



The Impact of Technological Innovation on Dentistry

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Abstract

Technology has revolutionized the way dentists are able to treat their patients. These technological advances have paved the way for the creation of virtual patient models utilizing these 3-dimensional intra-oral patient models, cone beam computer tomography (CBCT) radiograph scans, extraoral 3-dimensional scans, and jaw motion tracings to create a patient-specific model. These models are advantageous in planning surgical treatments by providing 3-dimensional views of vital anatomical structures to accurately identify the location, size, and shape of a structure or defect in order to plan accordingly. Virtual augmentation of either hard tissue (bone) and/or soft tissue (i.e., gingiva) can also be accomplished.

Technology has allowed the capture of the dynamic motions of the jaw and combined them with the virtual patient to develop permanent restorations in harmony with the patient's orofacial complex. With the introduction of new technology in the realm of digital dentistry, patient care is being brought to a new and higher level. This creates a level of more optimal care that a dentist can deliver to patients.

Keywords

Digital dentistry · 3-dimensional model · Virtual model · Virtual patient · Patient-specific model · Jaw movement tracing

5.1 Introduction

Advances in the area of digital dentistry have propelled the profession of dentistry into a completely new era. Historically, impressions of patients' teeth were taken using an alginate material and poured in dental stone to create models. These models were then utilized, along with 2-dimensional radiographic images, to evaluate bony structures. However, dentists now use wands that intraorally scan the patient and are able to create 3-dimensional virtual models of the patient's teeth. These 3D models from the scan allow for the beginning of the creation of virtual patients—both general models for educational use and patient-specific models (Joda et al. 2019). The creation of these comprehensive patient models can be accomplished with the combination of any number of components, including 3-dimensional intra-oral patient models or surface scans, cone beam computer tomography (CBCT) radiograph scans, 3-dimensional extraoral scans, and jaw motion tracings.

Definitive advantages are associated with these patient-specific models when planning various surgical treatments because they are able to

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provide the dentist with 3-dimensional views of vital anatomical structures that may have not been able to be visualized on a traditional 2-dimensional radiograph. An enormous benefit associated with these new 3-dimensional views is that the models are to scale, allowing the surgeon to plan treatment effectively by providing enhanced accuracy in identifying the location, size, and shape of a structure or defect. Whether planning surgery on the maxilla (upper jaw) or mandible (lower jaw), the surgeon must be cognizant of the vital structures, such as blood vessels and nerves, that are located in these areas. If these structures are injured, it could result in extreme and/or prolonged harm to the patient. The knowledge of the location of these defects enables the surgeon to alter the plan to be able to lessen the effects the defect can have on the surgery. For example, one can virtually examine the complex anatomy of a sinus, location of various septa, and various neurovascular bundles of a patient prior to performing the actual surgical procedure. This translates into decreased surgical time as the surgeon is more familiar with the patient's anatomy prior to beginning the procedure. The need for virtual augmentation of either hard and/or soft tissue during a surgery can also be determined based on these virtual models, along with the ability of the surgeon to attain an accurate measurement of the amount of grafting material that will be utilized for the surgery.

In the area of restorative dentistry, the ability to conduct a 3-dimensional oral reconstruction of the patient's dentition is incredibly useful. This is accomplished by combination of intra-oral scans, facial photographs, and 3D radiographic images to create a "virtual model" of a patient. These virtual models allow the development of permanent restorations that are in harmony with the patient's orofacial complex—both esthetically and functionally. Specifically in esthetic dentistry, the virtual patient enables the dentist to evaluate the shape and position of the patient's teeth relative to their facial structure and create a virtual simulation of proposed restorations (Garcia et al. 2018). This virtual mock-up is incredibly useful for communication between the patient, dentist, and laboratory technician.

Historically, the fabrication of dental restorations was created on an analog articulator—a mechanical device on which the dentist would mount upper and lower jaw models to simulate the patient's functional jaw movement. However, this device is limited by linear movements, so it does not completely model the patient's function because jaw movement occurs in multiple planes. Nowadays, technology has allowed us to capture the dynamic motion of the jaw and combine it with the virtual patient to design patient-specific restorations that are in synergy with the patient's actual jaw movements (Lepidi et al. 2020).

A promising area emerging in digital dentistry is the utilization of diagnostic imaging of a patient's airway to aid in the diagnosis and treatment of sleep apnea which affects approximately 1 billion people worldwide. Therefore, development of these new technologies, both hardware and software, in the realm of digital dentistry, is bringing patient care to a new and higher level. This tremendously facilitates the role of the dentist in providing more optimal care that a dentist can deliver to their patients.

5.2 Creating the Virtual Patient

The creation of a virtual patient begins with a scan of the patient's teeth using the digital impression system. The scan renders a 3-dimensional virtual model of the teeth that can be created in two different ways. The first way involves scanning the traditionally made stone models with either a laboratory scanner or intra-oral scanner (IOS), while the second way involves directly scanning the patient's oral cavity with the utilization of an intra-oral scanner (Fig. 5.1).

Intra-oral scanning (IOS) has several distinct advantages over the conventional impression materials and techniques (Marques et al. 2021; Rutkūnas et al. 2017). For patients, IOS provides less discomfort by eliminating the need for impression trays loaded with a considerable amount of impression material that tends to elicit the gag reflex which is overall unpleasant. The second advantage which patients enjoy is the decreased amount of time needed for the



Fig. 5.1 Intra-oral scan of patient capturing both hard (teeth) and soft (gingiva) tissues. Color is picked up by the scanner

3-dimensional model. An experienced clinician is able to complete a scan in just a few minutes. For the clinician, digital impressions allow for a cleaner, faster, and more accurate representation of the patient's oral cavity. Utilizing the traditional method requires mixing and pouring dental stone into the impression, along with a period of time in which the dental stone must be set. After which, trimming and cleaning the models are needed. Also, legally, dentists are required to keep patient models for a specific number of years depending on where their practice is located because they are considered a part of the patient record. Virtual models facilitate this requirement by allowing the models to be stored virtually and not requiring an actual physical space. This is a considerable benefit to those clinicians with thousands of patients in their practices.

Intra-oral scanners are handheld devices that typically consist of a wand with a camera in the tip. The wands are moved to capture all angles of the patient's teeth, taking hundreds of pictures as it progresses. The ability to scan is easily accomplished and dentists find that there is a short learning curve associated with it. While the technology used in these scanners varies, the result of the pictures is a 3D mesh created from a point cloud using a mathematical algorithm. This 3D mesh is the virtual model of the patient's dental arch, capable of capturing both hard and soft tissue (Fig. 5.2).

Intra-oral scanners are most often used to scan a patient's oral cavity while the individual is

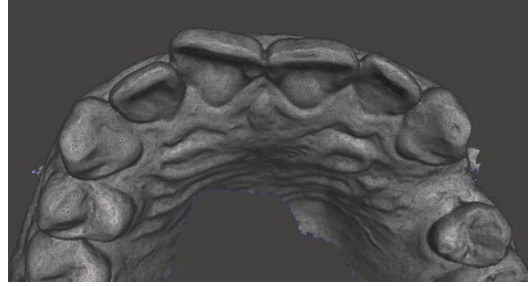


Fig. 5.2 Intra-oral scan of patient illustrating the point cloud that actually makes up virtual models

sitting in the dental chair, which is the reason they are often referred to as chairside scanners. There are numerous scanners on the market with features that target different types of users. Some of these scanners employ the technology that also allows the capture of various shades and colors of the anatomical structures and embeds that information in the 3D mesh, creating life-like recreations of the patient's intra-oral cavity (Haddadi et al. 2019). This colored mesh is an advantage over the monochromatic lab scanners because it allows for the visualization of a more realistic virtual model of the patient, which can aid in some diagnostic procedures.

Chairside scanners embed 3-dimensional positioning coordinates into the digital scans during the scanning process (Fig. 5.3). These coordinates provide the relationship of the maxilla, to that of the mandible, whenever the scans are viewed in the software. However, this captured relationship between the dental arches is static and only represents when the two jaws are biting together fully. While this is useful and might be all that is necessary for some applications (for example—smile analysis), other applications require the dynamic movement of the mandibular arch with respect to the maxillary arch (ex—fabrication of nightguard for teeth grinding or a crown). Some intra-oral scanners claim to capture this dynamic movement; however, these scanners are only capturing the beginning and end, which results in a straight line of movement. This is not a true representation of the human body and the movement of the temporo-mandibular joint, which is

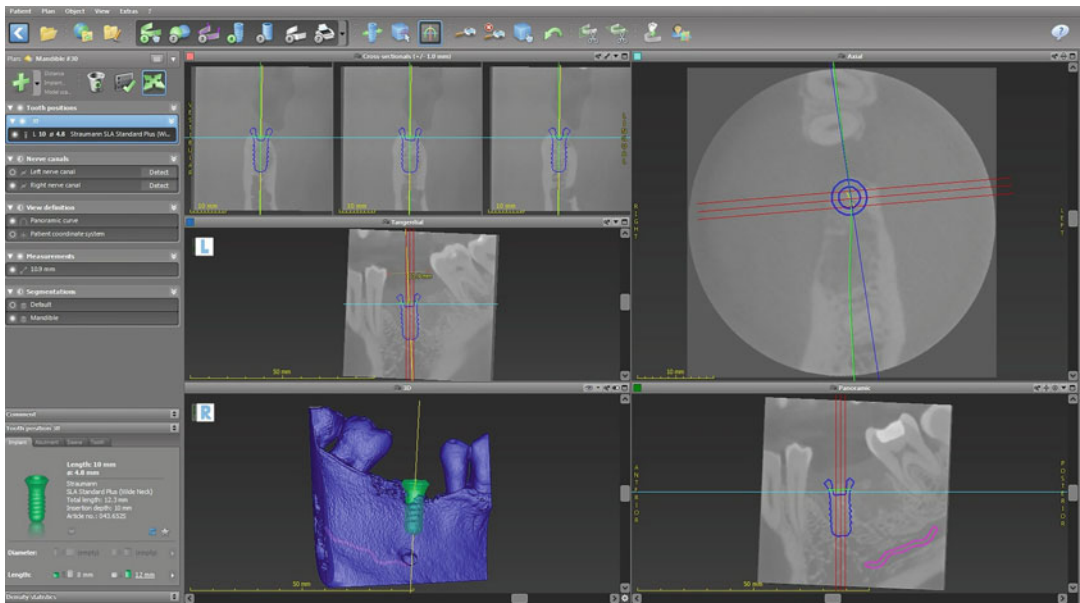


Fig. 5.3 Implant planning software demonstrating the integration of virtual models (blue) to the CBCT to facilitate planning

more fluid and more curvilinear in nature (Clayton et al. 1971).

5.3 Utilization of the 3-Dimensional Model

Cone-beam computed tomography (CBCT) is a radiographic imaging technique that utilizes round or cone-shaped x-rays to capture numerous images as the scanner rotates around the patient. This type of image creates certain advantages over traditional 2D radiographs, including the elimination of image magnification, overlapping of anatomical structures, and image distortion. These images are saved as Digital Imaging and Communications in Medicine (DICOMs) files, which consist of a collection of voxels—the unit of graphic information that defines a point in three dimensions. This radiographic imaging method provides an accurate, 3-dimensional model of hard tissue structures that is accomplished

through either “surface” or “volume” rendering. Surface rendering utilizes gray scales of the CBCT to create the model. The model can be used for digitalization of 3D landmarks; it also can be aligned with other 3D meshes, and even enables the user to plan virtual osteotomies or bone removal surgery. Volume rendering creates the model by using the volume of voxels, to which parameters are set based on the shading algorithms. The disadvantage of this method is the inherent inability to perform virtual surgeries or the lack of the ability to align the model with other 3D meshes. The utilization of CBCT scans has become quite widespread and essential in dentistry in all disciplines. Not only are they used for diagnosis and treatment planning, but also for the creation of detailed patient-specific models and surgical guides (Baan et al. 2021).

For oral and maxillofacial surgery, the use of a CBCT allows for the determination of the precise location of anatomical features, such as neurovascular bundles and tumors, as well as

impacted and supernumerary teeth. For Endodontics, a specialty that focuses on teeth requiring root canals and their associated pathologies, CBCTs allow for the differentiation of apical pathologies, visualization of fractured teeth, and visualization of complex root morphology. For periodontics, CBCTs can aid in the diagnosis of furcation involvement due to bone loss, bone defects around teeth, pathologies, and periodontal cysts. The primary use of CBCTs in orthodontics is to aid in assessing age, adolescent facial growth, and disruptions in tooth eruptions. CBCTs have created one of the largest impacts in implant dentistry. The technology allows for the measurement of the patient's bone height and width. It also enables localization of important anatomical structures in the area of the planned implant placement, as well as provides the capability to assess the need for additional surgical procedures such as bone grafting.

As in all radiographs, any metal present in the oral cavity like amalgams (silver fillings), crowns, or existing implants can create radio-opacities. These radio-opacities result in the decreased quality of the CBCT due to masking and distorting of the anatomical structures and tooth morphology being evaluated for diagnosis on the X-ray. Several methods exist to decrease the amount of scatter and improve the CBCT scan, however, these do not help restore accurate morphology if it has been distorted. To overcome discrepancies within the oral cavity related to scatter, certain software allows the merging, or fusion, of a patient's CBCT DICOMs with their 3-dimensional digital model created by the intra-oral scan (Fig. 5.4).

This fusion creates an accurate 3-dimensional model of the patient's oral cavity, replicating both hard and soft tissue in both radiographic and dental model forms. In addition to the creation of this fused virtual model of the oral cavity, certain specialty areas of dentistry also require the ability to relate the oral cavity with external landmarks and features of the patient's face. This is of key importance when performing esthetic reconstructions either through oral and



Fig. 5.4 Patient stone models being mounted onto articulator

maxillofacial surgery or with dental restorations. The simplest and most common approach at this time is to align the intra-oral digital models to a 2-dimensional photograph of the patient. While this accomplishes the goal of enabling the use of facial features in treatment planning and restoration design, there are inherent limitations.

The first limitation, and the one with the largest impact, relates to the alignment of a 3-dimensional dental model to a 2-dimensional object, the patient photograph. Malalignment of the patient models can result in a tilt of the occlusal plane, the plane of the chewing surfaces of the teeth, compared to the patient's true occlusal plane. This will have a negative influence on the esthetic reconstruction which may not be possible to recognize until treatment is rendered. For this reason, this method is primarily used in esthetics involving dental restorations; the proposed design can be fabricated in temporary restorations,

allowing the dentist to identify the issue and correct it before proceeding to the fabrication of the final restorations. A second limitation is the ability to only view this type of virtual reconstruction from the anterior, or front. One cannot rotate the model to view from different angles due to the constraints inherent with a 2-dimensional photograph. The ability to rotate the images through various viewpoints could be an advantage as it would help evaluate the reconstructions in a more realistic 3-dimensional environment.

In order to overcome these limitations associated with 2-dimensional photographs, 3-dimensional scans of a patient's head can be obtained utilizing specialized equipment and can be accomplished by two methods. The first method involves the integration of a facial scanner within a CBCT machine. This method accurately relates the 3-dimensional head scan to the patient's DICOMs, which can then be aligned to intra-oral digital models. There is a limitation associated with this method. It requires the patient to obtain a full CBCT of the maxillofacial region, which may be unnecessary if the patient is not going to have any surgical procedures and results in more radiation exposure than needed for the patient. The second method involves the use of a "handheld" scanner that captures a photorealistic 3-dimensional image of the patient's head. For alignment, additional scans are needed which incorporate specialized markers that allow for the accurate alignment to the 3-dimensional facial scan. This method involves several more steps in order to achieve optimum alignment but does not expose the patient to unnecessary radiation. While each of these methods has advantages and disadvantages, both result in a 3-dimensional model of the patient that can be viewed from any angle, both with and without facial features. This provides the dental provider an accurate and more complete virtual patient model that allows for comprehensive diagnosis and treatment planning, something that had not previously existed. It also leads to enhanced interdisciplinary communication among various providers.

These virtual models discussed above are generally excellent tools for certain diagnosis and treatment planning, interdisciplinary communication, and help keep a record of the patient as they are presented in the dental chair. However, the majority of dental treatment takes place in the stomatognathic system, a functional environment that is composed of skeletal structures, muscles of mastication, the temporomandibular joint, and the dental arches (maxillae/mandible). This system is an incredibly dynamic environment, meaning it is in motion for most of its various functions—speaking, chewing, parafunctional habits, etc. (Peck 2016).

From the simplest restorations to complex full-mouth rehabilitations, this dynamic jaw movement must be taken into consideration, otherwise it could lead to the failure of the restoration(s). While simple dental restorations (i.e.—fillings) are easily done directly in the mouth and, therefore, adjusted to this dynamic movement intraorally, more complex restorations (i.e.—crowns) are created indirectly on the patient's dental models. Traditional methods consisted of these restorations being fabricated on stone dental models of the patient's upper and lower arches which were mounted on a dental articulator through the utilization of a facebow record.

A facebow (Fig. 5.5) is an intra-oral dental device that records the position of the patient's arches and then translates that position to the articulator. Articulators can range from simple to fully adjustable models, but all share the same limitation—they are mechanical devices, which are limited in the range of motion they can mimic because of the dynamic and non-linear movement of the lower arch.

In today's world, digital workflows for the fabrication of dental prostheses can also generate basic mandibular movement. This is accomplished by the movement of the surface scan, or 3-dimensional model, of the mandible in a direction (right, left, forward) along a flat plane that exists between the maxilla and mandible. When the mandibular scan collides with the maxillary

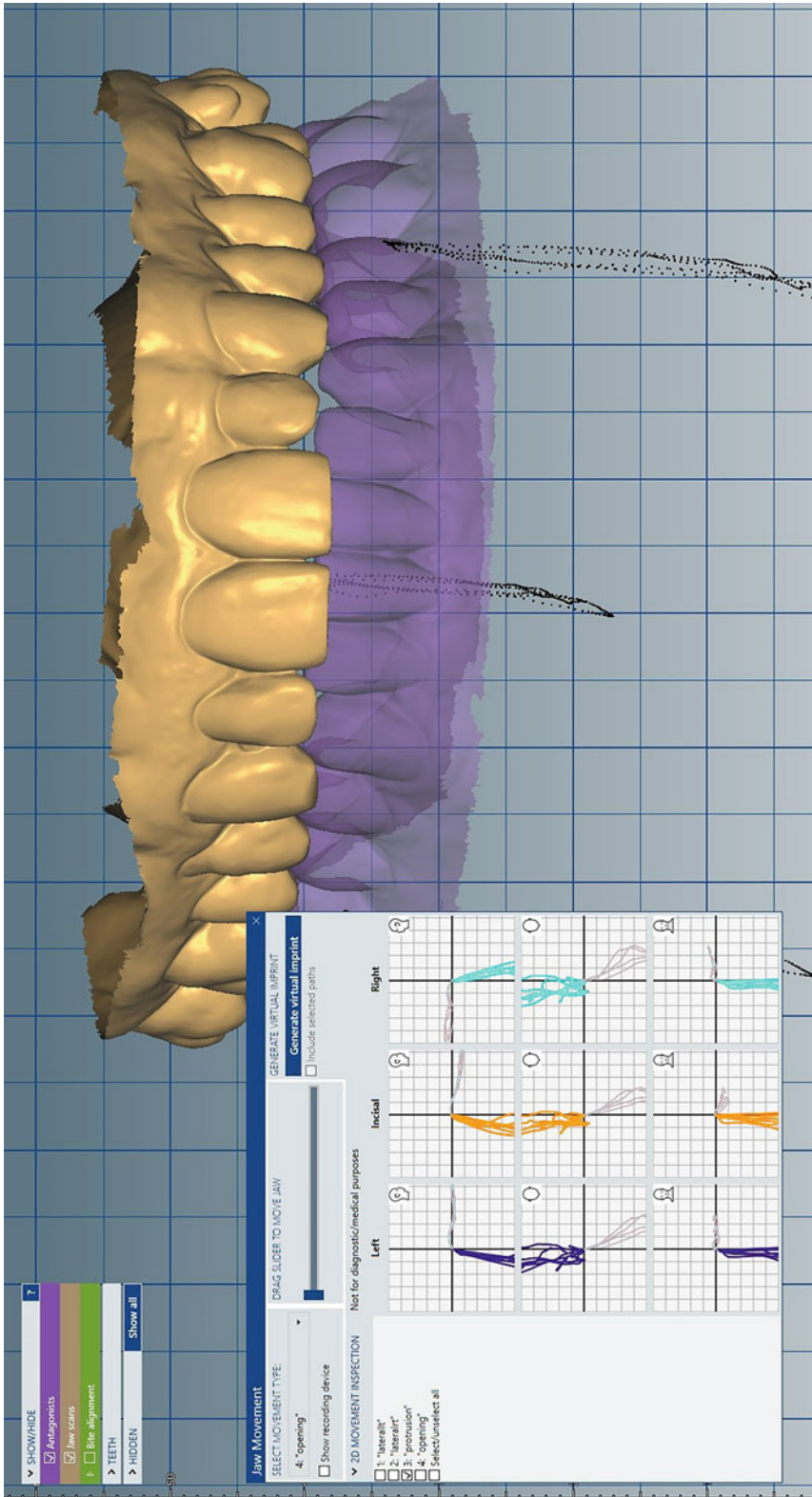


Fig. 5.5 Digital pathways of mandible being illustrated with virtual models in design software illustrated by the black dots

scan, the software will continue to move the scan but make adjustments that eliminate the intersection of the scans. This movement mimics intra-oral mandibular movement in that it replicates tooth-guided movement. However, the generation of this movement fails to consider the influence of the neuro-musculature system. To counteract this issue, specialized extraoral systems have been developed that capture the dynamic motion of the mandible (Kwon et al. 2019). These systems vary in the way data is captured but are consistent in that the dynamic motion is transferred into the design software. This allows the software to mimic the actual movement of the patient's mandible, with all factors included. Deviations, non-linear pathways, and other 3-dimensional movements can be recreated within the software, eliminating the solely mechanical movements associated with mechanical articulators (Fig. 5.6).

This digital workflow is comprised of digital versions of the facebow and articulator. In order to capture the movement of the jaw, sensors are attached to the patient's head that act as a digital facebow. The first step is registering the maxilla

to the sensors, and then registering it to the mandible.

After this is completed, the patient is instructed to move their mandible through specific positions, during which the sensors record the 3D movement pathway of the mandible. This data is imported into specific software that allows the user (either clinician or dental technician) to accurately replicate the patient's actual curvilinear jaw motion with the patient's mandibular virtual model. This allows the user to evaluate the mandibular path of movement as it relates to maxillary arch and recognize "interferences" or occurrences where the movement is limited, between the teeth of the opposing dental arches. This technology can be used in combination with CBCT to diagnose temporomandibular joint disorder, or TMD (Liao 2021). Evaluation of the jaw movements, along with the analysis of both the shape and wear in the condyle and fossa of the joint, can aid the dentist in diagnosing the causes specific for each patient to determine the most effective treatment for that individual. The ability to record and analyze a patient's actual mandibular movement is important in the evaluation of temporomandibular jaw disorders and the ability to track them over time. More research is currently needed in this area, but it indicates huge potential for this field of dentistry.

The digital applications described above are being routinely done today for the creation of dental restorations. Clinicians are also using these 3-dimensional virtual models to better evaluate and discuss treatment options, with their patients and other oral health care providers. The intra-oral scan is the simplest and most basic 3D model of a patient, and it is also the foundation upon which other technologies can be utilized.

A limitation that currently exists with digital dental technology is the inability to create a patient model that combines all of the various digital scans into one virtual model that is able to mimic the dynamic movement of the patient's extraoral soft tissue during mandibular movement that is smile, or any other facial animation. This type of virtual model would prove incredibly beneficial and would have the greatest impact in



Fig. 5.6 Sensors embedded in the cranial apparatus are used to track sensors located in the mandibular apparatus, which is attached to the patient's teeth

the area of *esthetic* dentistry and smile design. These two areas require the analysis of a patient's animated lip line to be able to achieve the optimal *esthetic* outcomes for the patient.

So far in this chapter, it has been explained how a patient-specific model for dentistry is created, including the advantages and disadvantages of the pathways and the limitations of these virtual models. The use of virtual models is easily appreciated in reference to the fabrication of various dental prostheses due to the fact that they are a replacement for traditional stone models. However, there are numerous other ways in which these virtual models are being used in general dentistry and the various dental specialties that warrant discussion in further detail.

5.4 Virtual Model Utilization in Oral Maxillofacial Surgery

One of the areas that benefits the most from these virtual models is oral maxillofacial surgery, which was first discussed at the beginning of the chapter. From orthognathic jaw surgery to implant surgery, virtual models have become mainstream in the diagnosis and treatment planning for these surgeons (Otranto de Britto Teixeira et al. 2020). Orthognathic surgery is used to correct deformities in the upper or lower jaw and the associated incorrect positioning of the teeth. To do this effectively, the surgeon utilizes a specialized software that allows the user to simulate various osteotomies (ex-sagittal split or vertical ramus osteotomy) on the virtual model while taking into consideration the patient's specific anatomical structures. For example, when planning mandibular osteotomies with a virtual model, the user is able to virtually track the inferior alveolar canal (IAC), a canal that houses an important neurovascular bundle, and creates a mesh of the pathway as it goes through the length of the lower jaw. This mesh provides the user a 3-dimensional view of the IAC pathway, allowing for more precise planning to avoid the vital

structures within. This is incredibly important because any damage to the inferior alveolar nerve can cause symptoms including: numbness, pain, burning or tingling in the lips, chin, and gums; drooling; or impaired speech. In addition, once the virtual osteotomies are performed, the sections can be repositioned and allows for a virtual generation of the model that depicts the proposed surgical outcome.

In addition to creating a virtual rendering of the final surgical results of osteotomies, surgeons are able to use certain specialized software to predict the soft tissue and hard tissue outcomes of orthognathic surgery. The software utilizes databases of documented cases to predict the soft tissue outcome based on the hard tissue changes. It has been shown that the predicted outcome for hard tissue changes is reasonably accurate, within 1 mm of the actual surgical outcomes. However, the predictions for soft tissue outcomes are more varied with the greatest area needing improvement being the region around the lower lip.

5.5 Virtual Model Utilization in Orthodontics

In the area of orthodontics, the use of lateral cephalometric analysis via a 2D image more widely used over CBCT due to the reduced amount of radiation exposure to the patient. However, there are certain cases when the CBCT and 3D visualization are superior for diagnosis and treatment planning. The primary advantage in 3D visualization is due to the inherent issue with 2D radiographic images; the fact that impacted teeth are superimposed over the other anatomical structures, and it is difficult to ascertain the exact position or impact on the tooth or anatomical structure. The 3D models allow complete visualization of these areas (Baan et al. 2020).

One of these cases involved the impaction of maxillary canines, which are the second most

commonly impacted tooth, after third molars (wisdom teeth). Impacted teeth are teeth in which tissue, bone, or another tooth has prevented it from reaching its normal position in the mouth. The surgical exposure of these teeth is one of the most common indications for CBCT imaging in orthodontics. In this type of case, the virtual model improves the treatment planning by allowing visualization of the precise location in the arch, including the proximity to adjacent teeth and other vital structures. In addition, it allows for a more accurate evaluation of the tooth follicle and enables the assessment and extent of any existing adjacent tooth resorption. This visualization enables the orthodontist to better plan the surgical access, orthodontic bracket placement, and extrusion path for the impacted tooth, which results in a better outcome for the patient.

Supernumerary teeth are extraneous teeth that can develop anywhere in a person's mouth. The most common area for these teeth to be found is in the anterior maxillae and they can be difficult to differentiate from normal dentition. These teeth are usually impacted or unerupted. Virtual models allow the orthodontist to precisely locate the teeth and determine their true morphology. This is important as it will aid in treatment planning and help determine whether the teeth are retrievable and able to be retained or if they need to be extracted.

5.6 Virtual Model Utilization in Endodontics

In dentistry, endodontics is the area that focuses on the dental pulp, the roots of teeth, and the tissue surrounding the roots. The majority of endodontics revolves around the treatment of the root canals of teeth. Root canal morphology is a complex three-dimensional structure that varies between teeth and is even found to be distinct within certain populations. Maxillary molars present with numerous variations that challenge even the most experienced endodontist. Traditional 2-dimensional radiographs are the most widely used method to diagnose and treatment plan endodontic therapy, however, these images

provide limited information and are influenced by X-ray angulation, the overlapping of anatomical structures, and contrast. For these reasons, the use of CBCT has been shown to be incredibly useful for complex cases.

The ability of a clinician to navigate through a 3D image of a tooth allows for better visualization and, therefore, a better understanding of the root canal morphology (Shah and Chong 2018). Curves, accessory canals, and even fractures of the root can be seen from different angles, allowing the clinician to better diagnose, plan, and provide treatment for the patient. It has also been used to help differentiate between endodontic and non-endodontic pathologies. Emerging dental software allows the user to virtually plan endodontic treatment by identifying anatomical abnormalities, calculating exact measurements, and choosing which instruments should be used prior to the actual treatment. Currently, the main drawback in using CBCT and virtual modeling for endodontics lies with the amount of radiation exposure, which is higher than the conventional 2D radiographs. For this reason, the use of CBCT in endodontics is only recommended for complex cases at this time.

5.7 Virtual Model Utilization in Implant Dentistry

Dental implantology involves the combination two different areas of dentistry—surgery and prosthetics—to provide treatment for a patient. This treatment can range from a simple, single-tooth replacement to full arch reconstruction supported by numerous dental implants. For any case, accurate placement is essential to achieve optimal esthetic and functional prosthetic outcomes. However, patient anatomy may limit the proposed location of the implant, requiring additional planning or even a completely different approach (Kernen et al. 2020).

The first step in digital treatment planning of a dental implant is the acquisition of surface scans of the patient. For dentate patients, this is accomplished with the use of an intra-oral scanner, as discussed previously. Edentulous patients,

however, are more complex as soft tissue can be more challenging to capture and does not exhibit a definitive shape like hard tissue due to its mobility. For this reason, there are distinctive and different pathways to create virtual models for dentulous and edentulous patients.

For edentulous patients, a well-fitting removable prosthesis (denture) is required—one that is well adapted to the patient's soft tissue. At the CBCT scanning appointment, fiducials (specialized small metal spheres for use in CBCT) are attached to the patient's current prosthesis. The patient is then scanned with the modified prosthesis in place. Subsequently, the prosthesis itself is scanned separately while sitting on a CBCT table. Afterwards, the CBCT scan of the patient wearing the prosthesis and the prosthesis alone are imported into a specific dental implant planning software that utilizes artificial intelligence to align the patient CBCT to the prosthesis CBCT using the fiducials. The software will take the prosthesis CBCT scan data and create a virtual replica (mesh) of the prosthesis. The position of the prosthesis to the patient's hard tissue is accomplished by the alignment of the fiducials. The next step in the software is to create a virtual mesh of the soft tissue by reverse engineering the tissue side of the prosthesis. Once completed, a virtual model of the patient's bone with overlying tissue mesh is formed (Fig. 5.7).

For both edentulous and dentate patients, the next step after merging of the surface scans to the CBCT file comes the actual planning of the implant case.

Dental implants come in a wide range of lengths, diameters, and shapes. Historically, 2-dimensional radiographs (panographs), along with acetate overlays depicting different implant sizes, were used to plan for surgical placement. Surgical guides were then fabricated on stone models that had a diagnostic wax-up of the proposed final restorations. The main limiting factor with this method was the inability to take the patient-specific anatomy into consideration when planning. While some anatomical structures are visible on 2D radiographic film (ex-inferior alveolar nerve), others are hidden due to

overlapping of other anatomical structures (ex-palatal foramen).

For dentate patients, a proposed design of the prosthesis replacing the missing teeth must be created. By doing this, the restorative doctor is conveying to the surgeon the ideal position of the implant based on the patient's existing dentition. This proposal takes into account a number of factors including the placement of the final restoration with respect to adjacent teeth and opposing dentition. The goal is to place dental implants in positions that will support final restorations that are in harmony with the patients existing dentition and maxillomandibular relationships. Failure to do this results in a significantly higher probability of a broken prosthesis and/or failed implant. Current dental technology supports the virtual design of the patient's final prosthesis by allowing the restoring dentist to create a virtual prosthesis that takes all of these important factors into consideration and ensures the final prosthesis is in harmony with the patient's dentition. Once completed, the design is integrated into the surface scan and aligned with the patient's CBCT. Afterwards, the surgeon can plan and place the implant in the optimal location using the proposed prosthesis as a reference.

Once the planning for both the prosthesis and the implant is complete, either in dentate or edentulous patients, a surgical guide can be created based on the virtual implant plan. Surgical guides are aids that help the surgeon orient the implant during the implant surgery to achieve the proposed correct location, depth, and angulation needed for the prosthesis. Surgical guides can be utilized in simple, straightforward cases requiring the replacement of some teeth with implants, or in more complex cases. Complex cases require more advanced guides, usually multiple guides for a single case, which require advanced virtual modeling techniques to create.

In certain implant rehabilitation cases, an alveoloplasty (bone reduction) is needed to create restorative space for the final prosthesis. The workflow is similar to the ones already stated, however, during the implant planning phase, the amount of bone needing to be removed can be determined based on the restorative components.

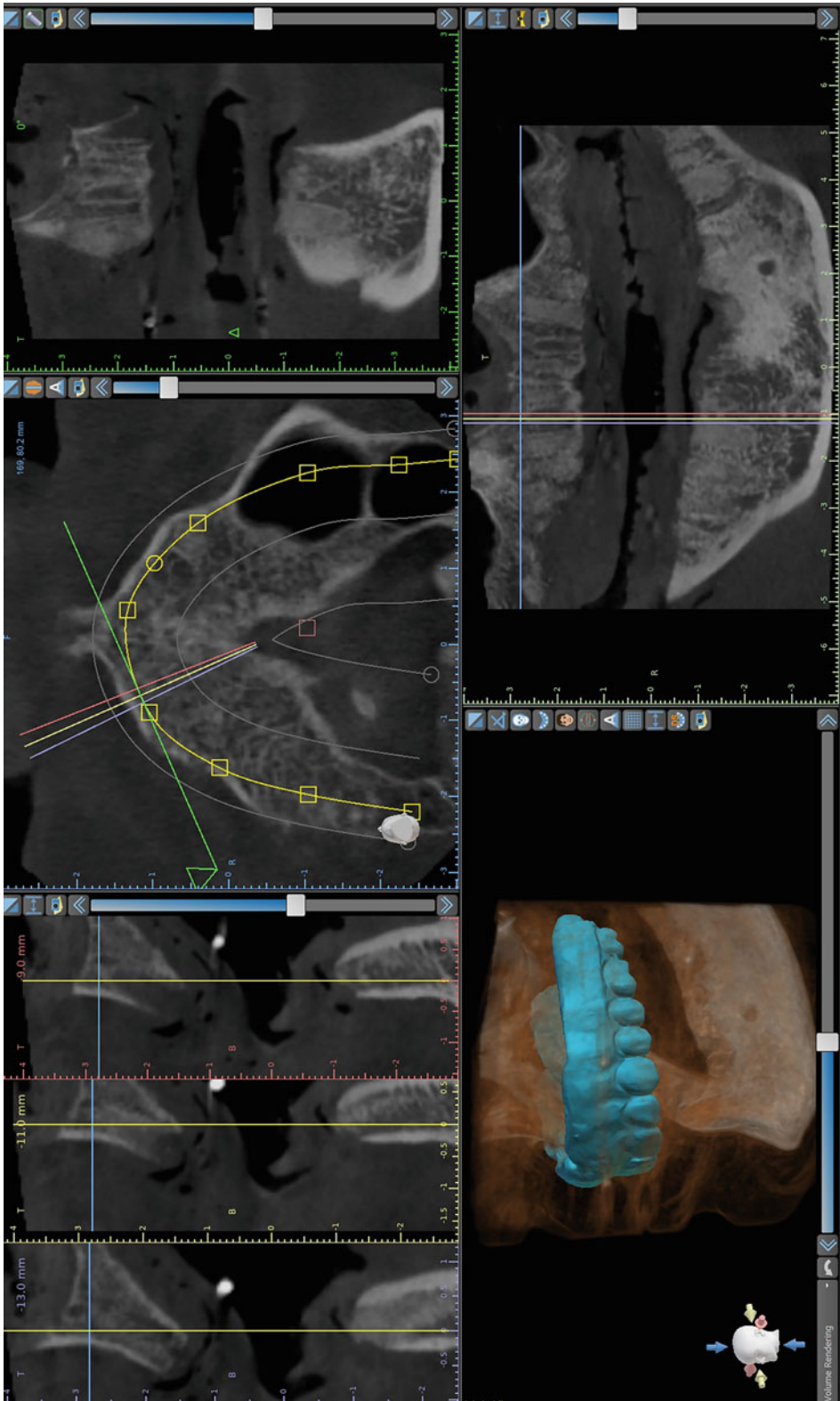


Fig. 5.7 Patient intra-oral scan aligned to patient CBCT for implant planning

Once the surgeon virtually arranges the implant along with the restorative components in place, the amount of bone needed to be removed can be measured on the virtual model. Once that amount is determined, the software will allow the user to remove and recontour the bone, creating a virtual bone reduction that gives the surgeon a guide for what has to be done to accomplish the alveoloplasty. This workflow is best undertaken by experienced clinicians who have a thorough understanding of bone physiology and remodeling and who can predict the outcome of the bone reduction surgery. Once this workflow is completed, the complex surgical guide can be designed. The original, unaltered virtual model is used to create the first part of the guide, while the modified model that has undergone the virtual alveoloplasty, is utilized to create the bone reduction and implant placement. While there are limitations to these complex surgical guides, it has been shown that the use of these guides decreases surgical time and improves prosthetic outcomes, which warrants the time spent creating them.

It is not uncommon for some type of bone grafting procedure to be necessary in conjunction with implant placement. While it is difficult to determine the real-world outcome of virtual grafting due to various factors, such as patient health and behavior, virtual modeling allows the surgeon to predict if grafting is going to be needed and the amount of graft material that should be used. It is well established that at least 1.5 mm of bone is needed to surround a dental implant for successful integration. If it is determined that the proposed implant location lacks the 1.5 mm of bone in an area while virtually planning the implant, the surgeon can plan for the placement of a bone graft. There are various types of bone that can be utilized for a bone graft and the amount of bone grafting needed aids the surgeon in determining which of these materials will be the best fit for the specific situation.

An additional area that commonly requires bone grafting is the maxillary sinus region. Often, the sinus is located too low for the desired implant to be completely encased in bone, so additional bone is placed in the bottom of the

sinus to ensure the implant is fully in bone and does not protrude into the sinus. It is not uncommon for a sinus lift to be performed at the same time of the implant placement. This procedure can also benefit from virtual planning for numerous reasons.

The most common approach for a sinus lift is to access the sinus through a lateral window that is surgically cut into the lateral wall of the sinus and the sinus membrane is carefully elevated from the floor of the sinus. Once the access is made, grafting material is then placed below the sinus membrane and the bone window is replaced. During the planning phase, a virtual model can illustrate the position of any septa or deviation in the internal area of the sinus that could complicate the surgical approach. More importantly, the model allows for the visual tracking of the posterior superior alveolar artery and nerve to determine the best approach to avoid injury. Some implant planning software will even allow the user to determine a specialized model of the sinus and calculate the amount of bone grafting material needed to accomplish the sinus lift (Fig. 5.8).

This aids in eliminating the unnecessary waste of bone grafting material by providing the amount needed. An alternative approach to accessing the sinus is through the residual crestal ridge of the jaw. However, for this approach to be successful, certain anatomical features must be present. For example, the area must be free of any septa and have a certain amount of bone thickness remaining. If not, then the lateral window approach is recommended. While there has been many of these surgeries accomplished before patient-specific modeling, this technology has helped to better prepare the surgeon and decrease the surgical time.

Examples of some cases are provided below:

5.7.1 Case Example #1

A patient presented with a removable appliance (“flipper”) replacing her four anterior teeth. The patient was happy with the existing esthetics of the appliance, including the tooth shape and

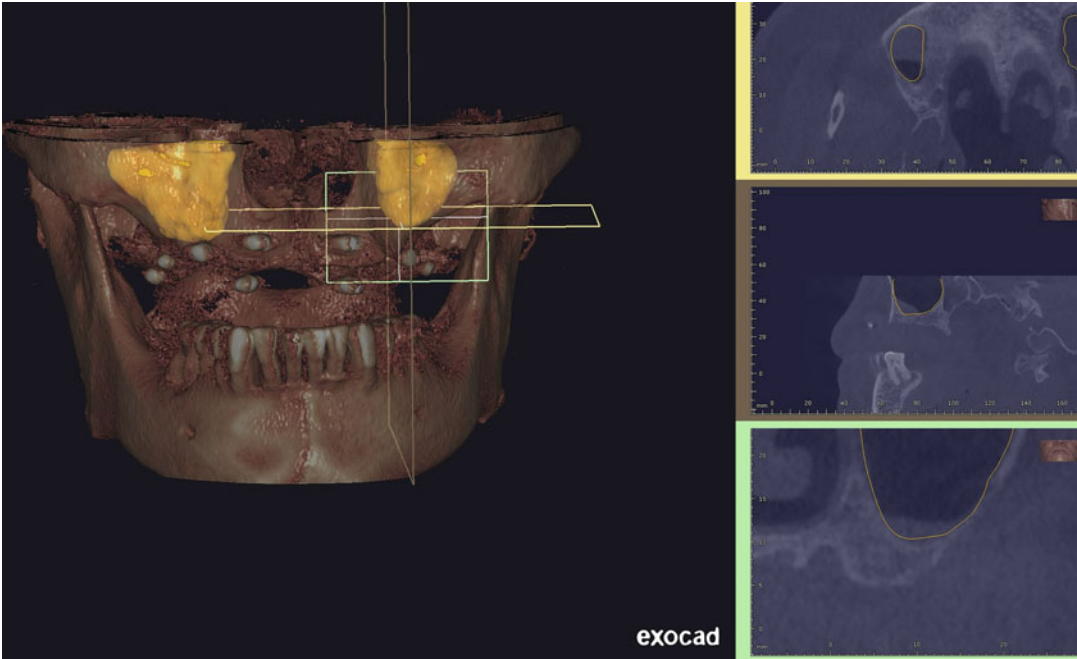


Fig. 5.8 The yellow areas outline the patient sinus in this implant planning software which aid in planning of implants in this region

position of the teeth, but did not like the poor fit and the fact that it was removable and not a fixed prosthesis (Fig. 5.9).

The patient was interested in obtaining a more permanent fixed restoration that could mimic her natural teeth, so she was referred for implant therapy.



Fig. 5.9 Intra-oral picture of patient wearing their removable appliance

Initially, a traditional panograph was taken and a clinical examination of the patient's maxillary alveolar ridge was performed. Both the panograph and the clinical examination revealed that the patient had an adequate alveolar height and the necessary ridge width for the placement of implants (Fig. 5.10).

The standard of care at this clinic required the dentist to obtain a CBCT for all patients receiving dental implant therapy, so the patient was referred

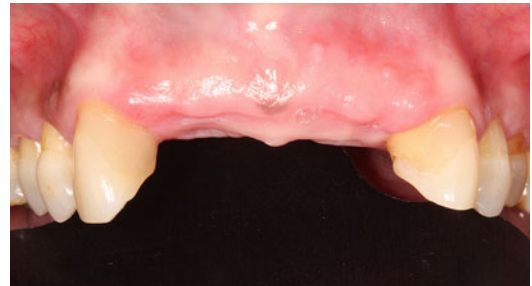


Fig. 5.10 Intra-oral picture of patient without the removable appliance

Fig. 5.11 Virtual model of patient rendered from CBCT



to the Radiology clinic for the CBCT and subsequent radiology interpretation. Intra-oral scans were also taken of the patient's maxillary and mandibular arches, along with her existing removable partial appliance to be used as a diagnostic wax-up for the final prosthesis.

Upon interpretation of the CBCT, it was determined that the alveolar ridge had more buccal-lingual resorption than what was initially observed, with alveolar defects due to previous extractions. It also revealed thin and immature bone, as opposed to the more solid buccal cortical plate (Fig. 5.11).

When placing implants, the density and volume of existing bone are critical for successful osseointegration. If the existing bone is not ideal, bone grafting or more advanced surgical procedures are required. In this particular case, a virtual model of the patient was created to better visualize the situation that revealed the true extent of the bone loss in the anterior region. While virtual models from CBCT's are not 100% accurate, they can provide the clinician with a clearer picture of the clinical situation. Given the anterior location of the planned dental implants, the patient's concern for the most esthetic outcome, and the amount of bone loss observed, it was decided to virtually plan the implant case.

The first step was the creation of the virtual model from the patient's CBCT. For this case, the teeth were segmented in the maxillary bone to better visualize the trajectory of the roots of the canines (Fig. 5.12).

When segmenting different areas of the model, it has been found that the ability to assign a different color to each area and adjust the transparency of each segment are useful tools for the dentist. These tools allow for better visualization of the different areas, including bone, roots of the teeth, etc. It is particularly useful when overlaying various surface scans that contain multiple segmentations.

After the CBCT model was completed, the surface scans (maxillary and mandibular) were then aligned to it, followed by the scan of the interim appliance (Fig. 5.13).

For this case, a virtual scan of the face would have been useful given the importance placed on esthetics. However, due to the fact that the patient was happy with the esthetics of the current removable appliance, it was decided to import a scan of it to aid in planning. At this point, a complete virtual model of the patient had been created within the dental implant planning software.

The replacement of anterior teeth with dental implants can be esthetically challenging, especially with multiple missing teeth complicated by bone loss. In this case, it had to be determined whether two implants and a bridge or four implants with separate crowns would be used to replace the missing teeth. There are advantages and disadvantages associated with both, however, the existing bone architecture and the possibility of necessary additional procedures must be considered to achieve the desired outcome.

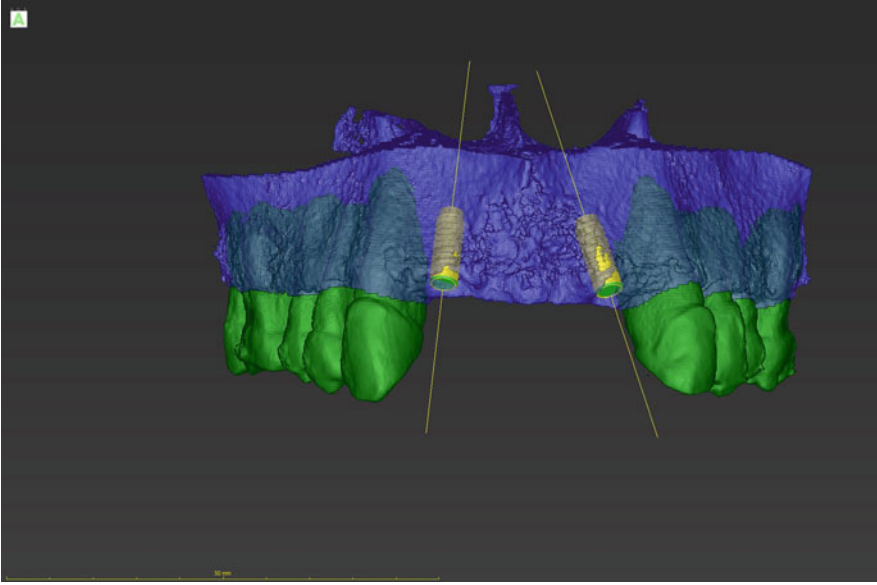


Fig. 5.12 Virtual model of patient showing segmentation of teeth/roots and proposed implant locations

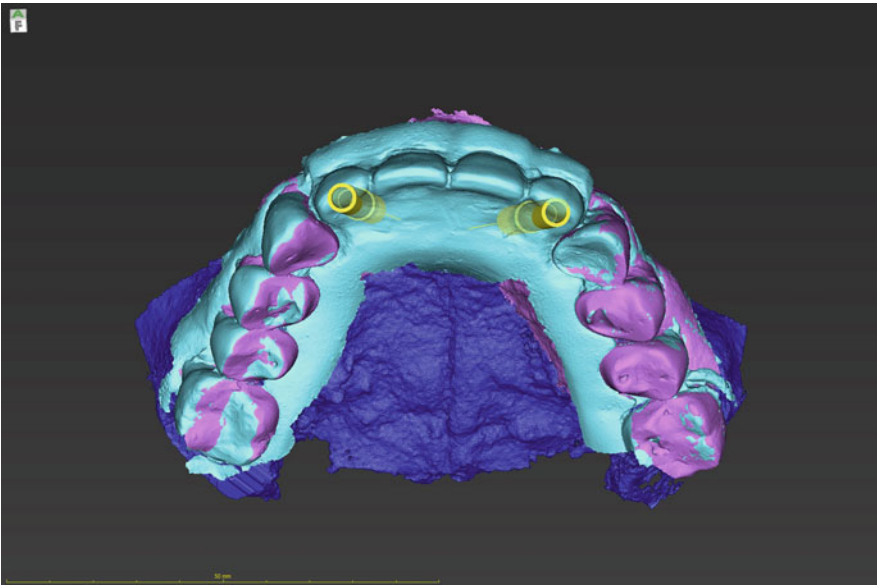


Fig. 5.13 Virtual model of implant planning showing proposed position of implants (yellow) to the patient's removable appliance (light blue)

Once the full virtual model was completed and the virtual planning of the case had begun, it was realized that the width of the remaining ridge was

insufficient for the placement of four dental implants without requiring a large bone graft. It was also determined that the placement of just

two dental implants at certain positions would only require a minimal grafting procedure.

The ability to place implants in the virtual model also provides visualization of the necessary implant trajectory. This is important in the restorative phase of implant therapy as it will dictate the type of restoration that can be placed. Therefore, when planning an implant, the desired restorative plan must be balanced with the available bone to achieve optimal outcomes. This is where the scan of the patient's existing prosthesis becomes important. By overlaying her appliance in the virtual model, the clinician can visualize the effect that the trajectory of the implant will have on the final prosthesis. In this particular case, it was determined that the preferred method of restoration would not be feasible since the trajectory emerged from the incisal, or bottom edge of the teeth. The decision had to be made either to change the restorative design or perform larger and more complex grafting techniques. After consulting with the patient and informing her of the possibilities, she elected not to undergo additional large surgical procedures and the restorative plan was changed to accommodate the necessary implant trajectory. Once the implant size and position were finalized, a surgical guide was fabricated to facilitate the planned placement of the implants into the proposed positions. As with all implant surgeries, the surgical guide was fabricated using additive technology (3D printing) and a specialized biocompatible sterilizable resin was utilized.

At the time of surgery, a full-thickness periosteal flap was created and reflected, which allowed complete visualization of the alveolar ridge. In the model, the center point of the ridge appeared rough and thin—this is usually indicative of thin, immature bone. While in the photograph the bone appears to be solid clinically, it was thin and porous (Fig. 5.14).

As predicted by the virtual model, a small grafting procedure was needed.

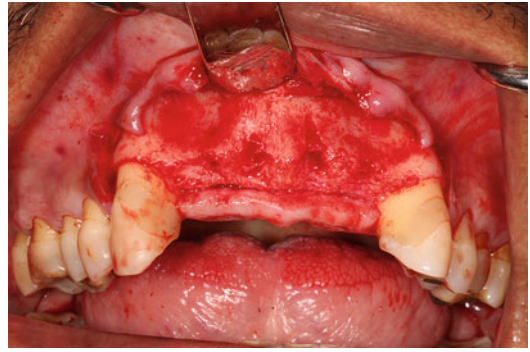


Fig. 5.14 Intra-oral picture showing osseous architecture after reflection of soft tissue

5.7.2 Case Example #2

When performing prosthetic reconstructions of patients' dentitions, one must take the mandibular movement into account, otherwise the restorations will fail, or the patient will generate temporomandibular symptoms. In traditional analog workflows, the first step is to obtain a maxillomandibular relationship utilizing a facebow. Facebow complexity ranges from simple to fully adjustable, with the fully adjustable being the most complex and requiring hours for an experienced clinician to use. The facebow is then used to transfer the position of the maxillary arch to an articulator to represent the patient's temporomandibular joint and both upper and lower arches. The movement allowed by the articulator depends on the model used—a simple articulator only allows for an open/close movement, while the fully adjustable models allow for more complex movements which more accurately mimic the patient's jaw movement. However, it is still a mechanical device that is limited by the features and build—namely the moving parts are restricted to flat rails. Therefore, the natural movement of the mandible is not accurately reflected. For example, when a patient opens and closes, the mandible may not move in a straight vertical line but has a deviation to either side

during the movement. This deviation could be the result of the person's natural joint, previous trauma to the joint, or a result of temporomandibular disorder. Due to the lack of movement accuracy, the provider will need to perform chairside adjustments in order to get the prosthesis in harmony with the patient's oral complex. The amount of time required for these adjustments is related to the extent/size of the restoration being done. A single tooth may be five to ten minutes, while a full-mouth rehabilitation can take several hours. Additionally, the more accurately the articulator mimics the natural movement of the patient, the less time is spent in adjustments at the time of delivery.

As mentioned earlier, digital technology that allows for the capture of a patient's mandibular movement can be used with surface scans to create an accurate virtual model of a patient's orthognathic system. This model can be used for numerous diagnostic and therapeutic treatments, but its biggest advantage lies with the development of patient-specific restorations. To create this type of virtual model, intra-oral scans of the maxillary and mandibular arches are taken. The next step is to capture the mandibular movement. To do this, specialized headgear containing infrared cameras is placed on the patient. A sensor is then used with specialized bite plates to register the position of the maxillae and then the mandible. At this point, the same information from the traditional facebow has been obtained.

The next step in this digital process involves the attachment of the sensor to the mandibular biteplate and having the patient perform jaw movements in a specific order. As the patient goes through the motions, the infrared cameras in the headset capture the 3-dimensional movement of the sensor on the biteplate. The software then creates a demonstration of all mandibular movements performed by the patient. At the same time, the software creates tracings of the patient's condyles that can be used for diagnosis (Fig. 5.15). These tracing can be used in identification of pathologies or unusual jaw movement, as discussed previously.

Once the movements are tracked, the intra-oral scans are imported into dental-specific Computer-

aided design (CAD) software along with the algorithm from the digital facebow. The algorithm orients the surface scans onto a virtual articulator, creating a virtual setup resembling the traditional analog articulator.

The CAD software can replicate the patient's mandibular movement without any limitations. The user is able to see any deviations from normal and the software creates visual aids by displaying a series of dotted pathways the mandible goes through during functional movements. Specific movements (example—left lateral movement), may be individually selected and visualized. Since these movements are in the virtual world, they will reflect any deviation that the patient may have in reality.

The software is also capable of generating meshes of individual movement pathways, which prove incredibly useful for the development of prostheses by eliminating various interferences that would have been present if only a static relationship was used.

Interferences arise when tooth cusp tips hit opposing teeth prematurely or out of harmony with the other parts of the orthognathic system. These interferences were referenced earlier and are the cause of necessary chairside adjustments that extend the time the patient must be in the chair. When activated, the CAD software will utilize the dynamic jaw movements to create a restoration that will function most effectively for the patient (Fig. 5.16).

These pictures illustrate such a case. This patient needed two full coverage posterior restorations. For various reasons, the most posterior tooth in an arch is a little more challenging to develop a proper occlusion when restoring. For these restorations, the digital facebow was taken, along with intra-oral scans of the patient. The virtual patient was created as described above. During the design process, the user was able to visualize and toggle among the various occlusal contacts on both the existing dentition and the proposed prostheses to determine the best occlusion for the final restorations. In addition, the user was also able to move the virtual mandible through various motions to help better visualize

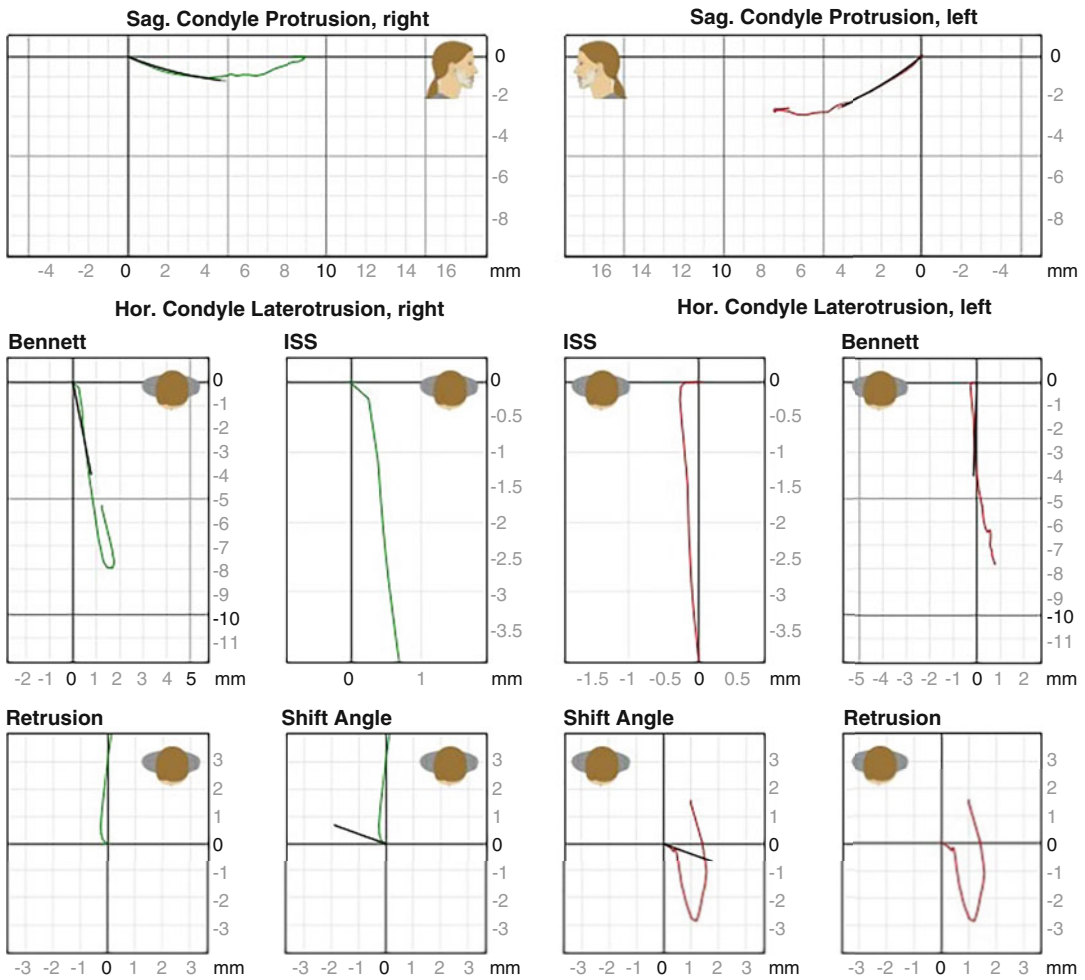


Fig. 5.15 Condylar pathway tracings obtained from mandibular tracking

the mandibular pathway and possible interferences.

The software is able to illustrate the patient’s occlusion utilizing a heatmap to demonstrate the degree of contact. Red and yellow colors indicate intersection of surfaces, while the blues indicate areas of contact—light blue indicates a heavy contact while dark blue indicates light contact between teeth. When the restorations are first generated by the software, they have red and yellow spots indicating they are actually intersecting with the opposing surface scan (Fig. 5.17).

Using the adapt function, the software adjusted the proposed design of the restoration to be in harmony with the rest of the patient’s dentition (Fig. 5.18).

During the try-in of the two restorations, the patient was instructed to go through all the various mandibular movements while marking paper was placed between the restorations and opposing dentition. One can see how close the markings on the final restorations align with those indicated in the design software (Fig. 5.19).

This demonstrates the accuracy involved in how the digital facebow translates both

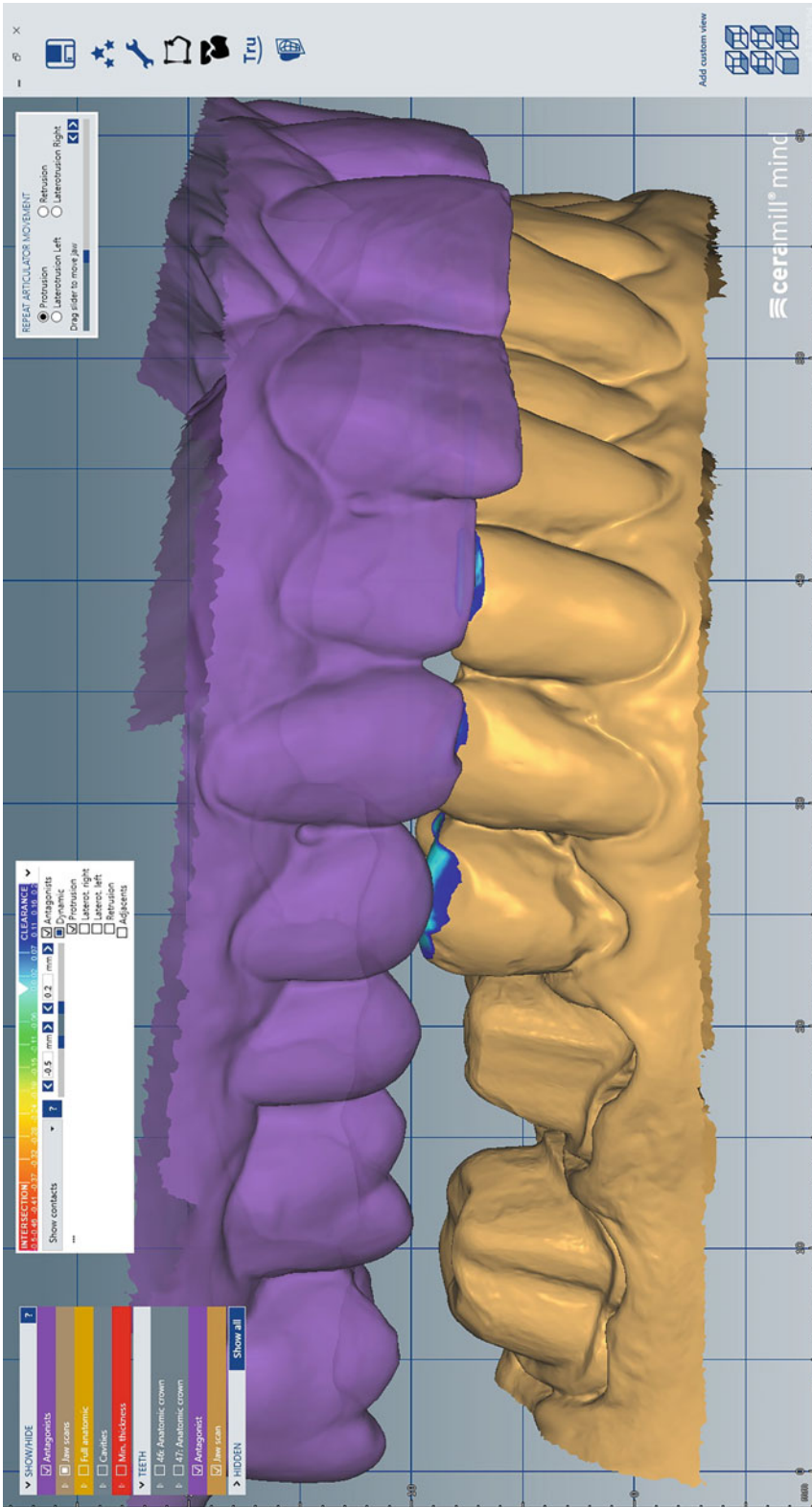


Fig. 5.16 Virtual models in lateral excursion with heat map visible (blue/light blue on teeth) illustrating interfering points

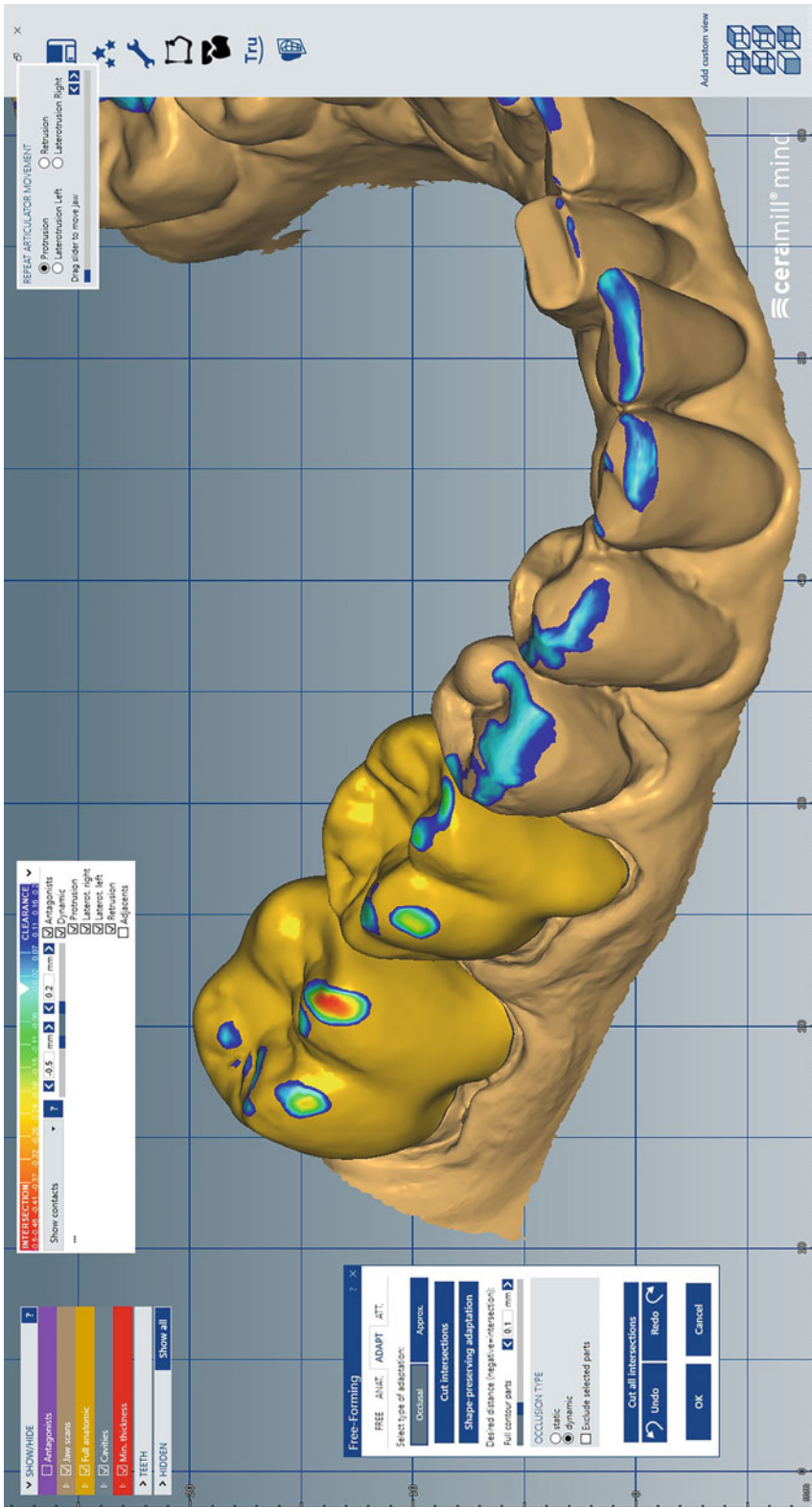


Fig. 5.17 Virtual model of patient with proposed crowns (yellow) design showing interferences via heat map

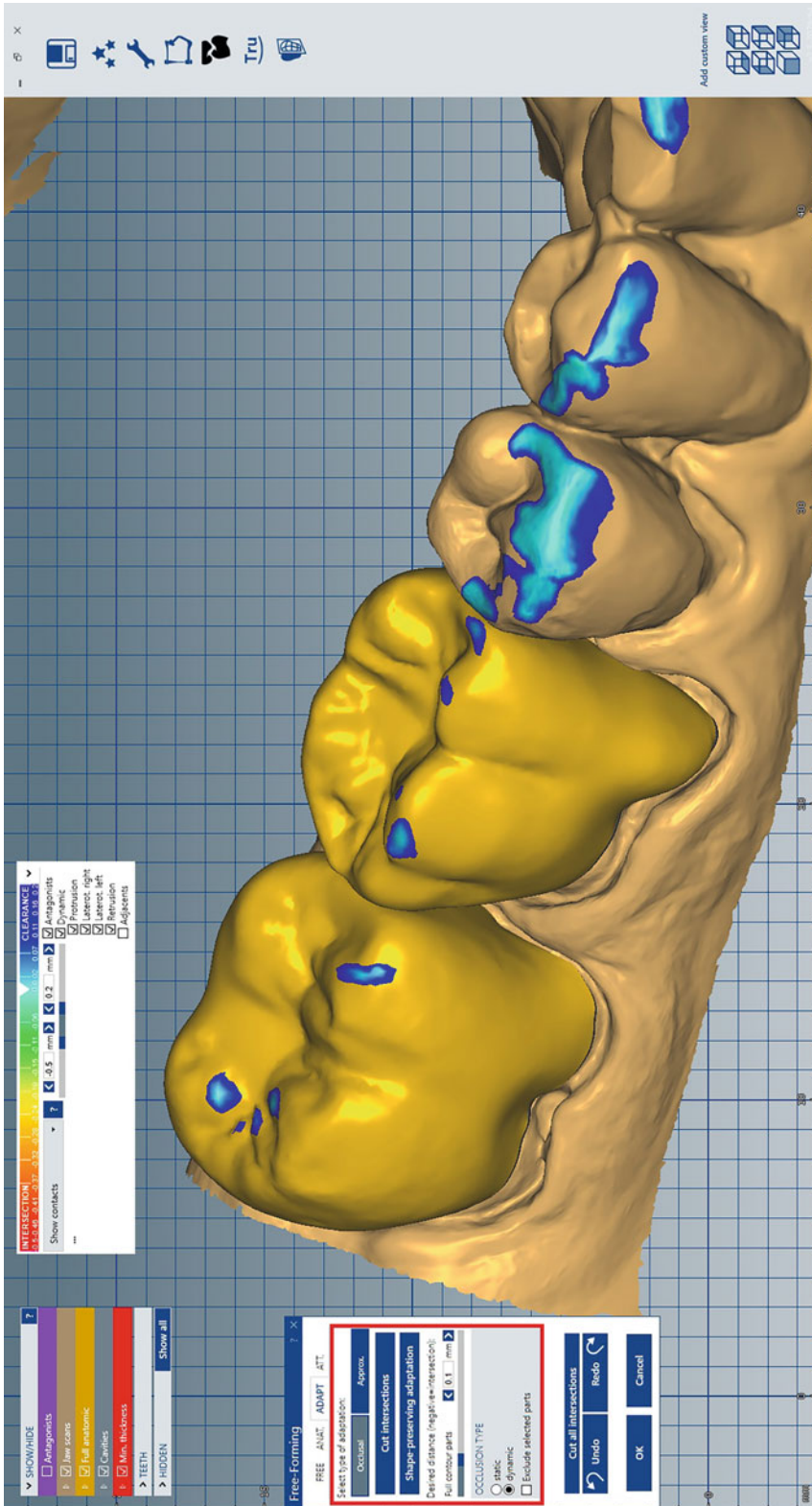


Fig. 5.18 Proposed crown design after adjustment for interferences



Fig. 5.19 intra-oral picture of crowns at initial try-in

maxillomandibular relationships and mandibular movement. While this case illustrates the use of virtual models and workflows to increase the accuracy of restorations, one can easily appreciate the benefit of using this technology on larger cases as well.

5.8 Conclusion

The exponential rate at which digital technology is advancing in dentistry is apparent in the discussion in this chapter. Consequently, the outcomes for both dentists and patients are constantly improving. New developments in both hardware and software are allowing for better diagnosing, planning, and treatment with the creation and utilization of virtual models and virtual patients. Dental procedures will be associated with less treatment timeframe and fewer complications for the patients, along with many other advantages, due to these advances. However, based on recent technological developments, it seems the best is yet to come.

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