have an integrated prosthetic module so the temporary crowns can be printed or milled at the surgical planning step.

9.4.2 File Superimposition and Anatomical Structure Identification

As mentioned earlier, modern implant planning software allow to merge STL files from either IOS or EOS with images from CBCT scans. In this procedure, geometries of the key structures are automatically recognized. The resulting images and files can be used to plan the implant treatment and fabricate models and surgical guides. Most software packages require advanced knowledge to benefit from the full potential of this technology.

Software systems that allow file merging such as Implant Studio® (3Shape, Copenhagen, Denmark) enable the operator to combine images either automatically or manually. The automatic algorithm depends on the software development and similar geometries structures, whereas combining manually requires the selection of similar points of reference on both files (DICOM and STL), as shown in Fig. 9.5.

Either automatic or manual superimposition method provides a color bar analysis of 3D merging accuracy. Quantitative deviation values represented by colors can also be assessed, as seen in Fig. 9.6.

An important issue is that metal artifacts on CBCT scans commonly interfere on merging quality analysis and consequently on the imaging superimposition step. In this case, manual superimposition is generally required. Figures 9.7 and 9.8 show a case with significant metal artifacts, before and after performing manual superimposition.

Different analysis methods can be applied to ensure accuracy of manual superimposition. As introduced before, color bar analysis is a visual method by which

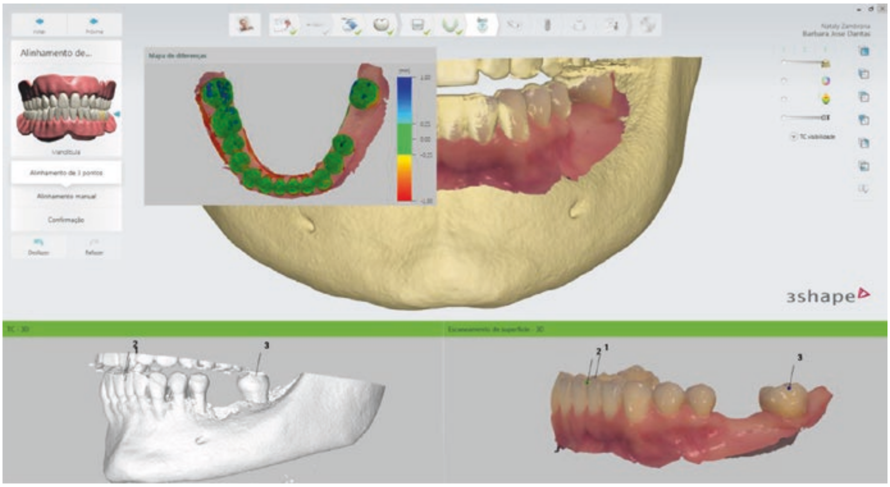


Fig. 9.5 DICOM and STL selection of points of reference for superimposition procedure on Implant Studio® (3Shape, Copenhagen, Denmark)

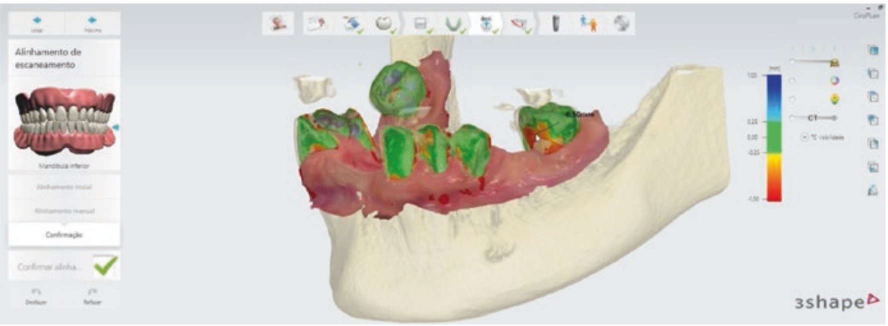


Fig. 9.6 Color bar analysis of 3D merging accuracy. Green points represent trustable points for file merging (i.e., areas where alignment between images is trustable and within a deviation range previously defined). Blue and red areas may require additional manual alignment

quantitative alignment accuracy information can be obtained by selecting aleatory points over the model (Figs. 9.9 and 9.10); another method for achieving superimposition accuracy is the use of transversal slice selection, by which it is possible to evaluate file merging by selecting planes of slicing on the merged 3D model, as seen in Figs. 9.11 and 9.12.

Image-guided software also have additional tools for better identifying anatomical structures such as the mandibular canal. By using panoramic, sagittal, and axial views, some software virtually reconstructs the inferior alveolar nerve (Fig. 9.13). The image-guided software will warn the professional about implants virtually placed in areas too close to the nerve (Fig. 9.14).

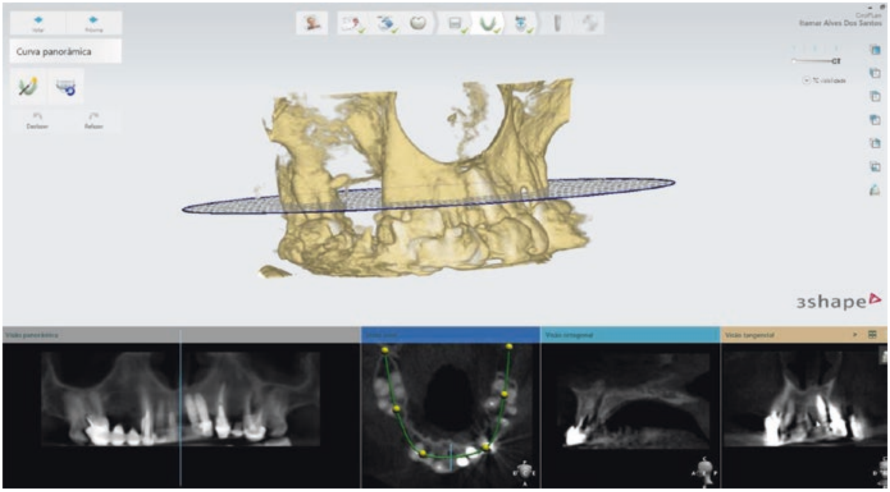


Fig. 9.7 Metal artifacts preventing adequate superimposition of DICOM and STL images

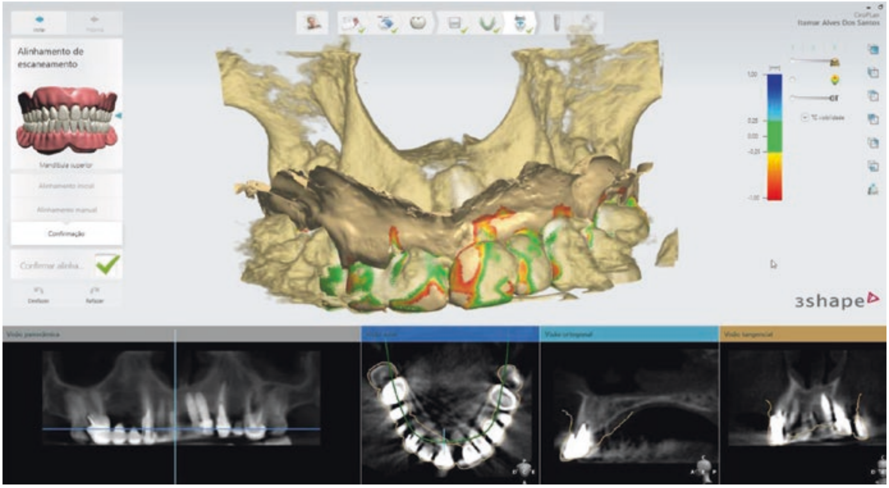


Fig. 9.8 Manual superimposition for adequate STL and DICOM merging

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.

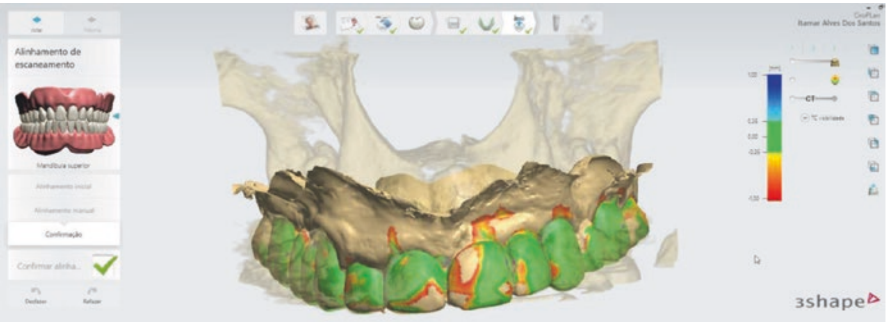


Fig. 9.9 Color bar analysis of manual superimposition

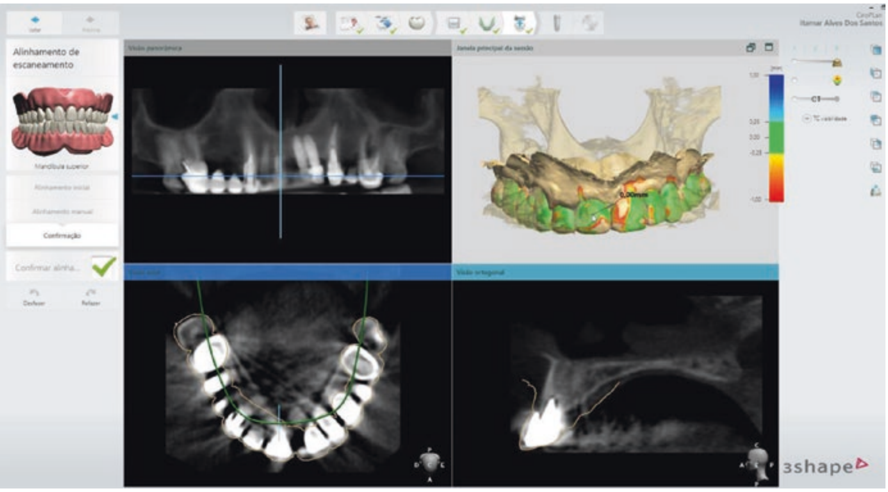


Fig. 9.10 Point selection and sagittal slice analysis for image alignment

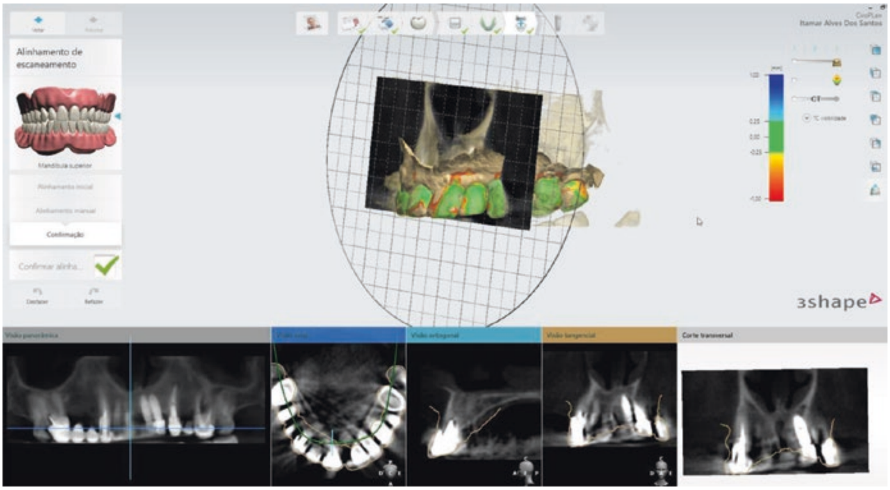


Fig. 9.11 3D model slicing analysis of file merging

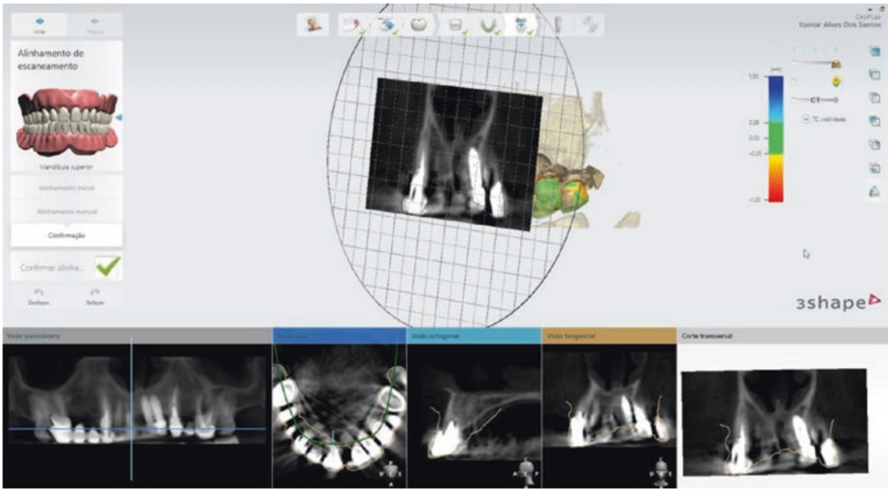


Fig. 9.12 3D model slicing analysis for combining DICOM and STL images

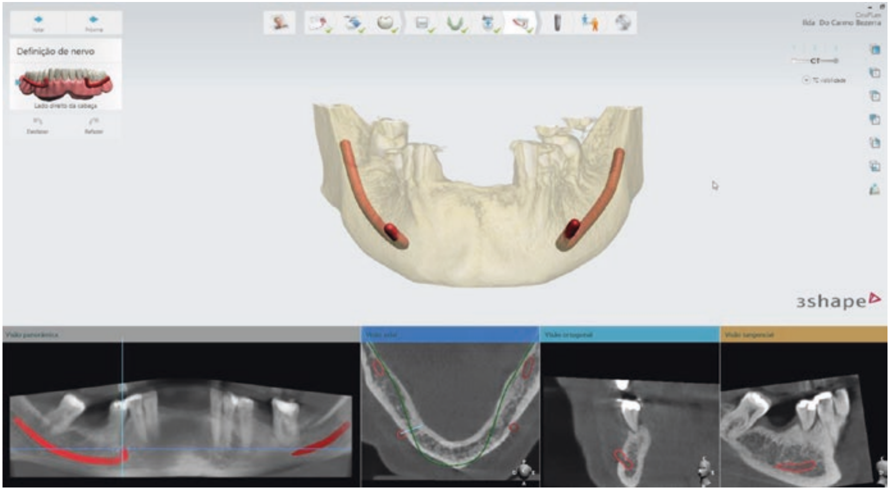


Fig. 9.13 Identification of the inferior alveolar nerve by an image-guided surgery software (Implant Studio, 3Shape)

Ideally, the implants should be placed at least 1.5 mm away from adjacent teeth, 3.0 mm away from adjacent implants, and 2.0 mm away from adjacent anatomical structures (mandibular canal, etc.); some planning software have those parameters set by default (1.5 mm radial and 2.00 mm apical distances); however they can be individualized if needed, as seen in Fig. 9.15.

Also, the implants should be placed in alignment with the occlusal forces in order to avoid eccentric loading. Since axial implant occlusal loading is desirable, 3D implant inclination should be planned taking into consideration the position of

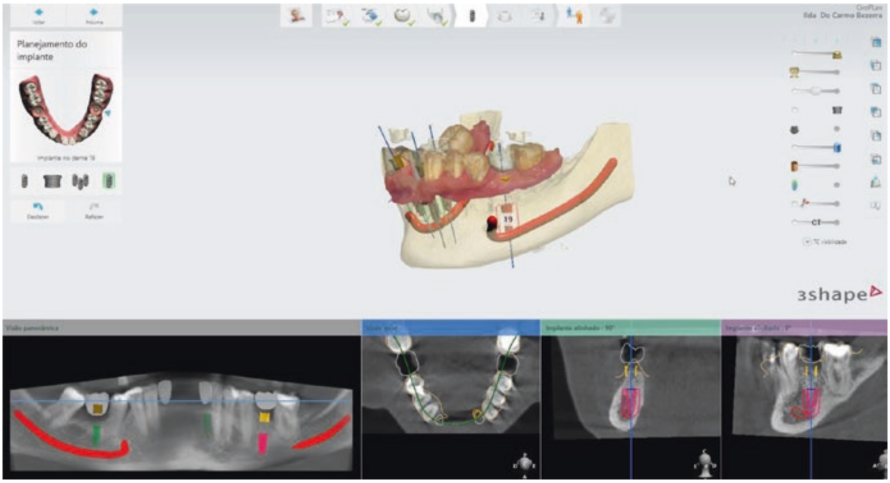
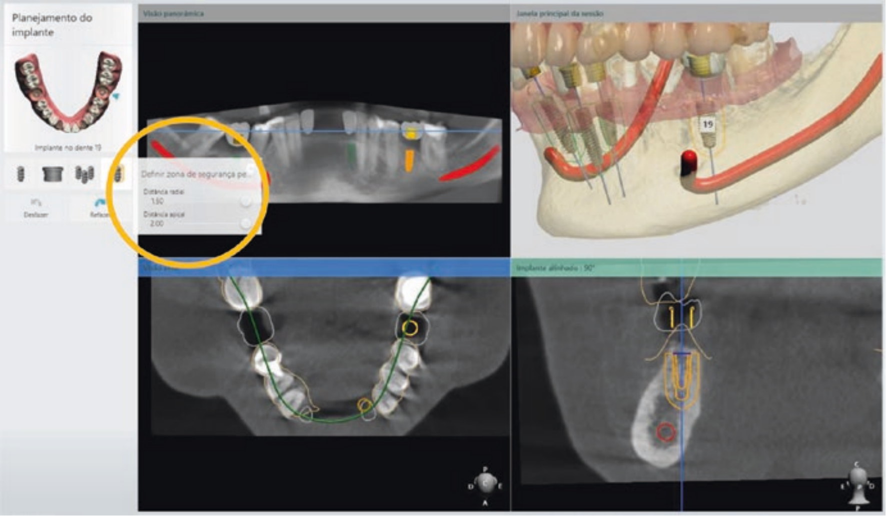


Fig. 9.14 Software indication of wrong position of a virtual implant. Please note that the virtual image of the implant is displayed in red color, indicating that the surgical guide cannot be created yet



Definir zona de segurança pe...
Distância radial 1.50
Distância apical 2.00

Fig. 9.15 Default parameters of implant distances showed by the image-guided surgery software

the antagonist arch, aiming for a balanced occlusion, which can be digitally assessed and planned beforehand [16, 17]. This is why the opposing arch should be included in the *digital impression, either intraoral or extraoral* scans.

Virtual planning software for image-guided implant surgery usually include multiple prosthodontic-related tools to create pre-designed crowns and bridges. The shape of these virtual prosthetic restorations can be edited in the computer, in order to prepare the exact design of the prosthesis intended as final restoration (Fig. 9.15).

If prosthodontic-related tools are not available, an additional software dedicated exclusively to digital prosthetic planning should be used.

Ultimately, an optimal digital treatment plan should combine endosseous implant placement that respects patient's anatomy, with prosthetic rehabilitation that is able to restore patient's esthetics, function, and occlusal stability. Once the implant position is determined according to the prosthetic needs of the patient, the dental professional can proceed with the fabrication of a surgical guide that can transfer the digital treatment plan to the patient's oral cavity. Such surgical guide is generally designed by the image-guided surgery software to have a shape allowing for stability in the patient's mouth during surgery. Surgical guides are designed with metal sleeves to guide the drills during implant site preparation, ensuring implant placement in the exact region virtually planned. Such metal drills generally have the diameter of the implant to be placed or the diameter of the last drill to be used for implant site preparation. Additional metal rings can be applied for diameter reduction of the metal sleeves for using the initial thinner drills.

There are a number of different digital workflow systems for image-guided implant surgery in the market. One of them is compatible with some implant systems such as Straumann (Institut Straumann, Basel, Switzerland) and is composed of three software of the same company (Dental Wings Inc., Montreal, Canada). The first software is mainly used for working with STL files from intraoral scanning (*Dental Wings Open System*). The second is used for virtual implant planning (*Dental Wings coDiagnostiX*®), and the third is used to communicate between the first two software (*Dental Wings Synergy*®), enabling combination of STL and DICOM files, as well as visualization of the integrated treatment planning in the first two software (Fig. 9.16). Such CAD/CAM system has been validated in the literature [22]. Both virtual implant (Fig. 9.17) and prosthetic planning can be

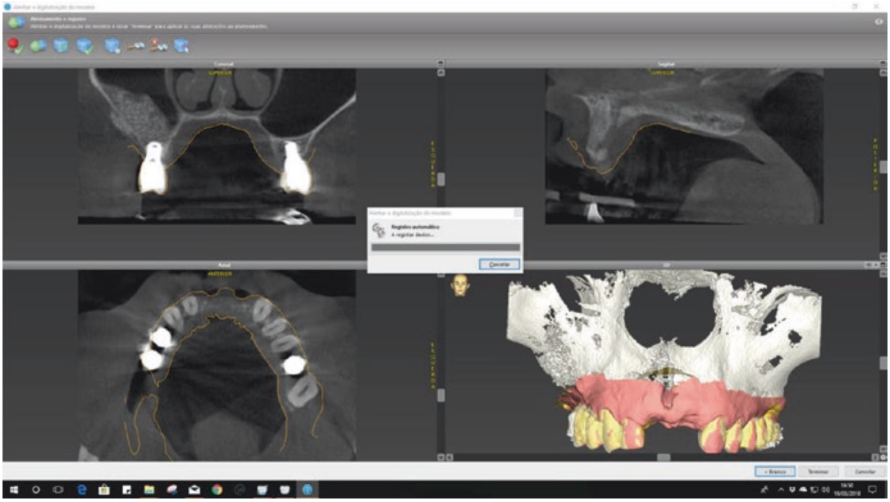


Fig. 9.16 Combination of STL (from intraoral scanning procedures) and DICOM files (from CBCT), viewed in the Dental Wings coDiagnostiX®software. The yellow lines overlapping DICOM images depict soft tissue information taken from STL files (Courtesy by *Doc Digital* radiologic center)

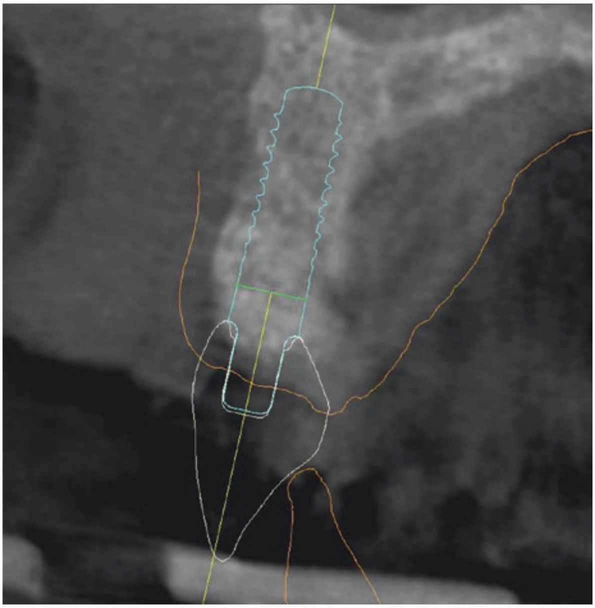


Fig. 9.17 Virtual implant planning. Note the visualization of soft tissue contours and prosthetic planning available from STL files originated from intraoral scanning

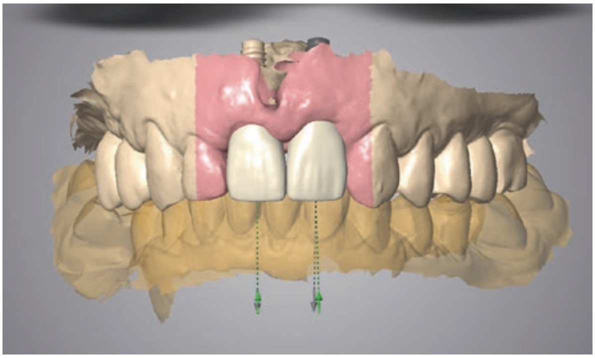
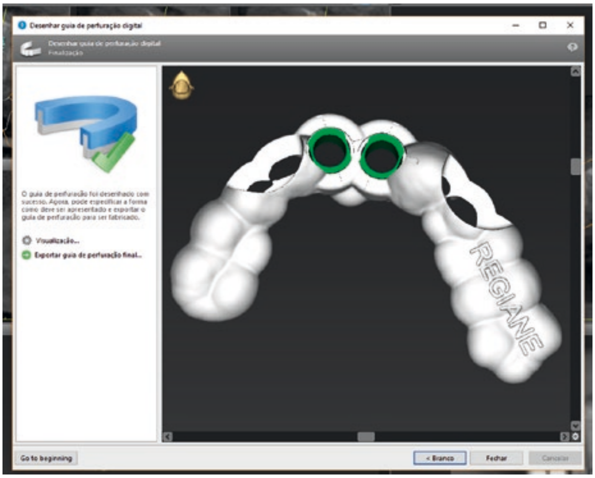


Fig. 9.18 Visualization of both virtual implant and prosthetic planning of the case depicted in Fig. 9.4, using the software dedicated for intraoral scanning (Dental Wings Open System)

also visualized in the software dedicated to work with intraoral scanning (Fig. 9.18). This will be followed by surgical guide design and CAD/CAM fabrication (Fig. 9.19) and, finally, image-guided implant surgery (Figs. 9.20, 9.21, 9.22, and 9.23).

9.4.4 Types of Surgical Guides

Digital implant dentistry requires the combination of radiological and intraoral data in order to proceed with virtual implant planning and subsequently design the surgical guide in the form of an STL file for final manufacturing. Digital surgical guides



O guia de perfuração foi desenhado com sucesso. Agora, pode especificar a forma como deve ser apresentado e exportar o guia de perfuração para ser fabricado.

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

Fig. 9.20 CAD/CAM fabricated surgical guide

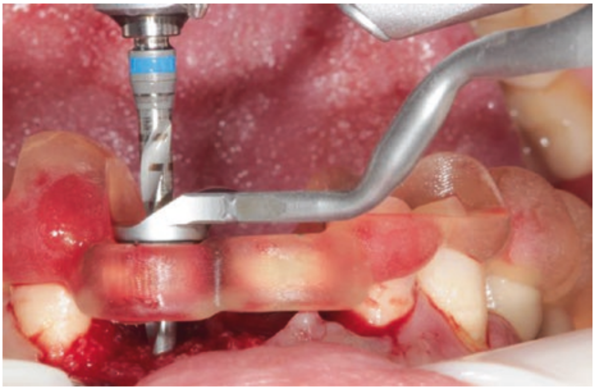


Fig. 9.21 Image-guided implant surgery

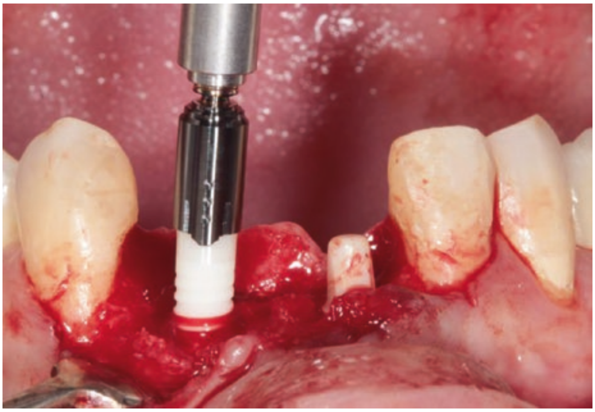


Fig. 9.22 Two zirconia implants (Straumann) were placed to rehabilitate both central incisors

Fig. 9.23 Provisional crowns used to immediate rehabilitate the patient

can be divided into three categories according to the type of support they use for stabilization in the oral cavity [16, 17, 23]. First, there are tooth-supported guides, which make use of the remaining teeth to anchor the surgical guide in place; second, there are mucosa-supported guides, which get support solely on the soft tissues; and third, there are bone-supported guides, which are fixed directly into the bone. Surgical guides supported by both mucosa and bone can be stabilized with fixation pins that are inserted directly into the bone. Research has shown that both mucosa- and tooth-supported guides offer reliable accuracy, while bone-supported ones seem to be less accurate [24, 25].

9.5 Fabrication of Surgical Guides

After designing them virtually, digital surgical guides can be fabricated using 3D printing additive processed like rapid prototyping (RP) or subtractive manufacturing methods such as computer numerical control (CNC) machining and milling. See details underneath [24, 26].

9.5.1 Subtractive Manufacturing (CNC Milling Machine)

For subtractive manufacturing, the surgical guide design produced with the designing software is converted into milling strips for the CAM processing and finally loaded into the milling device [27]. This involves computation to control CNC milling, including features such as sequencing, milling tools, and tool motion direction and magnitude. Due to the anatomical variances of dental restoration, the milling machines usually have burs with different sizes. The accuracy of milling is usually within 10 μm [28, 29].

The milling machines used to prepare surgical guides have at least three axes of movement (*X*, *Y*, and *Z*) such the inLab (Sirona), Lava (3M ESPE), and Cercon brain (DeguDent) systems. However some more costly devices can have additional axes of movement to allow for the fabrication of more complex structures. With a five-axis milling device, in addition to the three spatial dimensions and the rotatable tension bridge (fourth axis), there is also the possibility of rotating the milling spindle (fifth axis) [28, 30, 31].

9.5.2 Additive Manufacturing (3D Printing Rapid Prototyping)

As explained above, 3D printing was initially set up to increase the speed of prototype manufacturing in the manufacturing industry. Recently, different types of 3D printing have been used for different applications in the fields of medicine [32] and dentistry [33, 34].

Additive 3D printing techniques include SLA, digital light projection (DLP), jet (PolyJet/ProJet) printing, and direct laser metal sintering (DLMS)/selective laser sintering (SLS).

SLA technique uses ultraviolet (UV) laser for layer-by-layer polymerization of materials. Such technique is used for manufacturing dental models from UV-sensitive liquid resins. DLP uses visible light projection for polymerization and is used for the manufacture of dental models, from visible light-sensitive resins, wax, and composite materials. After the material is printed, it is cured using a light-emitting diode lamp [35]. In addition, polymethyl methacrylate (PMMA) can also be used in the DLP technique [36]. Jet (PolyJet/ProJet) printing involves a series of ink-jet printheads and small pieces of material jetted onto support material and create each layer of the part. Next, each jetted layer is hardened by using a UV lamp or heating. This technique is used for the manufacture of dental models and for surgical drill guides. DLMS/SLS is a powder-based technique in which a high-power laser beam is used to hit the powder, resulting in melt and fusion of the powder particles. Such technique is used for the manufacture of copings, dental models, and surgical guides made from cobalt-chrome, palladium chrome, and nylon [35, 37].

9.5.3 Manufacturing Accuracy

Production of the fine details by milling is largely dependent on the diameter of the smallest milling bur, which usually is around 1 mm [11, 24]. On the other hand, bur diameter seems not to influence milling accuracy [38, 39]. Drilling compensation features have been found to produce small fit errors, dramatically increasing the internal gap between surgical guide and teeth or mucosa surface. Excessive cement space results in a loose fitting surgical guide that may affect the accuracy of seating, thus resulting in loss of guide retention [40].

Milling accuracy is also affected by materials properties. Excessive hardness of materials may lead to surface chipping and chattering, especially under high feed rates, high cutting speed, and deficient cooling [41, 42]. Such cutting conditions may also cause excessive vibrations and exert thermal and mechanical stresses, contributing to dimensional distortions on the workpiece, especially around thin edges [43].

Among the advantages of additive manufacturing is the production of detailed and customized workpieces that fit patient hard and/or soft tissues [32, 33]. The workpieces can be edited in regard to morphology details, sharp corners, undercuts, or voids. Such features may be also useful for manufacturing facial prostheses. Since no drilling tool is involved, no compensation feature is needed, in contrast with subtractive manufacturing. However, due to the steps of production involving sequential layering, the external surface tends to have stepped and coarse morphology [44]. Such stepping adversely affects surface texture and overall dimensional accuracy of the workpiece [44] and could be a clinical issue if the prosthesis is not polished or veneered [45, 46]. Vertical walls were minimally affected by stepping, while the corrugated or sloping surfaces are more prominently influenced [47]. Therefore, concerns have also been raised regarding the accuracy of prosthetic occlusal surfaces produced with this technique [48]. The accuracy of additive technique is dependent on layer thickness and the width of curing beam. The thinner the layers are and the narrower the curing beam is, the more accurate the final product will be. On the other hand, an increasing number of layers and reduction of beam diameter exponentially increase fabrication time [44, 49, 50].

9.6 Surgical Procedure

Image-guided surgeries can be performed with either flap or flapless techniques depending on the amount of keratinized tissue and on the type of surgical guide to be used (Figs. 9.21, 9.22, 9.23, and 9.24). To use a surgical template for guided surgery, a special drill kit is necessary. This kit may include a tissue punch, drill sleeves, and drills of various lengths and diameters. Such drills are compatible with specific surgical guides and dental implant manufacturers.

Fig. 9.24 Panoramic radiography after a 3-month follow-up

For a flapless approach, the first step is to remove soft tissue with a punch drill to allow access to the underlying bony crest; for the flap approach, a conventional flap is performed on the ridge. Subsequently, preparation of the implant sites is done using drills of increasing diameters. Drilling is always guided in terms of placement, angle, and depth by the surgical guide. As explained before, angle and depth control during the use of thinner drills is achieved with a series of diameter reducers positioned inside the metal sleeves. As the size of the drill increases, the diameter reducers are changed until the final diameter is reached, as determined during surgical planning.

Implant insertion and tightening can then be performed either with the implant motor or a torque wrench through the template, hence with the surgical guide in position. On completion of implant placement, the surgical guide can be removed from the oral cavity. The dentist is then able to check the depth of the implants in relation to the mucosa. X-Rays of the intraoral implants can be taken right away, and either healing screws or temporary abutments and PMMA restorations can be placed and adjusted in case of immediate loading.

9.7 Clinical Evidence

There are still a small number of articles in the literature comparing and addressing the accuracy of different digital workflow systems for image-guided implant surgery. Scientific evidence, however, have recently confirmed the usefulness of such methodologies for implant placement in partially edentulous patients. For such cases, implants can be placed with flapless surgery following a computer-assisted planning procedure with minimal deviation rates, as compared with the respective planned positions [51].

A systematic review of nine different computer-assisted (static) guided implant systems shows that the clinical performance of these systems achieves an implant survival rate of 97.3% after a 12-month follow-up. However, there are still no sufficient scientific evidence suggesting that computer-assisted surgery is superior to conventional procedures in terms of safety, outcomes, morbidity, or efficiency [52].

Another systematic review concluded that image-guided surgery with digital workflow leads to less self-reported pain and swelling, as compared with conventional workflow [53]. Static digital implant surgery offers higher patient satisfaction and less discomfort and complications compared to the conventional methodology. In addition, flapless digital implant surgery leads to less postoperative pain in full-arch cases than open-flap procedures. However, implants with flapless digital workflow may be placed outside the area with keratinized mucosa, which needs to be carefully assessed during treatment planning [54].

Two other recent systematic reviews verified that, although accuracy of CBCT measurements and image-guided surgery are clinically acceptable for most cases, CBCT images can be affected by patient motion and metallic artifacts [55, 56]. Since measurements can be slightly under- or overestimated, a safety margin of at least 2 mm should be always respected, when working with CBCT measurements for implant planning and CBCT-based image-guided surgery. A recent consensus report on digital technology by the International Team of Implantology (ITI) assessed the highest impact-factor reviews on differences in accuracy between conventional and digital workflow for implant surgeries [54]. The accuracy of CBCT measurements can vary across different types of software; nonetheless using a digital workflow, it is expected to have a mean 3D deviation of 1.2 mm at the implant entry point, as well as a vertical discrepancy in final implant position of up to 1.13 mm.

One of the perspectives for future research of digital implant surgery is the advent of CAD/CAM technology to create cutting and grafting guides for maxillofacial and reconstructive surgeries [57]. In addition, flapless implant surgery seems to be a viable option in cases of reconstructions with free flaps after tumor resection or gunshot trauma, despite that some complications have been reported and many challenges remain. A high degree of patient satisfaction has been reported. Nonetheless, there is still only limited research available in the literature on image-guided surgery involving bone regeneration procedures. The feasibility of retrieving onlay autogenous bone grafts with guides has been recently confirmed. However, future clinical trials would still be recommended to address the accuracy and precision of such methodology.

In conclusion, considering the current accuracy of IOS and CBCT measurements, static implant image-guided surgery should be only considered as an additional tool that can be used for comprehensive diagnosis, treatment planning, and surgical procedures.

9.8 Conclusions

The use of guided dental implant surgery raises concerns regarding cost- effectiveness and professional responsibility. A high initial investment and an increase in operating costs are the major challenges for the advent of a complete digital workflow in implant dentistry, especially for developing countries. Also, this novel workflow requires well-qualified personnel to manage a more sophisticated operation that otherwise would not yield the desired results. Nonetheless, despite these challenges the abovementioned technologies save time, and in full-arch implant rehabilitations, the literature shows that computer-guided implant surgery is much more accurate than freehand surgery.

Digital implant dentistry also implies a change in professional accountability. Traditionally, dental professionals can be held responsible for poor treatment outcomes cause by using inferior techniques when well-proven superior methods are available. This concept could eventually be applied to traditional and digital implantology.

Despite its already great precision, computer-assisted implant surgery seems not yet to have reached its full evolution. It is still undergoing continuous improvements, in relation to the equipment for capturing diagnostic images, the planning software, and the surgical instrument and templates used in the technique.

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Digital Implant Prosthodontics

10

Hesham Nouh

Abstract

More than 36 million Americans do not have any teeth, and an estimated 120 million people in the United States are missing at least one tooth. An estimated two in three Americans have one or more missing teeth, mainly due to the rise in periodontal disease, as the population grows older. Individuals with missing teeth find it difficult to eat properly and may suffer adverse nutritional deficiencies as well as confidence and morale concerns. Today, dental implants are considered a routine treatment modality in dental practice along with the prosthodontic procedures associated with it. From single crowns to full-arch prostheses, dental implants can be utilized to treat patients for a variety of needs. Over the past 10 years, CAD/CAM dentistry has evolved from simple crown or inlay and onlay restorations to planning and designing surgical guides for dental implants as well as designing and milling abutments and screw-retained restorations. Even though the accuracy of the intraoral scan may decrease in full-arch cases, it is as good as or better than elastomeric impressions when scanning sextant or quadrant sized areas. Chairside CAD/CAM fabricated abutments and crowns do not require extra clinical visits and shorten the laboratory work time compared to the conventional workflow. They are a clinically viable option even for immediate implant provisionalization. Even with large CAD/CAM fabricated zirconia and titanium frameworks, they had a superior fit compared to cast alloy frameworks. Technology will continue to evolve, and it is incumbent upon us to assess the existing systems by evaluating the available evidence supporting its use.

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10.1 Introduction

Since the introduction of endosseous dental implants to the United States in 1986, there has been an exponential increase in the number of implants placed each year. This is due to the relative reliability of the osseointegration process, as well as ease of use.

Tooth loss has a negative impact on quality of life, particularly when it involves anterior teeth [1]. According to the American College of Prosthodontics (ACP), more than 36 million Americans do not have any teeth, and 120 million people in the United States are missing at least one tooth, affecting a majority of adult Americans. These numbers are expected to grow in the next two decades; in the geriatric population, the ratio of edentulous individuals is 2 to 1. About 23 million geriatric Americans are completely edentulous, and about 12 million are edentulous in one arch. Of those who suffer from edentulism, 90% have dentures. The number of partially edentulous patients will continue to increase in the next 15 years to more than 200 million individuals.

Furthermore, the profession has seen a significant broadening of the background of dentists placing and restoring implants. Initially limited to only prosthodontists and oral surgeons, today for a variety of reasons, implant placement has become more commonplace in any number of specialty practices, including periodontists, endodontists, and prosthodontists. Additionally, it has become routine practice in a growing number of general dentists' practices. This can in part be attributed to the introduction and integration of various digital technologies, taking some of the risk and uncertainty out of the placement and restoration processes.

CAD/CAM systems have primarily been used for the fabrication of fixed prosthetic restorations, such as inlays, onlays, veneers, and crowns. Presently, there is an immense interest in CAD/CAM systems for implant-supported prostheses, as they have recently begun to be used for the manufacture of implant abutments and surgical guides in implant dentistry. CAD/CAM technology has transformed the technique of fabricating implant-supported prostheses and abutments utilizing conventional methods. From single implant-supported restorations to full-arch rehabilitations, not only has CAD/CAM simplified the process but also expanded the possibilities with different materials and workflows.

10.2 Impressions

An accurate impression is crucial for obtaining proper intraoral details and anatomical relationships to manufacture an appropriate implant prosthetic restoration. The accurate transfer of the position and angulation of the implants is a critical factor for achieving a precisely fitting prosthesis [2], and inaccurate transfer of the implant position intraorally to a gypsum model is a major problem that can compromise treatment success. Possible causes for impression errors include, but are not limited to, unseated impression copings, shrinkage and distortion of the impression materials, as well as unstable repositioning of the analog during the laboratory process [3–5].

Digital technologies that were originally developed for tooth-supported fixed prostheses can now be used for implant impressions as well. Direct intraoral scanning of an implant can create a three-dimensional (3D) virtual model to design and fabricate physical models and restorations. Implant digital impression is generated via direct intraoral scanning or indirectly via scanning casts made from conventional impressions [6]. Direct scanning of the oral cavity generates a digital file that can be sent electronically to a milling unit to fabricate a digital model; thus, intermediate steps involved in conventional impression taking are bypassed, effectively reducing the margin of error produced from human or material shortcomings.

10.2.1 Elastomeric Impressions

Analog dental implant impressions involve replacing the healing abutment with a machined impression coping adapted to the dental implant, and subsequently the impression is taken with a tray using an elastomeric material. Implant impressions are supposed to be very accurate and precise because small discrepancies can compromise the final fitting of the implant restorations. However, the accuracy of implant elastomeric impressions could be influenced by several factors such as the properties of the impression material, the type of tray used, the impression technique, the implant angulation, and the platform geometry [4, 5, 7].

Elastomeric impression materials are highly accurate and have good dimensional stability and adequate tear resistance. Polyether is more hydrophilic than polyvinyl siloxane (PVS) and more forgiving of inadequate moisture control. Multiple studies have compared the accuracy of these two materials for implant impressions and have found no significant difference between them when used for in cases with 1–4 implants although cases with larger number of implants may benefit from the use of polyether [4, 5, 8–11].

An ideal impression tray should provide uniform space for the impression material and must be rigid and dimensionally stable because flexible trays cause distortion of the impression. There is some evidence indicating that custom trays may produce more accurate impressions in certain clinical situations; however, the clinical significance of the average difference of 10 μm may be difficult to identify and measure if extrapolated clinically [12].

Splinting the impression copings prior to impression-making improves the accuracy of the definitive cast of both partially and completely edentulous patients [13]. In partially edentulous patients, open- and closed-tray impressions show similar accuracy, but in completely edentulous patients, open-tray impressions are more accurate.

10.2.2 Digital Impressions

Digital impressions with intraoral optical scanners (IOS) eliminate all the inconveniences of an elastomeric impression, from tray selection to dispensing and polymerization of impression materials, disinfection, and shipping to the laboratory. They are also more comfortable to the patient leading to better treatment acceptance. In addition, cutting down on equipment footprints in the lab and dental office space and ease of storage of digital scans are extremely convenient and cost-effective for users [14].

In two-implant cases, intraoral optical scanning is at least as precise as conventional impression in terms of their ability to produce accurate casts for laboratory work [15]. Moreover, in some situations, optical scanners might be more accurate than conventional impressions, but this seems to depend on the type of scanner and implant system used [16]. For example, the "True Definition" intraoral scanner from 3M ESPE and the Omnicam from Dentsply have both been proven to be more accurate than conventional impressions on Nobel Biocare implants. However, these scanners are not superior to traditional impressions on Straumann implants, and in the case of the Omnicam scanner, it might even be inferior to conventional impressions on Straumann implants.

Regarding full-arch implant impressions, it is important to note that the accuracy of the intraoral scan decreases in the case of full-arch scanning versus sextant or quadrant scanning [17–19]. Nevertheless, the True Definition scanner and CEREC Omnicam have both been shown to be significantly more accurate than the conventional impressions with the splinted open-tray technique [20]. Additionally, digital impressions with the True Definition scanner had significantly less 3D deviations when compared with the Omnicam. In vitro comparisons between scanners have shown that the 3M True Definition and 3Shape Trios scanners are more accurate than the CEREC Omnicam, whereas the Lava C.O.S. was found to be unsuitable for making across-arch implant impressions in edentulous jaws [20, 21].

10.3 Dental Implant Abutments

An implant abutment is defined as "the supplemental component of a dental implant that is used to support and/or retain any fixed or removable dental prosthesis" [22]. Since its original conception, many advances have been made in the abutments of dental implants in regard to design, materials (i.e., titanium, zirconia, or plastic), angulation, (i.e., straight or angulated), esthetics (i.e., anatomic or cylindrical), and type of retention (screw retained or cement retained). Nowadays all these notions regarding abutment design are being revolutionized with the arrival of digital technologies.

10.3.1 Conventional Abutments

Implant abutments can be generally classified into two types:

1. Prefabricated
2. Custom-made

10.3.1.1 Prefabricated Abutments (Stock Abutments)

Prefabricated abutments are manufactured using subtractive manufacturing technology. These abutments are precision-milled to passively fit the implant with minimal machining tolerance [23, 24]. The height and thickness of the axial walls, as well as the location and width of the finish line, can be customized by the technician or the dentist for the final prosthesis, but with limitations. These abutments are made of biocompatible materials that impede biofilm formation and withstand masticatory forces, such as noble metals, commercially pure titanium, titanium alloys, and ceramics (alumina and zirconia). An example of a prefabricated abutment is shown in Fig. 10.1a. Prefabricated abutments are easily customized,

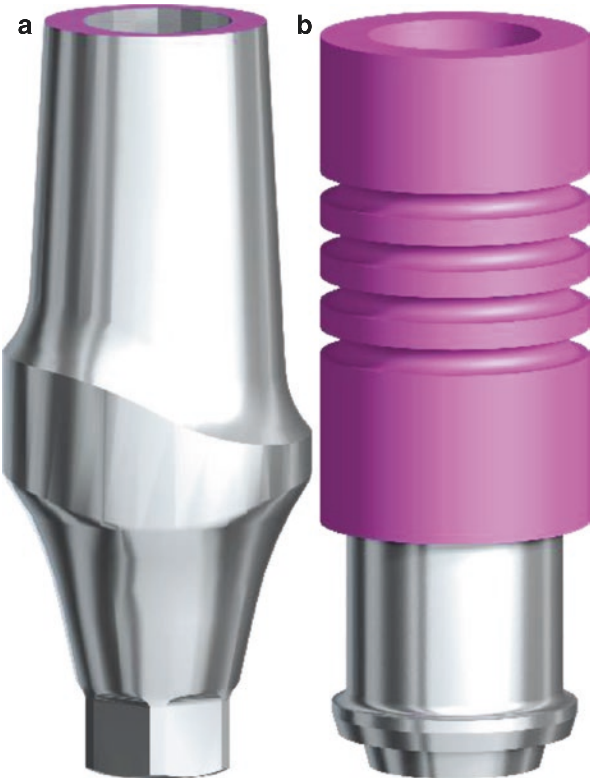

Fig. 10.1 (**a**) Nobel Biocare Esthetic Abutment, Conical Connection NP 3 mm. (**b**) GoldAdapt Non-engaging Conical Connection NP

widely accessible, and cost-efficient. However, most of the stock abutments are available in cylindrical form and do not support the surrounding soft tissues; this complicates the management of the emergence profile of an implant restoration from an esthetic standpoint. Since the platform size of the abutment usually equals that of the implant, the resulting emergence profile of the restoration does not replicate that of a natural tooth. They also have limited use in patients where there is excessive implant angulation. To overcome these issues, custom abutments are indicated [25].

10.3.1.2 Custom Abutments

Patient-specific custom abutments were first described in 1988 [26, 27]. Due to their anatomic design custom, abutments have many advantages including creating a natural emergence profile between the implant and the restoration, allowing for better hygiene and esthetics and better alignment with angled implants.

Traditionally, these abutments consisted of a plastic sleeve or a gold cylinder that could be contoured by wax or resin and subsequently cast using conventional methods. These abutments are then finished and polished and can be designed for cement- or screw-retained restorations. This labor-intensive process requires a high level of skills and numerous steps and significant temperature fluctuations that could compromise the final fit [28, 29]. In Fig. 10.1b, a custom abutment is shown before fabrication.

10.3.2 Digital CAD/CAM Abutments

Much like CAD/CAM crown fabrication, there are multiple available workflows to fabricate an implant-supported restoration. Each workflow has its indications and contraindications as well as advantages and disadvantages, outlined below.

10.3.2.1 CAD/CAM Lab Fabricated

An elastomeric impression of the implant is made to transfer the position and angulation of the implant to a master cast. This master cast is then scanned using a desktop scanner to create a digital master cast [30]. From that digital cast, custom abutments are designed up to specifications with regard to the anatomy, proper emergence profile, and margin design. Examples of this workflow include the ATLANTIS, NobelProcera, and BellaTek Encode® systems that are detailed underneath.

ATLANTIS: The ATLANTIS workflow enables the fabrication of abutments that support cement-, screw-, and attachment-retained prosthesis, on all major implant systems. It utilizes a patented technology that enables virtual design of abutments with anatomical contours based on the shape of the final tooth restoration. The abutments fabricated have exemplary function and esthetics [31]. ATLANTIS abutments are made from grade 5 titanium alloy, which could be coated with titanium nitride, to give a golden hue. They can also be made of yttria-stabilized zirconia in four different shades.

The master cast is scanned digitally creating a digital master cast. The opposing cast, the occlusal registration, and the wax-up of the proposed restoration or provisional are also scanned. After the abutments are designed, a hyperlink is sent to the requesting party (dentist or laboratory) to review the design. The design can be modified using the ATLANTIS 3D editor software. Once the design is approved, the abutments are constructed by DENTSPLY implants and sent to the requesting party for try-in and fabrication of the final restoration. In addition to abutments, ATLANTIS provides ATLANTIS 2in1, which provides primary and secondary suprastructures for removable prosthesis. The primary is fixed to implants, while the secondary attaches to the primary structure using friction and additional retention elements. They also provide the ATLANTIS Bar for removable dentures, which could be either standard or customized, and include a combination of various attachment options depending on the requirements of the case.

NobelProcera: NobelProcera abutments are fabricated utilizing a similar process as described for ATLANTIS. The master cast is scanned using a desktop scanner (The 2G Nobel Biocare or the KaVo LS 3 scanner). The 2G Nobel Biocare scanner is a 3D noncontact laser scanner that utilizes conoscopic holography technology, which is more accurate, precise, and stable than laser triangulation methods [32]. This system is particularly useful in complex cases with multiple implants or severely angled implants. The new KaVo LS 3 scanner can perform a complete jaw scan in under 60 s with an accuracy of up to 4 μm (according to ISO 12836). It is equipped with an optical system that captures the fine textures and colors of the dental model for true visualization and has the ability to mount a full articulator, improving efficiency within the dental laboratory.

DTX Studio design software offers laboratories heightened collaboration and data sharing. The NobelProcera offers the ability to engineer full-contour zirconia restorations including crowns, bridges, implant crowns, implant bridges, and overdenture bars as seen in Fig. 10.2a–c. Ekfeldt et al. [33] investigated the clinical outcomes of 30 NobelProcera customized zirconia abutments in 23 patients, at a minimum follow-up of 10 years. Restorations were either one-piece with veneering porcelain baked directly onto the screw-retained zirconia abutment ($n = 16$) or a cemented alumina crown ($n = 14$). No fracture was observed in any of the cases.

BellaTek Encode® System: Custom-designed coded healing abutments also known as encode abutments are used to communicate the information on the implant's position within the dental arch. The abutment is engraved with special markings on its occlusal surface that denote the abutment height, implant connection type, and hex position of the implant. This system was created to simplify the impression procedure while eliminating the ordering of multiple components, such as the impression coping, lab analog, healing abutment, and scan post if applicable. As such, that minimizes tissue trauma since there is no need to remove the healing abutment. The encode abutment could either be digitally scanned or impressed with traditional elastomeric impression material, and the master cast is then scanned. Multiple studies have revealed that the master casts fabricated from these abutments are less accurate than casts fabricated using conventional impression techniques [34–36].

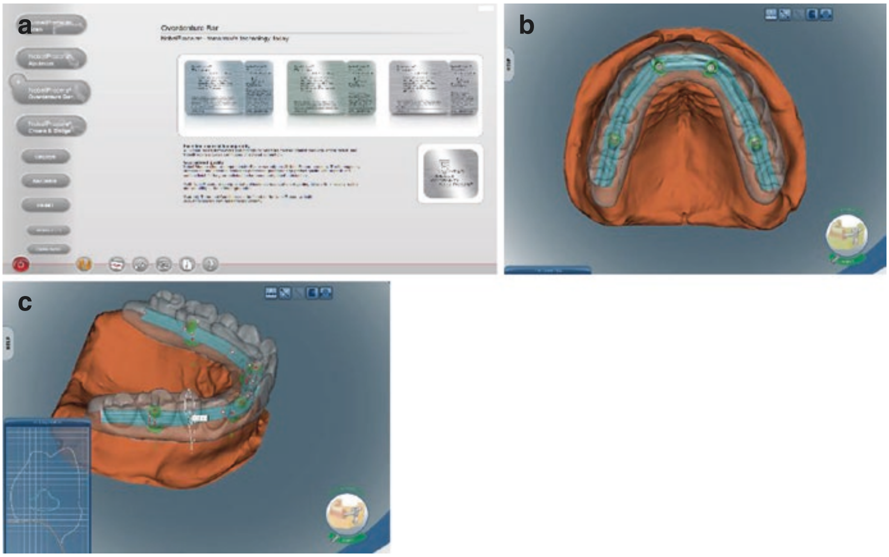

Fig. 10.2 (**a**) NobelProcera software interface (homepage). (**b**) Overdenture bar design (occlusal view). (**c**) Overdenture bar design (cross section)

There are two workflows that could be followed. The first workflow involves an elastomeric impression of the BellaTek® Encode® healing abutment in place. A master cast is fabricated using a low-expansion die stone. The master cast is then scanned, and the BellaTek® abutment is designed virtually. An implant analog is placed into the master cast using Robocast Technology. The BellaTek® abutment is then placed on the master cast for fabrication of a definitive restoration (Fig. 10.3a–f). The second workflow requires digital scanning of the BellaTek® abutment in place along with the adjacent teeth, opposing arch and occlusion using an intraoral scanner. The definitive abutment design is completed, and the file is sent to a milling machine for fabrication of the definitive abutment in titanium. The abutment is then delivered for placement and fabrication of the definitive restoration.

10.4 Frameworks

Brånemark's efforts using root-form titanium implants were mainly geared toward the edentulous jaw by means of fixed prostheses as he famously said, "No one should die with their teeth in a glass of water." While the original concept of osseointegration proposed by Brånemark focused on the treatment of the edentulous patient by a fixed prosthesis, today restoration of the partially edentulous with the use of dental implants has become common practice. It is important to understand that when splinting implants together with a framework, you will encounter many challenges such as the accuracy of the fit and choosing a material that is strong enough to withstand the forces.

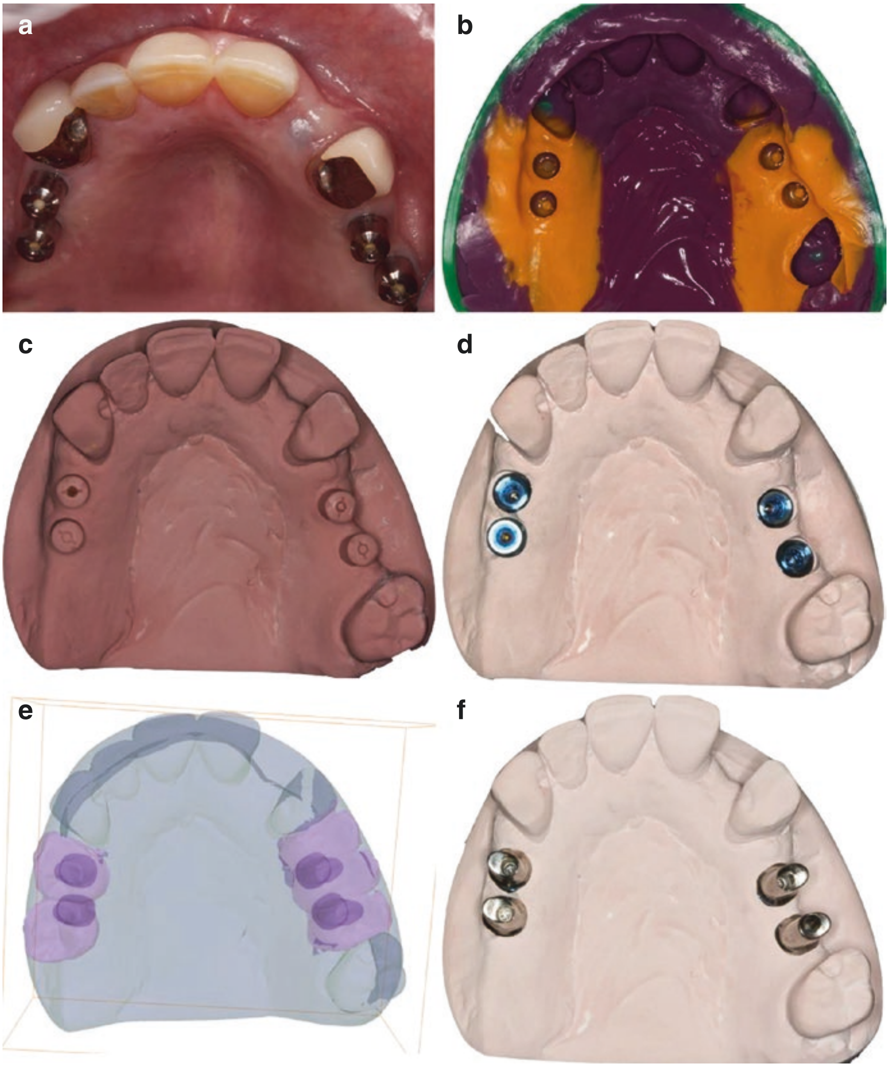

Fig. 10.3 (**a**) Encode abutments intraorally. (**b**) Elastomeric impression of the encode abutments in place. (**c**) Master cast poured from final impression. (**d**) Implant analog placement using Robocast Technology. (**e**) Digital proposal of the final abutment design. (**f**) Milled titanium abutments on master cast. Case courtesy of Dr. Osama Qutub

10.4.1 Types of Frameworks

- *Implant-supported fixed partial denture frameworks* (short-span bridges): Historically, 3-unit fixed partial dentures were considered the only fixed option to restore a single edentulous site before endo-osseous implants were introduced in the early 1980s. Today, patients with multiple edentulous sites can benefit from an implant-supported prosthesis. In the analog world, frameworks are fabricated by designing them using wax or resin that are then cast. The evolution of that was via copy-milling which still required a physical representation of the framework, which in turn is scanned and then copy-milled. Utilizing a fully digital workflow, implant frameworks are designed using software such as Sirona inLab, exocad, NobelProcera, or 3shape, to name a few.

- *Overdentures*: Overdentures have become a favored treatment option among edentulous patients. The concept of having two mandibular implants was proposed in the late 1980s [37], and 30 years later, it still is widely considered the option of choice and even proposed as a standard of care [38]. A connecting bar is not feasible with two implants, and sufficient stability is not provided in all cases. In cases of multiple implants (4–5), the implants could be connected with a bar, and a horseshoe denture design is suggested with a metal framework reinforcement [39]. Soldered bars from gold alloys are vulnerable to fracture in this case; however, CAM technology allows the fabrication of titanium bars, which reduce the risk of fracture.
- *Fixed prosthesis/hybrid*: Advantages to restoring fully edentulous patients with a fixed prosthesis include improved function, stability and retention, improved facial esthetics, and maintenance of hard and soft tissues, which in turn increase the patients' confidence and quality of life. Edentulous patients with a minimum of four implants can benefit from this design. It is screw-retained, with a hybrid design in which the prosthesis fitting surface is not in contact with the alveolar mucosa. The framework is made of precious alloy, and acrylic veneering was used for the superstructure. In today's CAD/CAM design world, major improvements to the design have occurred. Not only have materials evolved, but so has the design. From a technical standpoint, frameworks can be connected directly to the implant shoulder without abutments, involving fewer components in the superstructure and a more passive fit. The frameworks can be designed fully anatomically for fixed prosthesis (Fig. 10.4) or to full contour.

10.4.2 Material Choice

- *Milled titanium frameworks*: Titanium and titanium alloys are regularly used in clinical dentistry due to their high corrosion resistance, great biocompatibility, low specific gravity, cost-effectiveness, and mechanical properties [40].

Fig. 10.4 NobelProcera Zirconia Implant Bridge

- *Milled or additive manufacturing chromium cobalt*: The advantages of Co-Cr for dental use are its mechanical properties, such as its high elastic modulus, its corrosion resistance, and the strength of its chemical bond with porcelain [41]. Co-Cr can be processed using additive manufacturing methods such as direct metal laser sintering (DMLS), selective laser sintering (SLS), and selective laser melting (SLM).
- *Milled zirconium framework*: Patients' increasing interest in esthetics and concerns about toxic and allergic reactions to certain alloys, as well dentists' concerns regarding material strength and compatibility, has led to the development of zirconia dental frameworks. Zirconia is used in dentistry as a dental ceramic for all aspects of restorative dentistry such as crowns, frameworks, copings, and even endo-osseous implants. The zirconia used in dentistry is yttria-tetragonal zirconia polycrystal (Y-TZP). Y-TZP is a monophase ceramic material formed by directly sintering crystals together to form a dense, polycrystalline structure without any type of intervening matrix. The addition of 3–6% weight of Y_2O_3 to zirconia stabilizes and maintains the material's physical properties and prevents polymorphic transformation during heating and cooling.

10.4.3 Accuracy of the Fit

- *Implant-supported fixed partial denture frameworks*: Zaghloul and Younis [42] evaluated the effect of fabrication techniques and cyclic loading on the vertical marginal fit of implant-supported fixed partial denture (FPD) frameworks. They compared 3-unit frameworks made of base metal alloy with two CAD/CAM zirconia frameworks, the CEREC 3, and the Zirkonzahn copy-milling. Prior to cyclic loading, Zirkonzahn frameworks presented similar marginal gaps to those observed in metal frameworks but smaller than in the CAD/CAM CEREC 3 frameworks. However, after cyclic loading the fit of metal frameworks deteriorated, whereas the fit of the Zirkonzahn frameworks remained unaltered. Comparisons of 3-unit frameworks fabricated by either CAD/CAM zirconia, CAD/CAM cobalt-chromium, or conventionally cast cobalt-chromium reveal that, upon tightening of all the screws, the CAD/CAM frameworks exhibited better fit and accuracy than the cast frameworks [43].
- *Overdentures*: CAD/CAM technology allows for quicker, cheaper, and more accurate fabrication of complex prosthesis than conventional casting techniques (Rubén A). Regarding framework accuracy, Finite element analysis has revealed that horizontal misfit of overdenture frameworks can increase the mechanical stress in the structure and this is more pronounced in bar frameworks made of silver-palladium alloy, commercially pure titanium, or cobalt-chromium alloy than in those made of gold alloys. Framework stress could also be affected by other factors such as interarch relationship, degree of jaw atrophy, orientation of implant, dentition/prosthesis in the opposing jaw, and type of occluding materials, occlusion, and loading [44].

- *Fixed prosthesis/hybrid*: Multiple studies have reported that CAD/CAM titanium frameworks achieve implant/framework fits superior to those obtained with cast metal frameworks [28, 45–47]. Long-span screw-retained zirconia frameworks have also been found to have better fit than cast alloys [48]. However, among milled CAD/CAM frameworks, those made of zirconia have been found to produce less strain and have more passive fit than those made of titanium [49].

10.4.4 Complications

According to Zarb and Schmitt, implant prosthetic complications could be classified as either structural, cosmetic, or functional.

In one of the first studies on implant prosthodontics (a.k.a. the Toronto Study), Zarb and Schmitt [50] followed 46 patients treated with 274 implants (49 frameworks) for 4–9 years and reported a high incidence of prosthodontic complications associated with fixed implant prostheses. These complications included 9 abutment screw fractures (3.3%), 53 gold alloy screw fractures (19.3%), and 13 framework fractures (26.5%). However, it has to be kept in mind that these patients were treated with early prosthetic protocols including cast alloy frameworks and minimal understanding of screw mechanics, torque, preload, and A/P spread.

In contrast to the above results, more recent studies show varying outcomes. In a 5-year clinical study conducted by Hjalmarsson et al. [51], they reported clinical outcomes associated with screw-retained fixed implant prostheses manufactured with laser welding versus frameworks made with milled titanium. Their results showed significantly increased numbers of complications with laser-welded frameworks than with milled frameworks. A 10-year clinical study conducted by Ortorp and Jemt noted that the frequency of prosthetic complications was low, demonstrating similar clinical results for CAD/CAM milled and cast gold alloy frameworks. Their results included one lost prosthesis in each group and one fractured prosthesis in the CAD/CAM milled group. Ortorp and Jemt observed that increased frequency of maintenance appointments was needed for maxillary prostheses. Typically, an implant is thought to be a “lifetime” solution, with minimal complications, however, that is not necessarily the case with prosthetic restorations. Nevertheless, with innovations in implant technology continuing to advance, maintaining knowledge of all the latest developments can be a challenge for clinicians.

10.5 CAD/CAM Chairside Restorations

Today, more and more clinicians, from general dentists to specialists, are restoring dental implants. A key clinical decision they must make regarding planning an implant restoration is how is the restoration going to be retained: cement-retained or screw-retained. That decision is made on an individual case basis where multiple considerations should be taken. A myriad of factors should be considered when making that decision such as retrievability, location, esthetics, occlusion, and interocclusal space. In fact, it is a combination of these factors that makes the best decisions. Each case has its uniqueness which makes it difficult to consider the factors objectively, and therefore criteria are singled out to present the effect of a specific retention type. The decision made will affect the overall prognosis of the case. CAD/CAM chairside workflows can provide both screw-retained and cement-retained restorations that can be fabricated in the clinic and delivered to the patient within the same appointment. Underneath we discuss one type of chairside workflow, the CERERC TiBase system.

CEREC workflow: This workflow is based on a kit of components designed for both scanning and restoring the implant. The kit is called the CEREC TiBase Kit, and each kit includes three main components, the titanium base, the abutment screw, and the scanbody. The titanium base is screwed to the implant using the abutment screw, and it serves two purposes: it is used for scanning the implant with the aid of the scanbody, and it is also used to build the final restoration.

The implant is scanned digitally along with the adjacent teeth and tissues, using a scanbody (cap) adapted onto a TiBase. In cases in which the surrounding structures prevent proper scanning, it is possible to replace the TiBase with a longer version of itself, called the scan post, which is only used for scanning. The scan post is the analogous of the impression coping, and it is used to transfer the position of the implant from the patients' mouth to the virtual 3D model. It is crucial that the scanbody and scan post are aligned to properly record the three-dimensional position of the implant.

Once the scanning is complete, a computer software is used to design a customized abutment or crown with the desired emergence profile based on the size and shape of the tooth restoration. Custom abutments or crowns are then milled from ceramic or composite blocks that have a pre-drilled hole for screw access. These blocks come in two sizes, size A14 to mill abutments and size A16 to mill crowns (Fig. 10.5a, b), and can be made of a wide range of materials that are compatible with many different implant systems such as lithium disilicate, zirconia, and Enamic.

10.5.1 Screw Retained

10.5.1.1 CEREC Hybrid Abutment Crown

As described above, the implant is scanned digitally using a scan post that has a scanbody (cap) along with the adjacent teeth and surrounding soft tissues. The scanbody has geometrical features that enable the software to relate the scan post to the implant position. This is followed by designing a screw-retained implant-supported crown with the desired emergence profile. Much like any CAD/CAM crown design, the tools used to modify the shape, size, and contour of the restoration are the same. The individually manufactured crowns are then cemented onto the TiBase. TiBases could be scanned in place of the scan post, but that depends on the implant position in relation to the gingival margin. Due to the size difference between the TiBase and scan post (scan post is 5 mm longer than TiBase),

Fig. 10.5 (**a**) e.max abutment block A14 (L). (**b**) e.max abutment block A16 (L)

obtaining an acceptable intraoral scan can be challenging if the implant is placed too far below the gingival margin. This has to do with the proper alignment of the scan body with the TiBase. The cementation process for the hybrid abutment crown is very similar to cementation of the hybrid abutment. The main difference is that since it is a one-piece restoration, all adjustments such as proximal and occlusal contacts should be adjusted before cementation onto the TiBase. The hybrid abutment crown is then polished and or glazed, depending on the material used, prior to cementation on the TiBase, extra-orally. This is done to ensure that the hybrid abutment crown is fully seated on the TiBase as trying to seat it intraorally may be challenging due to the soft tissue and adjacent dentition. The cemented parts are then screwed into the implant with the abutment screw in the patient's mouth. The

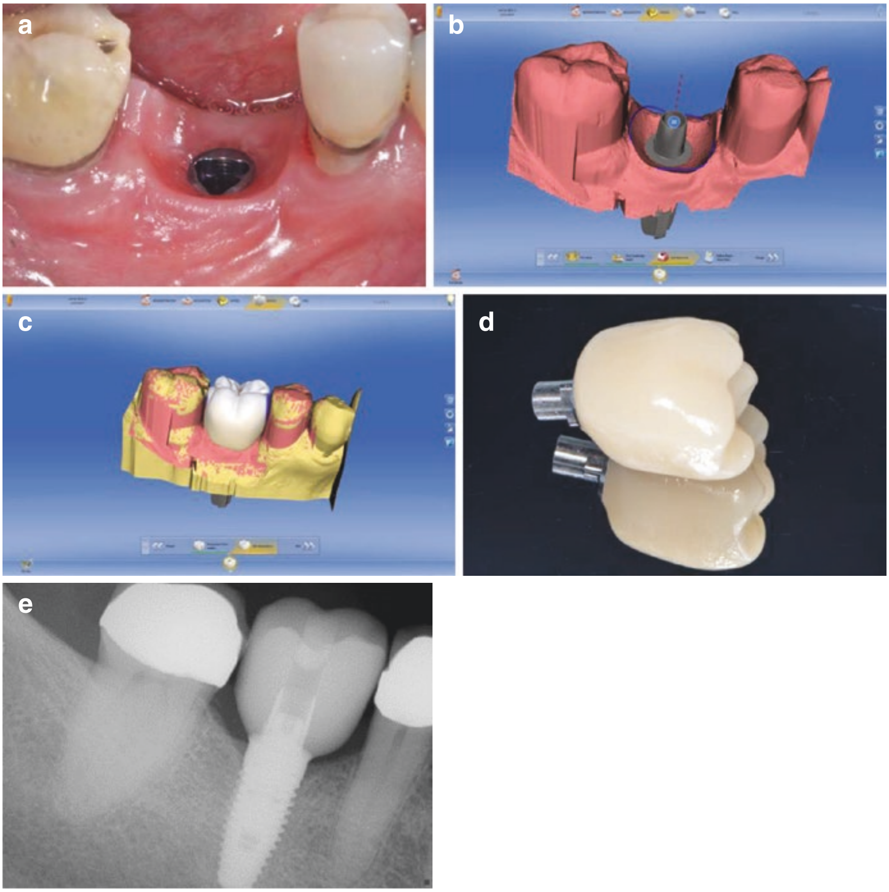

Fig. 10.6 (**a**) Nobel Biocare Replace Select 5.0 in the position of #30. (**b**) Determining the emergence profile with the chairside CEREC software v 4.4.4. (**c**) Designing the screw-retained crown with the chairside CEREC software. (**d**) Enamic hybrid abutment crown (screw retained). (**e**) 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. 10.7 CEREC hybrid abutment with veneering crown and Tibase

crown, and it does not require an abutment block as it will be cemented onto the mesostructure.

First the abutments are milled and cemented onto the TiBase outside the oral cavity. Several steps should be observed when cementing the abutment (mesostructured) onto the TiBase:

1. Blocking material, e.g., silicone, should be applied to protect the emergence profile and the screw channel.
2. The bonding surface can be carefully blasted according to the instructions of the manufacturer.
3. Removal of the silicone and subsequent cleaning with ultrasound in a water bath or with a steam jet.
4. Bonding agent is applied to the clean bonding surface and allowed to react and air dry.
5. The screw channel is sealed with a foam pellet or wax.
6. Etching the mesostructure with Etching Gel. Subsequently, the restoration is rinsed with water and blown dry.
7. A bonding agent is applied to the etched mesostructure bonding surface and allowed to react and air dry.
8. The mesostructure is placed on the TiBase in such a way that the position markings are aligned. The parts are pressed lightly and evenly together and checked for the correct relative position of the components.
9. Excess cement is cleaned away before polymerization.
10. The cement is allowed to fully polymerize before moving any of the components.

The cemented parts are then screwed, with the abutment screw, into the implant in the patient's mouth, and a crown for cemented restorations can be cemented on top. The Sirona TiBase comes in various versions, each of which is compatible with a specific implant system.

10.6 Maintenance

Implant restorations are complex treatments that require patient home care, and the dentist must follow standard guidelines for prosthodontic design and maintenance. The prosthesis fabricated must have anatomic contours and proper emergence profile, and the pontic design should be hygienic and self-cleansable. If the prosthesis is designed up to standards and the patient follows proper home care instructions along with professional recall appointments, a successful outcome can be expected.

10.6.1 Biological Maintenance

1. Medical history should be reviewed for changes at least once a year.
2. Complete evaluation of the soft tissues surrounding the implants for signs of inflammation including redness, swelling, change in probing depths, bleeding on probing, and suppuration.
3. The presence of plaque and calculus must be evaluated. Baseline probing depths and radiographs after delivery of the prosthesis for comparison are essential [52]. Baseline probing depths should be measured within 2 weeks after delivery, allowing for peri-implant soft tissue healing to occur.
4. Radiographs should be retaken every 1–2 years thereafter or if any signs of infection occur.
5. Clinicians should confirm that their patients can perform proper oral hygiene and should advise brushing at least twice daily and use of floss, interdental cleaners, and/or water irrigators.
6. Removal of a fixed, screw-retained implant prosthesis for evaluation is not needed unless there are signs of peri-implantitis, a demonstrated inability to maintain adequate oral hygiene, or there are mechanical complications that require removal.
7. Based on a patient's risk profile, in-office implant maintenance appointments should be scheduled at 2- to 6-month intervals (e.g., history of smoking, history of periodontitis, systemic conditions, patient's limited vision and dexterity).

10.6.2 Mechanical Maintenance

1. The interface stability between the restoration and supporting intermediate abutments or implants is key. The stability of these interfaces is determined by the passive fit of the restoration and the proper assembly techniques at delivery [53]. Passive fit is thoroughly evaluated at delivery but generally confirmed in a recall scenario with radiographs. The assembly method at delivery includes critical elements such as torque level, screw coatings, the pattern of tightening, and a second torque application to overcome the initial mechanisms of screw relaxation.
2. If the restoration is in function and free of mechanical complications, there is no indication for removal and/or replacement of screws. The frequent replacement of screws to prevent complications may lead to more severe mechanical complications, such as implant fracture [54].
3. When a restoration must be removed, the use of new screws assists in achieving ideal assembly conditions for stable interfaces [55, 56].

The American College of Prosthodontists [57] recommends that removal of full-arch, implant-supported restorations at regular maintenance intervals is discouraged unless adequate professional hygiene is not possible with the superstructure in place or the restoration presents with mechanical complications.

10.7 Conclusion

In this chapter, multiple systems and workflows utilizing CAD/CAM have been described. Each workflow has its advantages and disadvantages and indications and contraindications. Thus, case selection plays a major role when selecting which workflow will be utilized including number of implants, angulation, and type of prosthesis to name a few. Technology will continue to evolve, and it is incumbent upon us to assess the existing systems by evaluating the available evidence supporting its use.

Regardless of which system or workflow is utilized, it is important to accurately transfer the implant position from the patient's mouth to a digital cast via an impression. The accuracy of intraoral scanning with implants depends on the size of the area being scanned. When scanning a quadrant or sextant, the optical scan is at least as precise as conventional elastomeric impressions and stone master casts prepared using prefabricated transfer. When scanning the full arch, the accuracy of the intraoral scan decreases.

Prefabricated abutments should be selectively used due to their lack of anatomical features and characteristics which may affect the esthetics and function of the final prosthesis. Custom abutments have many advantages such as an anatomic design allowing for better esthetics and easier maintenance and cleaning by the patient. However, it is a lab-sensitive procedure that requires skills and time. On the other hand, chairside fabricated abutments and crowns do not require extra clinical visits and shorten the laboratory work time compared to the conventional workflow. They are a clinically viable option even for immediate implant provisionalization [58].

Digital workflows have simplified and improved the fabrication of implant-supported frameworks by digitizing the design process and allowing the use on new better materials such as zirconia or Enamic as substructures or even as full-contour implant-supported fixed restorations. Nevertheless with such complex and advanced restorations, extra care must be taken in order to maintain the prosthesis and have a successful outcome.

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Digital Technology in Endodontics

11

Alexis Gaudin, Fabienne Pérez, and Johnah Galicia

Abstract

Following the growing digitalization occurring in many fields of restorative dentistry, digital technologies are now started to be applied in endodontics as well. This chapter describes how we can take advantages of digital technologies in endodontics. There is a common understanding that digital information provided by conventional 2D periapical radiograph or 3D cone beam computerized tomography are essential for diagnosis. However, merging this information with that coming from intraoral scanners is relatively recent in the field of endodontics. This approach is borrowed from implant dentistry where preparation for an implant can be virtually planned three-dimensionally (3D) and the optical surface scan allows the production of an accurate guide. Thus, microguided access, in particular where teeth present pulp canal obliterations, and endodontic surgery with surgical templates can now be considered. These two main applications are described in this chapter along with their advantages and drawbacks.

11.1 Rationale for Digital Endodontics

Cone beam computed tomography (CBCT) and intraoral scanners are becoming increasingly popular among dentists. CBCT has improved substantially endodontic diagnosis. Moreover, in recent years, it has become possible to combine CBCT scans with optical surface scans of the same teeth [1]. This innovative matching of CBCT and

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intraoral images was first aimed for implant positioning [2–4]. CBCT imaging provides an accurate three-dimensional (3D) representation of oral structures, while optical surface scan allows the production of surgical guides. With this tandem approach, preparation for an implant can be virtually planned in 3D. As a result, implant placement can be guided accurately by a metal sleeve that is placed in the surgical guide to control the position of the drill. This technique reduces surgical intervention time and postoperative complications during treatment procedures. Furthermore, by using prefabricated 3D templates, steps such as production and chairside fitting of the conventional radiographic templates are eliminated. These new principles of guided implant surgery have been recently introduced into endodontics. Microguided access may be designed for root canal location, while a guided endodontic surgical approach can result in accurate osteotomy and root resection. These two main applications will be detailed in this chapter along with their advantages and drawbacks.

11.2 Radiographic Analysis and CBCT in Endodontics

Radiographic imaging is an integral part of endodontic diagnostic and therapeutic procedures. CBCT is a relatively new method that produces undistorted three-dimensional images of maxillofacial structures, including teeth and their surrounding tissues, with a lower effective radiation dose than medical CT scans [5–7]. Compared to two-dimensional (2D) radiography, CBCT offers several advantages. The third dimension allows a quantification of spatial relations and volumes. The AAE and the American Academy of Oral and Maxillofacial Radiology (AAOMR) published a joint position statement regarding the application of CBCT in endodontics [8]. According to their statement, CBCT should not be used routinely and should be limited to complex endodontic conditions such as the following.

11.2.1 Detection of Apical Periodontitis (AP)

Currently, the accepted reference standard for the radiological detection of AP is periapical radiography. However, in the early stages of AP, periapical bone destruction may be minimal or be masked by adjacent anatomy (Fig. 11.1). CBCT is more specific and sensitive in the diagnosis of periapical pathology than periapical radiographs [9]. Lofthag-Hansen et al. found 38% more periapical lesions with CBCT than with conventional radiographs [10]. CBCT may also be indicated to help confirm the absence of an odontogenic aetiology of pain when looking for diagnosis of nonodontogenic causes of pain [11].

11.2.2 Vertical Root Fracture (VRF)

Although CBCT may reveal radiographical signs of subsequent bone loss related to VRF, CBCT is not recommended for the diagnosis of VRF particularly in root-filled teeth. Indeed, the image scatter produced by the root filling masks the area of the

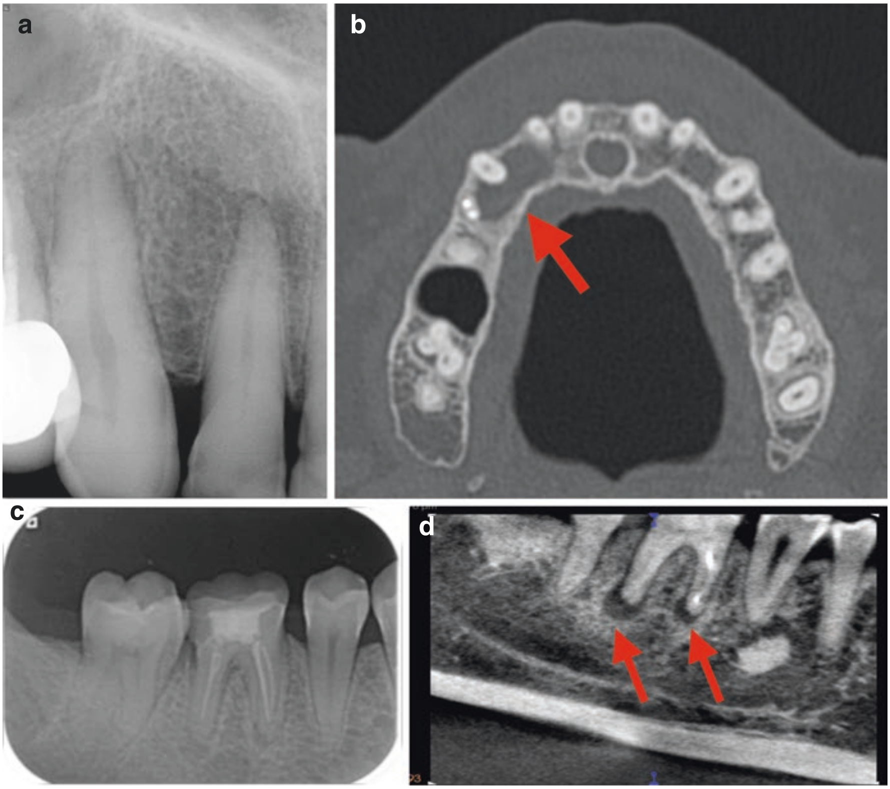


Fig. 11.1 Detection of apical periodontitis using conventional radiographs and CBCT. On initial periapical radiographic examination of the right maxillary canine (**a**), periapical lesion is almost not detectable, whereas axial section of CBCT reveals a lesion extending from the first premolar to the second lateral incisor (**b**). Periapical lesions are more prone to be masked by the width of bone at the mandibular level: periapical lesion of the first mandibular molar, previously endodontically treated, is barely detectable and visible on a periapical radiograph (**c**). CBCT 0.076 mm axial and (**d**) parasagittal images clearly demonstrate an additional canal that was not previously treated

root that needs to be assessed. Moreover, CBCT scans cannot reliably detect small cracks [12]. Larger fractures are likely to be evident clinically (Fig. 11.2) or on periapical radiographs.

11.2.3 Periapical Surgery

When planning surgical access in endodontic surgery, CBCT is useful to provide accurate information as to the size and location of the endodontic lesion. Moreover, CBCT scans accurately determine the relationship of adjacent anatomical structures (the maxillary sinus and inferior dental canal) to teeth with endodontic lesions. CBCT also help to determine whether membranes and grafting procedures are mandatory in case of lesion involving both cortical plates.

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

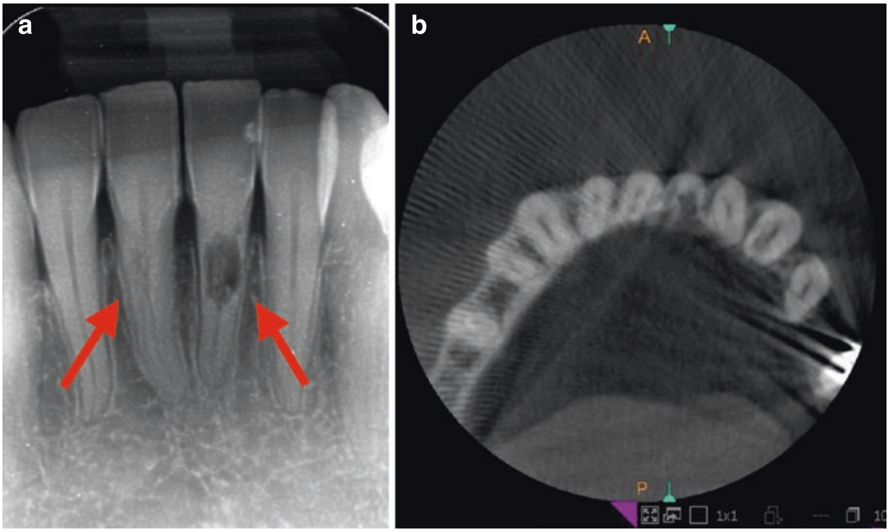


Fig. 11.3 Radicular root resorptions of the central mandibular incisors are visible on the conventional 2D periapical radiograph (**a**). The CBCT helps clinician to know the extension of the resorption (class IV Heithersay) (**b**). In this clinical case, the left central incisor cannot be treated because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

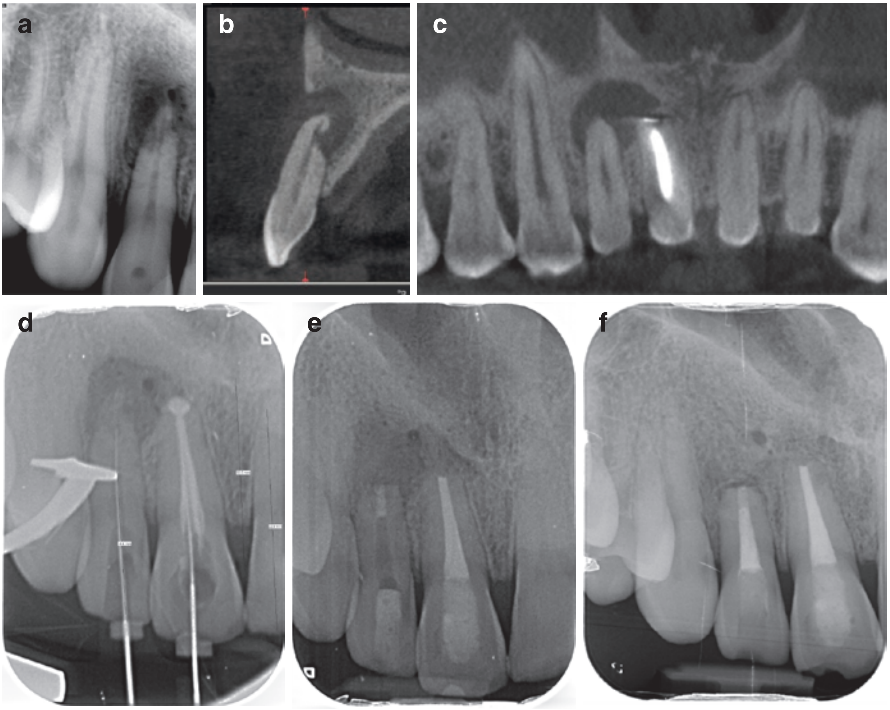


Fig. 11.4 Clinical case of periapical lesion involving central and lateral right maxillary incisors. Radicular root resorption is detectable on periapical radiograph; however it does not really help for managing the case (**a**). On the CBCT, the location of the resorption is visible on the palatal site of the apex of the right lateral maxillary incisor (**b**, **c**). This case had been treated with a combined approach. First, orthograde retreatment of the right maxillary central incisor and initial treatment of the right lateral maxillary incisor were performed (**d**). Then, periapical surgery was done in order to manage surgically the external root resorption (**e**). Healing is complete around the apices, and a residual connective tissue can be seen 4 years after surgery (**f**)

11.2.5 Dental Alveolar Traumatology

CBCT reveals a considerable amount of information about the nature, location, and extension of dentoalveolar injuries in particular in cases where clinical and conventional radiographic assessments are inconclusive, such as horizontal root fractures [11] (Fig. 11.5). Moreover, patients are likely to find the extraoral CBCT imaging technique far more comfortable than tolerating intraoral beam holders, in particular when teeth are mobile or fractured or when there are soft tissue lacerations. This information may not only aid formulating a diagnosis but also improve treatment management and outcome.

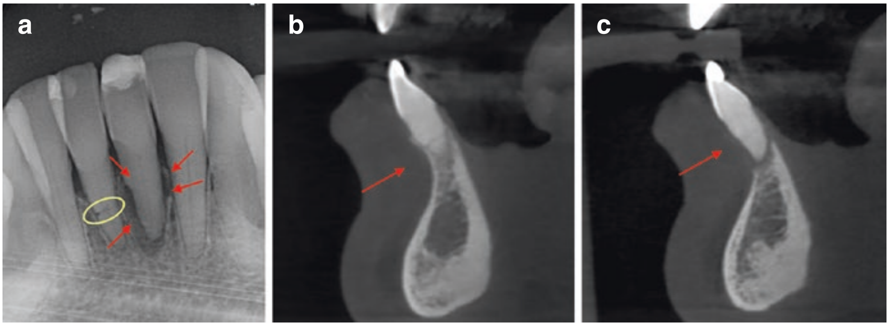


Fig. 11.5 Horizontal root fractures after dental trauma on central mandibular incisors. The periapical radiograph was taken 1 month after the trauma. A horizontal root fracture is easily detectable on the right central incisor (yellow circle). However, on the left central incisor, the horizontal root fracture is not visible; note the bone lesion around the left central mandibular incisor (**a**). Horizontal fracture on the right central mandibular incisor on CBCT section (**b**). Horizontal fracture on the left central mandibular incisor on CBCT section (**c**)

11.2.6 Complex Endodontic Anatomy

CBCT is particularly useful for assessing teeth with known complex anatomy, such as dens invaginatus and fused teeth [13]. Location, entrance, and number of root canals result in predictable identification but also have the advantage of minimizing the size of the access cavity.

11.3 Guided Endodontics

Hence, guided access cavity for teeth with pulp canal calcification and surgical endodontics qualify for use of CBCT. 3D imaging helps in visualization and planning of endodontic therapy, but it does not physically guide an instrument. The purpose of a 3D template based on the 3D data obtained from CBCT is to guide clinicians to perform more accurate and less invasive surgical procedures. For better visualization, 3D images need to have high resolution and adequate contrast. Image quality is therefore essential and is associated with physical parameters of the acquisition such as linearity, geometric accuracy, homogeneity, and spatial resolution. Small field of volume (FOV) at 50–80 mm with high resolution (voxel size from 0.07 to 0.125 mm) is sufficient to provide workable digital imaging and communication (DICOM) files with less radiation and better resolution as a large FOV for endodontic use [14, 15].

11.4 Microguided Access for Orthograde Treatment

The goal of a root canal treatment (RCT) is to prevent or treat apical periodontitis by combination of mechanical instrumentation, disinfection, and filling of the root canal system. However, this goal can be difficult or even impossible to achieve when the root canal system is reduced or totally blocked by pulp canal mineralization or calcification. The dental pulp produces tertiary dentin or pulp stones as a response to an external irritation or trauma or as a result of aging. The exact cause and frequency of pulp mineralization remain largely unknown despite a number of microscopic and histochemical studies [16, 17]. Reported rates vary from 4% to 78% [18, 19] with higher incidence associated with aging and luxation injuries after dental trauma. External irritants include carious lesions, coronal restorations, orthodontic forces, and vital pulp therapy procedures [20, 21].

RCT is not recommended on teeth showing mineralization unless irreversible pulpitis occurs. Only 1–27% of teeth with pulp mineralization become irreversibly inflamed [22, 23]. If a RCT is required, difficulties in locating canal orifices and mishaps such as excessive preparation of access cavity, perforation, and file breakage are frequently encountered, which may lead to a reduced prognosis (Fig. 11.6). Mineralized or calcified canals are considered as high-difficulty cases by the American Association of Endodontists (AAE), especially in mandibular incisors [24]. Specialists in endodontics are more skilled to manage such cases with the help of specific burs, ultrasonic instruments, and microscopes

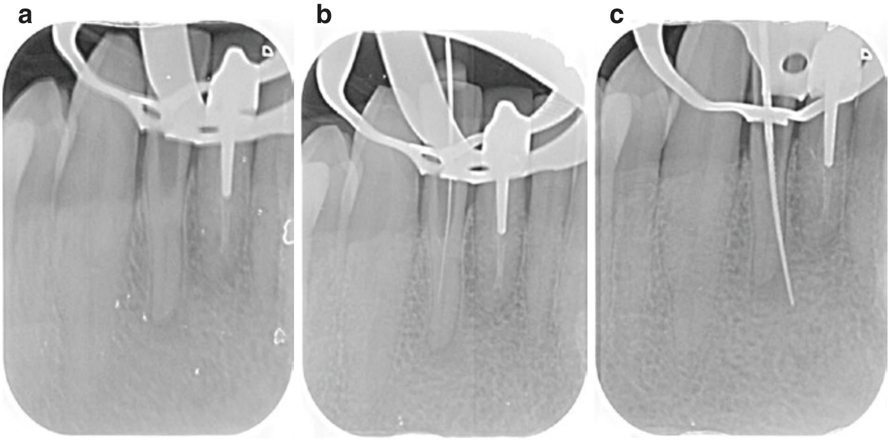


Fig. 11.6 Pulp canal obliteration in central mandibular incisor illustrating difficulties encountered by clinicians. (**a**) Attempt by general practitioner to treat tooth number 25. Periapical diagnosis was: acute apical abscess. Pulp canal obliteration and over-preparation of the access cavity are visible on the periapical radiograph. (**b**, **c**) Endodontic file showing perforation of the tooth

(Fig. 11.7). However, even in a specialist's hands, there is no guarantee that difficulties and mishaps associated with treating calcified canals will be hurdled or prevented. There is clearly a need for a better and more cost-effective technique that could be used, particularly by general practitioners, in addressing calcified cases.

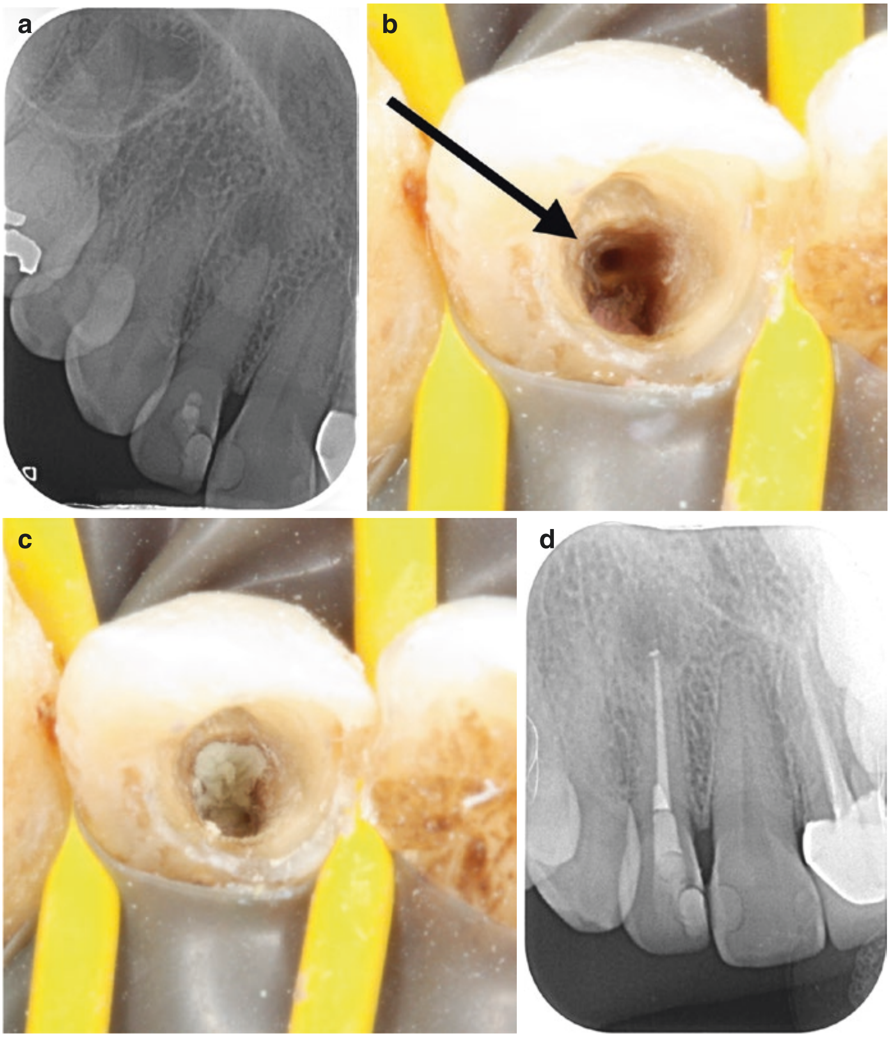


Fig. 11.7 Management of pulp canal obliteration and perforation in lateral maxillary incisor using operative microscope. (**a**) Preoperative radiograph of the maxillary lateral incisor showing apical lesion, pulp canal obliteration, and attempt to find canal. (**b**) Access cavity was modified and extended lingually, locating the actual canal. Black arrow shows an iatrogenic dentin defect from previous attempt to locate the canal. (**c**) Root canal treatment was performed. Defect was sealed with Biodentine®. (**d**) Periapical radiograph at 6-month recall

Guided access cavity with a prefabricated 3D printed template can be a potential tool to better address calcified canals. Its principles are based on the templates already used for implant placement. Stability and proper seating of the fabricated template are first checked. Once properly seated, a small portion of enamel is removed with a diamond bur to expose dentin. Guided access cavity preparation is then performed using a preselected drill. Irrigation is carried out intermittently to avoid overheating the tooth. As irrigant flow is not efficient at this point, the drill needs to be used with pumping movements. The apical target point is reached when the end of the shaft of the drill touches the sleeve.

Microguided access is new in endodontics and its literature is scarce; however, this should increase in the future as CBCT machines and intraoral scanners are becoming more and more popular in general practitioners' offices. Mandibular and maxillary incisors are the best candidates for microguided endodontics for the following reasons: first, templates are easy to use because inter-arch space usually allows positioning of the template and burs, and second, access to the canal is often straight in contrast with molars, where curves are often encountered. However, clinical cases using this approach for premolars and molars with pulp canal obliteration are also reported.

11.5 Endodontic Surgery

Endodontic surgery or apicoectomy is a viable treatment option in cases of nonhealing apical periodontitis. The prognosis of this intervention was considered uncertain with very variable success rates ranging from 25% to 90% [25–27]. During the last 25 years, however, endodontic surgery has changed tremendously due to the incorporation of magnification (endodontic microsurgery or EMS), CBCT, ultrasonic tips, and more biocompatible filling materials such as intermediate restorative material (IRM), Super EBA, mineral trioxide aggregate (MTA), and its derivatives [28]. These technical and material advances in EMS have significantly improved the treatment outcome to over 90% compared with traditional root-end surgery [29, 30], and the success rate of EMS is now similar to that of dental implants [31, 32]. The common challenges associated with the EMS are difficulty in accessing root tips (mandibular and maxillary molars) and proximity of critical structures such as the mental foramen, the inferior alveolar nerve, or the nasal cavity (Figs. 11.8 and 11.9). Without adequate planning, these difficulties can be a hindrance in successfully performing the procedure using a free-hand approach. Surgical guidance given by 3D printed templates may allow for a consistently accurate and reliable access to the apex of a root and, at the same time, minimize the risks of damaging adjacent critical anatomical structures [33, 34]. Moreover, such templates help preserve the cortical bone and surrounding structures, allowing the clinician to perform minimally invasive yet maximally effective endodontic microsurgery.

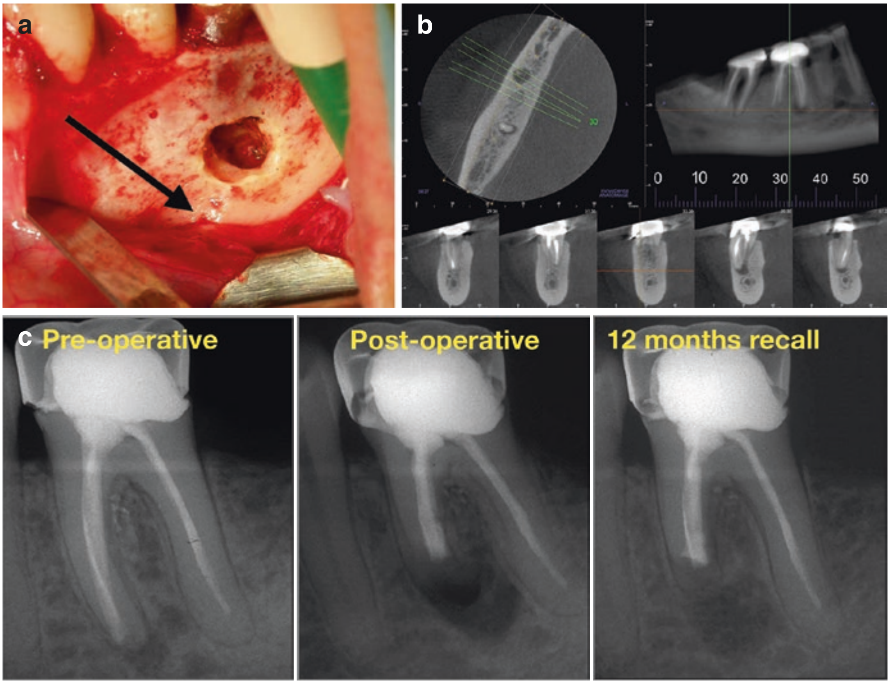


Fig. 11.8 Endodontic microsurgery on mesial root of first mandibular molar. (**a**) Black arrow showing the position of the mental nerve. Note the thickness of the buccal bone. (**b**) CBCT showing proximity between mandibular molar and inferior alveolar nerve and mental foramen that may be damaged by reflection of the flap or the vertical incision. (**c**) Pre-op, post-op and 1-year recall radiographs

11.6 Template Preparation

11.6.1 Impression

A virtual model is required for planning microguided orthograde RCT or guided EMS. Intraoral scanners (IOS) can be used for capturing the direct optical impressions needed to generate the virtual model. Similar to other three-dimensional (3D) scanners, IOS project a light source (laser or, more recently, structured light) onto the object to be scanned, in this case the teeth to be endodontically treated. These point clouds are then triangulated by the same software, creating a 3D surface model (mesh) [35]. The 3D surface model of the tissues obtained by optical impression is used for planning the position of the burs and to draw surgical templates that are useful for osteotomy during guided EMS. Due to its higher scanning resolution, IOS have replaced the old technique of double scanning with CBCT only, which was based on radiologic scans of the patient and of the patients' plaster models. The use of IOS allows the detection of all details of the occlusal surfaces with greater accuracy [36].

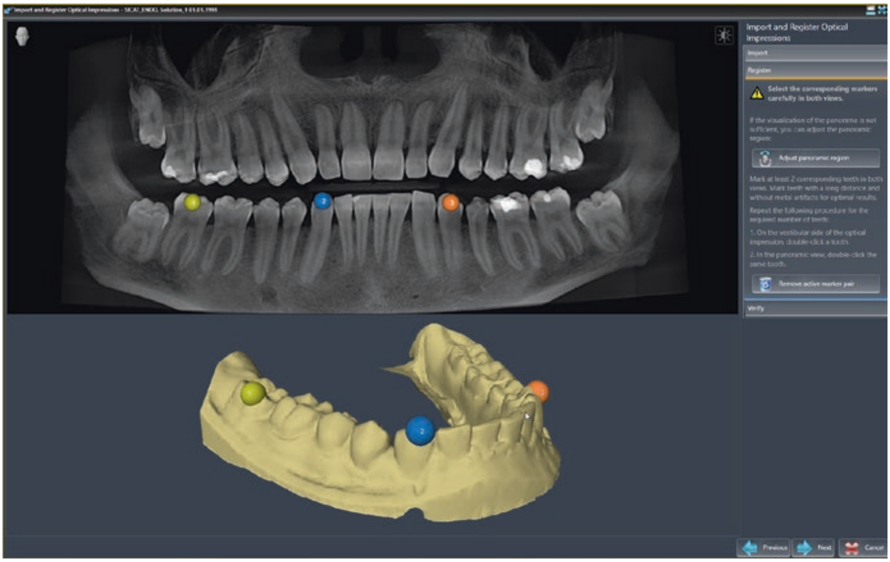
Fig. 11.9 Endodontic microsurgery on mesial and distal roots of a mandibular right first molar. (**a**) Preoperative radiograph showing apical lesion on both roots. Periapical diagnosis was acute apical abscess. Crown had good marginal seal with fiber posts in the mesial and distal roots. (**b**–**d**) In order to have access to the root apices, a bony lid approach was performed with piezoelectric ultrasonic vibration. This surgery was performed "free hand" and required particular focus on the position of the other roots and the position of the alveolar inferior nerve. (**e**) Immediate postoperative radiograph. (**f**) Three-month recall showing healing of the bony lid and decrease in the size of the apical lesion. (**g**) Twelve-month recall showing decrease in the size of the apical lesion in comparison with preoperative radiograph. Symptoms disappeared after the surgery

When considering single-tooth restoration and fixed partial prostheses of up to 4–5 components, optical impressions are clinically satisfactory and similar to that of conventional impressions; however, soft tissue scanning can be challenging in edentulous area [2, 37]. For guided access cavity, optical impression is quite easy to obtain, whereas for surgical endodontic applications, optical impressions are more difficult to obtain because more soft tissue registrations are needed. In case of surgical endodontic application, a conventional impression can be made with polyvinyl siloxane or irreversible hydrocolloid [38, 39]. Scanning data of the cast or direct impression allows generation of a 3D model. The most widely used digital format is the open STL.

11.6.2 Design

In order to design the template, digital impression and CBCT DICOM files are merged in implant planning software such as coDiagnostix® (Dental Wings Inc., Montreal, Canada), OnDemand3D® (Cybermed Co., Seoul, Korea), Mimics® (Materialise, Leuven, Belgium), and Blue Sky Plan 3® (Blue Sky Bio, LLC, Grayslake, IL). SICAT Endo® (SICAT, Bonn, Germany) is the only software designed specifically for endodontics (Figs. 11.10 and 11.11).

For microguided endodontic access in mineralized canals, a virtual copy of the drill that will be used is incorporated in the design template, and its correct position



Select the corresponding markers carefully in both views.

If the visualization of the panorama is not sufficient, you can adjust the panoramic region:

Mark at least 2 corresponding teeth in both views. Mark teeth with a long distance and without metal artifacts for optimal results.

Repeat the following procedure for the required number of teeth:

1. On the vestibular side of the optical impression, double-click a tooth.

2. In the panoramic view, double-click the same tooth.

Fig. 11.10 CBCT scan of the mandibular arch and surface STL data of an intraoral scan of the mandibular arch can be merged by identifying three landmarks (yellow, blue, and orange). Images from SICAT Endo® (SICAT, Bonn, Germany)

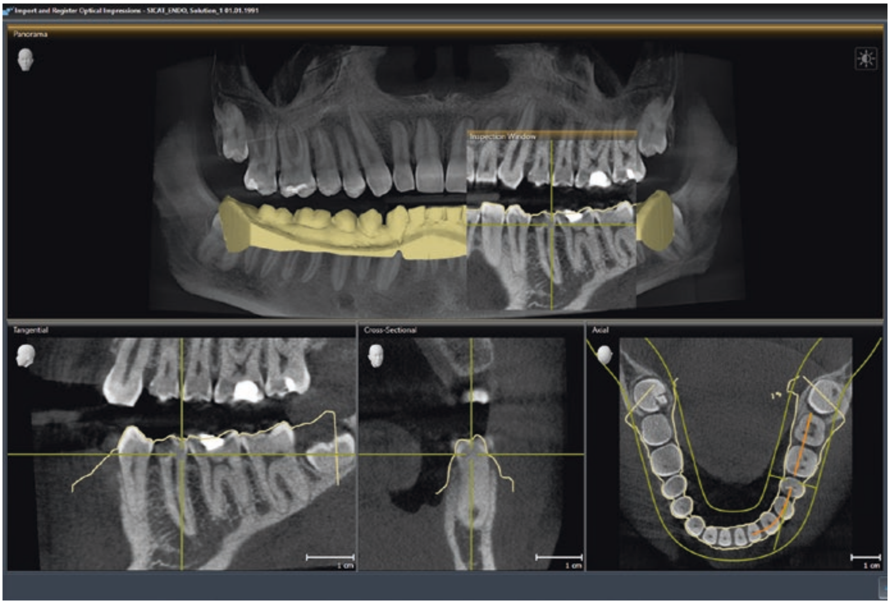


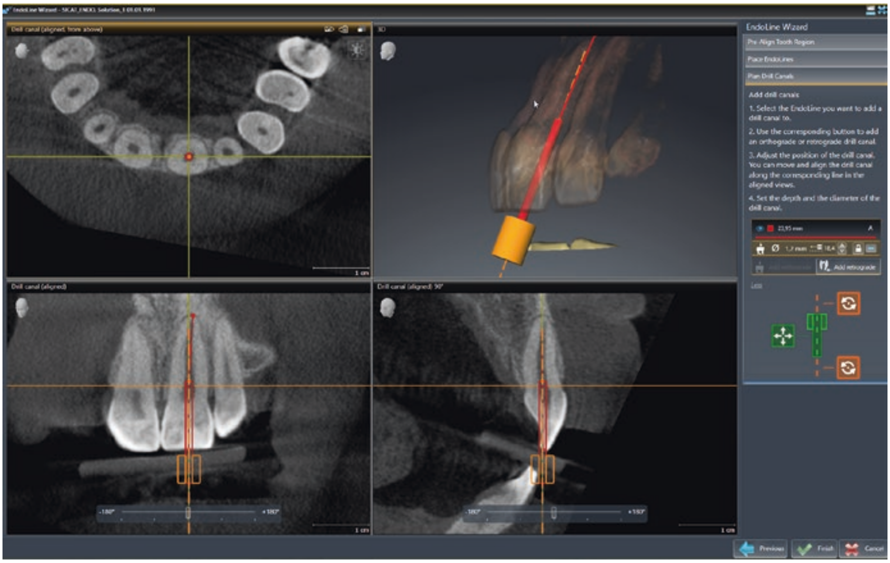
Fig. 11.11 Accuracy and adaptation of the CBCT 3D reconstruction and the 3D reconstruction from an optical impression can be visualized by adjusting transparency layers. The yellow lines show data from the optical impression. Images from SICAT Endo® (SICAT, Bonn, Germany)

is checked three dimensionally. Depth penetration is calculated so that the pulp canal is also prepared [40]. A small opening is to be created so the drill has to be less than 0.85 mm in diameter with sufficient length to go through template and trough the coronal and radicular portion of the tooth (Fig. 11.12). The total length of the drill is between 20 and 37 mm. A guide is customized and virtually incorporated into the planning prior to the template creation.

For EMS design templates, anchor pins can be used to target the root apices. Guide depth is adjusted until the anchor pin reaches the apex. Angulation of the anchor pin needs to be adjusted in order to avoid interferences with lips and buccal cheek. The depth penetration and angulation of the drill will be controlled by a stop. Appropriate osteotomy size, bevel angle degree, and apical resection level of the root ends are pre-planned virtually [39] (Fig. 11.13). In both microguided endodontic access and EMS, stereolithography files are generated and exported to a 3D printer.

11.6.3 Fabrication

3D printing technology has been adopted by surgeons at an impressive rate. For their clinical use, stereolithographic files are exported to a 3D printer to create a working model. In endodontics, 3D printers such as Objet Eden 260 V (Stratasys



Add drill canals

1. Select the EndoLine you want to add a drill canal to.
2. Use the corresponding button to add an orthograde or retrograde drill canal.
3. Adjust the position of the drill canal. You can move and align the drill canal along the corresponding line in the aligned views.
4. Set the depth and the diameter of the drill canal.

Fig. 11.12 Virtual planning of microguided access. The virtual copy of the drill is positioned so that the tip reaches the radiographically visible part of the canal. Images from SICAT Endo® (SICAT, Bonn, Germany)

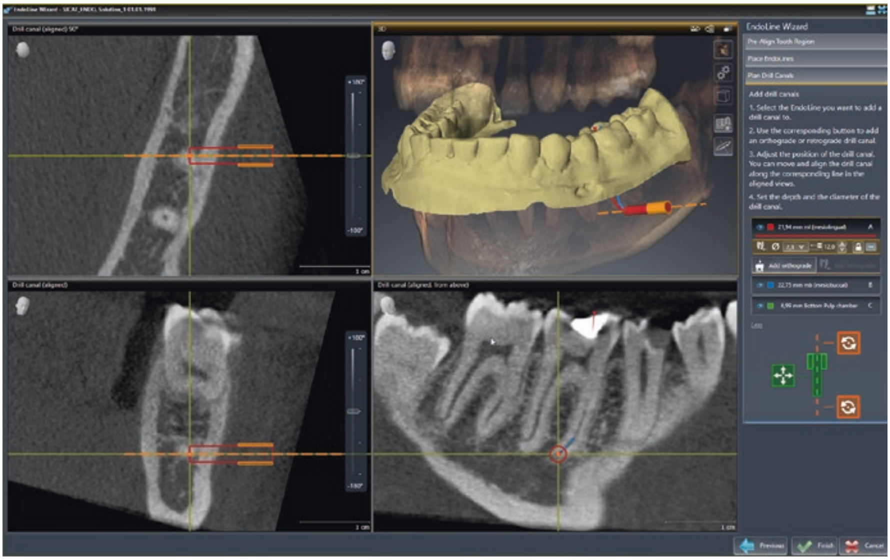


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Fig. 11.13 CBCT data and STL files are merged, and a virtual drill is placed to target the mesial root of tooth number 19. Thickness of the buccal plate, distance to the apex, and position of the different canals can be visualized to help decide whether the drill needs to be slightly tilted because of potential interference with the cheeks. Images from SICAT Endo® (SICAT, Bonn, Germany)

Fig. 11.14 Example of template and drill that may be used for microguided endodontics. Note the sleeve that gives accuracy to the direction of the drills. Images from SICAT Endo® (SICAT, Bonn, Germany)

Ltd., Minneapolis, MN, USA) or Objet350 Connex (Stratasys Ltd.) have been used, but any 3D printer that fabricates implant guides may be utilized. There are several 3D techniques, materials, and resolutions. In addition, 3D printer manufacturers provide a number of variations in materials that can differ in color, density, flexibility, texture, durability, and tensile strength. For endodontic applications, transparent template materials are desirable. The template also needs to be hard enough to withstand distortion, but at the same time, it should allow positioning on the tooth to be performed with ease. Moreover, sterilization methods must be compatible with the materials used [41]. Computerized numerical control (CNC) technology is used to fabricate designed sleeve, which are integrated into the printed template to guide the drills during cavity preparation or through the course of surgical endodontics (Fig. 11.14).

11.7 Clinical and Ex Vivo Reports on Guided Endodontics

Given that the use of 3D template technology has not been extensively explored in endodontics, the current reports related to it are limited to in vitro studies or clinical cases.

11.7.1 Guided Access Cavity

Guided access cavities seem to be very extremely accurate. In a study involving maxillary teeth that were accessed using a drill with a total length of 37 mm, a working length of 18.5 mm, and a diameter of 1.5 mm, deviations of planned- and prepared-access cavities were as low as 0.16–0.21 mm at the base of the bur and 0.17–0.47 mm at the tip of the bur [42]. Mean of angle deviation was only 1.81°. In another study in mandibular incisors, the deviations between the planned- and prepared-access cavities were also low, ranging from 0.12 to 0.13 mm at the base of the bur and 0.12 to 0.34 mm at the tip of the bur [43]. The mean of angle deviation was 1.59. Interestingly, in both studies the preparation time of these apically extended access cavities took less than 10 min, and there was no statistically significant difference between operators.

Using guided endodontic access primarily offers the advantage of significantly reducing mishaps in severely mineralized cases. At this time, there are no prospective in vivo outcome studies to fully support this technique, but it appears to be a promising adjunctive tool to address a known difficulty in RCT. Furthermore, there are obstacles that still need to be hurdled. Guided access endodontic may not be used for posterior teeth because of the space required for the template and the drill. Moreover, this technique may be used only in teeth with straight roots or in the straight part of curved roots. Forces generated by the drill are difficult to control, and there is a risk of producing microcracks in dentin, which have not been assessed at the moment [44]. Practitioners must therefore pay attention to use drills with good cutting efficiency and to irrigate and clean the drills to minimize initiating or propagating cracks.

11.7.2 Surgical Endodontics

Published studies on guided EMS are also limited to a few clinical cases [39, 45]. The reported advantages are decreased osteotomy size and reduced time in exposing root ends. All these advantages may contribute to less severe postoperative complications such as pain and swelling. Guided osteotomy using a 3D printed surgical template can also be useful in cases where access or vision poses a challenge (e.g., second molars) or when critical anatomical structures such as the maxillary sinus, greater palatine artery, and inferior alveolar and mental nerve become a concern. Although time spent during surgical phase is reduced, preoperative preparation requires technical expertise, equipment, and software to merge files and to design and print templates. These procedures are costly and still time-consuming in comparison with the traditional approach.

11.8 Conclusion

CBCT and intraoral scanners are becoming increasingly more popular among dentists. Eventually, the use of 3D guides may turn out to be the “go-to” technique to address difficulties in both orthograde and microsurgical endodontic access. However, compared to implant dentistry, we are still in the early phase of digital endodontics, and solid evidence is still largely lacking. The approach fits with the actual concept of minimally invasive dentistry, but the cost, time, and irradiation related to CBCT, the required expertise to operate the software, and the need to fabricate sterilizable templates with a chairside 3D printer can discourage some clinicians. Alternatively, commercial 3D printing laboratories with expertise in implant surgical guide fabrication may be able to deliver printed templates. Though in every case, clinicians must check every parameter of the guide to avoid mishaps as they are ultimately responsible for their work.

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