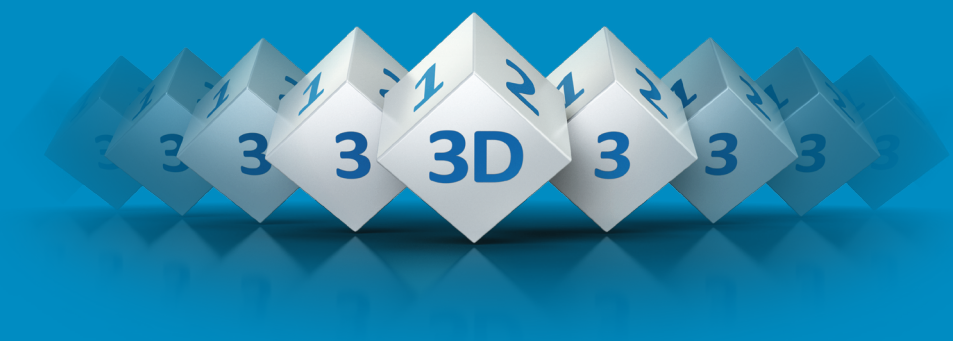
3D Workflows in Orthodontics, Maxillofacial Surgery and Prosthodontics



Wicher J. van der Meer

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Door W.J. van der Meer

Universitair Medisch Centrum Groningen, Rijksuniversiteit Groningen

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1

General Introduction and Aim of the Thesis

Introduction

In current dental practice, an abundance of digital technology is available aimed to improve diagnostics, assist treatment planning, increase efficiency and reduce costs. Especially three dimensional (3D) technology is rapidly entering most fields of dentistry.

Early attempts in the development of 3D technology focussed on converting facial anatomy, dental impressions and study casts into 3D digital models. For example in 1972, Van der Linden et al [1] described the Optocom system which could measure X and Y coordinates using a microscope followed by adding the Z coordinate by mechanical contact with the dental cast. The data collection of one set of models took an experienced operator about 20 minutes. Later attempts to convert plaster models of the dentition of the patient included holography [2-7] and demonstrated satisfactory precision of the virtual models for clinical measurements [2]. It even proved possible to superimpose holographic images of plaster casts in systems for holography, like the holodent system [6] , which unfortunately lacked major advantages over the traditional plaster models. A major disadvantage of holography was the poor quality of recording details of the study models, particularly in the incisor region. [4] The complicated equipment needed for holography and the fact that holography couldn't add major advantages over plaster models of the dentition prevented this solution from penetrating the commercial market. Other technology was developed or evolved thwarting the holographic solution.

The use of 3D scanners, e.g., that were introduced in the 90s [8,9] , seemed to be more appropriate for generating reliable 3D models. The acquisition time was considerably shorter as well as that the surface representation of the scanned dentition was much more detailed compared to the results of the aforementioned technologies. The resulting 3D models could be viewed on a computer allowing for diagnostic measurements.

In the early 2000s, optical scanners like laser scanners, photogrammetry and structured light scanners evolved rapidly. Optical scanners proved to be reliable for facial and dento-alveolar measurements. [10,11] Due to the favourable characteristics of the laser and structured light scanners, the obtained 3D models were suitable for designing crowns and bridges in the dental laboratory. Digital models proved to have many advantages including easy storage and immediate accessibility. Thus, 3D models quickly obtained a permanent position in the workflow in the dental laboratory and can be considered the initial stage of what soon evolved to a digital workflow commonly used in the dental laboratory.

Digital workflow

The first description of a complete digital workflow for producing a crown was in 1974 by Francois Duret.[12] In his PhD thesis, "Empriente Optique", he described the use of an intra-oral scanner to replace the traditional impression and proposed to use a computer for designing and a milling machine to produce the crown. The idea was later materialized by a Swiss dentist, Dr. Werner Mörmann, and an electrical engineer, Marco Brandestini, in 1980.[12] The system (figure 1) was introduced in 1987 for application in dental practice by Sirona Dental Systems as "CEREC" (Chairside Economical Restoration of Esthetic Ceramics), the first commercially available CAD/CAM system for the fabrication of dental restorations.[12] The basis of the CEREC system was, and still is, a 3D intra-oral scanner connected to a computer to design a dental restoration and a milling machine for the chair-side production of dental restorations from commercially available blocks of ceramic material.

Figure 1: The original CEREC I system.

The parallel development of 3D scanners for scanning plaster models of the dentition and intra-oral scanners for directly scanning the dentition without the need for an intermediate physical model, seems contradictory, as a direct 3D acquisition of the dentition was considered preferable over a procedure that involves multiple chemo-mechanical conversions (impression and subsequently pouring of the impression) followed by a 3D acquisition of the obtained physical model. However, at the time of the introduction of the first CEREC, the CEREC system was only able to make partial scans of the dentition and it application was restricted to produce only single unit restorations. A further restriction that prevented full adoption of intra-oral scanning as a replacement for traditional impressions, was the fact that a computer aided design of the restoration was experienced those days as a cumber-

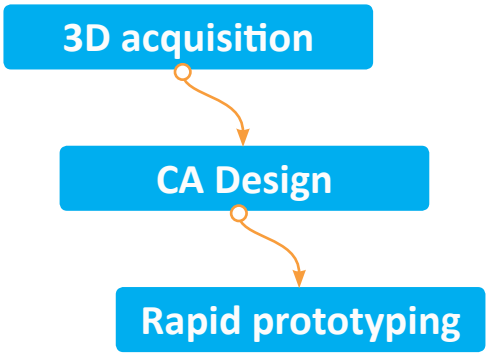

Figure 2: The 3D workflow used in other industries as it can be adopted in general dentistry. This workflow consists of a 3D scan, CAD and Rapid Prototyping of the end-product.

some work due to the limitations of the hardware and software that time. Furthermore, CEREC was a closed system making the export of the digital file in an industrial file format impossible, thus limiting the file to be applicable for the CEREC system only. The last decade the CEREC system and other, newly introduced intra-oral scanning systems, have evolved to a level that enable us nowadays to use a full 3D workflow in dentistry, almost 40 years after the application of 3D technology for dental applications was first proposed. Adopting a 3D workflow which is already widely used in other industries (figure 2) has enormous advantages, viz. it has the potential to deliver a high and constant quality while reducing the cost of the end-product. A 3D workflow typically consists of a 3D acquisition phase, a Computer Aided (CA) design phase and a rapid prototyping phase. In dentistry this workflow can be used as well.

3D acquisition phase

3D acquisition can be performed with the aforementioned intra-oral scanners. And even though some of the systems have proven themselves clinically for single unit restorations and small bridges, they still need to be further assessed for full arch restorations, which technically seems more of a challenge.

Computer Aided Design (CAD) phase

The computer aided design phase is being performed mostly in the dental laboratory with special software that enables to design crown and bridge restorations. However, besides crown and bridgework, other dental work such as partial prostheses, conventional dentures and other appliances are also desired. Also in the dental specialty fields like Orthodontics, Maxillofacial Prosthodontics, and Oral and Maxillofacial Surgery practitioners are in need for 3D workflows and software applications with specialized functionality which are not yet widely available.

Rapid prototyping phase

In the industry, the rapid prototyping phase is mostly focused on 3D printing. In dentistry, however, the lack of biocompatible products with proper mechanical properties seems yet to restrict the rapid prototyping phase to milling.

Differences with other industries

A clear difference between the industrial 3D workflow and the dental 3D workflow is that in dentistry a definitive end-product is produced which is supposed to function for a long time, sometimes even extending 30 years[13] under the harsh conditions of the oral cavity. In industry, the 3D workflow is mainly used for producing temporary products for testing purposes only. Furthermore, in industry the 3D workflow relies on the scan of an object which is then modified using CAD software, while in the dental field the end product needs to be designed from scratch, fitting the rest of the unique anatomy of that patient. This leads to a unique end-product for each individual patient. Lastly, the 3D information needed for a 3D workflow in dentistry comprises quite often of multiple datasets (intra-oral scan, facial scan, 3D X-Ray information, facebow registration, etc.) which is then combined in a model in an attempt to form a detailed simulation model of the patient.

Where are we standing?

Currently, the 3D digital workflow is primarily focused on the production of crown and bridgework and in most cases still requires traditional plaster models to incorporate the dynamics of the articulation of the patient in the final end product. These shortcomings are considered as transient technical flaws in the process that will be solved in near future. Once the 3D digital workflows for the different aspects of dentistry, orthodontics, maxillofacial prosthodontics, and oral and maxillofacial surgery have been fully developed and readily available, the speed at which this rather new technology will be embraced in dentistry depends on many factors apart from the availability. Incentives as time, and financial and clinical advantages seem to advocate the adoption of new technology whereas the high price and complexity of the software and hardware programmes are amongst factors that seem to hinder general application of new technology in dental practice.[14] These circumstances make it hard to predict when the 3D digital technology will become the standard of care in general practice. But when the technology has proven to result in better and more efficient care, universities will (start to) integrate the assessed 3D workflows into their educational curricula which in turn will result in an enhanced acceptance and application of these workflows in general dental practice.

When will 3D technology be common in dental practice?

When making a prognosis of the rate at which 3D digital dentistry will further develop, one could use a prediction model from the field of technology. A well-known model is described by Gordon Moore, one of the founders of the Intel cooperation. In 1965 Gordon Moore was asked to write a paper for the 35th anniversary issue of *Electronics Magazine* on the current state and potential future of the semiconductor industry. In this paper the prediction was made that the number of components on an integrated circuit would double every year for the next decade. At that time, the limit of components per circuit was 50 and the prediction that ten years later it would be possible to cram 65.000 components in a circuit[15, 16] was considered bold by many readers for the simple reason that technological progress was generally considered linear whereas Moore predicted an exponential course. Also the time between the events was considered too short and many doubted whether the predicted development could be sustained for more than a few years. Moore[15, 16] also made an economic commentary on the production of semiconductors; he predicted that the cost per component on a chip would fall exponentially while the amount of components would rise. Even though Moore's law currently still holds and is expected to hold at least for another decade, there are physical limits to the size of the components that can be realized using silicon.[17] Eventually a switch is needed from "traditional" silicon-based chips to molecular computers or quantum computers to carry "Moore's Law" to the next phase. If we would consider "Moore's Law" as a model for the future development of 3D digital dentistry and assume that we are somewhere at the beginning of the development line, we can envision a development that may seem linear and will be perceived as sluggish by many at first. But at a certain moment in time the development will reach the knee of the curve and the true exponential phase of progress will become evident.

Aim of the Thesis

3D workflows should result in clinical procedures that help clinicians to get better results with less effort and at lower costs. In other words, the 3D technology should make complex and difficult clinical procedures simpler and easier with reduced costs for healthcare. If 3D workflows are available with a low threshold for the clinician, both from an ease-of-use and a financial perspective, these workflows will be more readily accepted and adopted in the general practice. Therefore, the aim of this PhD research was to apply the available technology for optimizing 3D workflows in the dental and maxillofacial practice, specifically its applications in diagnostics (intra-oral dental scanners, 3D stereography), treatment planning (3D computer aided planning, digitally designed templates for placement of dental and craniofacial implants) and appliance manufacturing (single component and multicomponent appliances, and complex devices for maxillofacial rehabilitation).

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Diagnostics

Chapter 2	Application of Intra-Oral Dental Scanners in the Digital Workflow of Implantology. *PLoS One* 2012;7(8): e43312.
Chapter 3	Reliability and Validity of Measurements of Facial Swelling With a Stereophotogrammetry Optical Three-Dimensional Scanner. *British Journal of Oral and Maxillofacial Surgery* 2014 Dec;52(10):922-7.

2

Application of Intra-Oral Dental Scanners in the Digital Workflow of Implant Prosthetics

Abstract:

Aim: Intra-oral scanners will play a central role in digital dentistry in the near future. In this study the accuracy of three intra-oral scanners was compared.

Materials and methods: A master model made of stone was fitted with three high precision manufactured PEEK cylinders and scanned with three intra-oral scanners: the CEREC (Sirona), the iTero (Cadent) and the Lava COS (3M). In software the digital files were imported and the distance between the centres of the cylin ders and the angulation between the cylinders was assessed. These values were compared to the measurements made on a high accuracy 3D scan of the master model.

Results: The distance errors were the smallest and most consistent for the Lava COS. The distance errors for the CEREC were the largest and least consistent. All the angulation errors were small.

Conclusions: The Lava COS in combination with a high accuracy scanning protocol resulted in the smallest and most consistent errors of all three scanners tested when considering mean distance errors in full arch impressions both in absolute values and in consistency for both measured distances. For the mean angulation errors, the Lava COS had the smallest errors between cylinders 1-2 and the largest errors between cylinders 1-3, although the absolute difference with the smallest mean value (iTero) was very small (0.0529°). An expected increase in distance and/or angular errors over the length of the arch due to an accumulation of registration errors of the patched 3D surfaces could be observed in this study design, but the effects were statistically not significant.

Introduction

The basis for prosthetic work in dentistry has traditionally been an intra-oral impression that was subsequently poured in dental stone. The stone model forms the basis for the dental lab to manufacture crowns, fixed partial dentures and frames attached to natural teeth. Stone models are also used for producing frameworks for implant cases. This traditional workflow has proven itself in clinical practice, even though impression materials are prone to dimensional changes due to on-going chemical reactions[1] and stone will show expansion due to secondary reactions whilst setting.[2] Aforementioned dimensional changes may very well result in a misfit of the cast restorations. The misfit of fixed partial dentures on natural teeth will result in forces on the underlying teeth. Natural teeth, however, can move 25-100 µm in axial direction and 56-108 µm in lateral direction[3, 4] and adapt to a slightly different position in the bone due to the periodontal ligament should there be a slight misfit of the prosthetic work. Implants on the other hand will only show a range of motion of 3-5 µm in axial direction and 10-50 µm in lateral direction after osseointegration due to compression of the bone.[4] Ill-fitting framework will generate stress on the implants which may have a biological effect on the bone-implant interface.[5, 6] Also prosthetic complications as screw loosening or fracture may be related to ill-fitting framework fit.[7] A finite element analysis (FEA) study has also shown that passive fit will distribute masticatory forces more evenly over the implants.[8] The aforementioned factors have resulted in the paradigm that passive fit of the framework is one of the key factors for long-term success in implant dentistry[9, 10] stressing the importance of a reliable and precise impression procedure. Several strategies have been developed to ascertain passive fit.[3, 11] Even though none of the techniques has proven to be a panacea, the application of industrial-based digital production workflows is a solution that seems to gain popularity. As the impression procedure is at the origin of the workflow, the data collected during this phase is important as errors introduced in this phase will reverberate in the rest of the workflow. An intra-oral scanner could overcome some of the errors associated with traditional impression taking[12] and cast production[13] , as digital output data can be fed directly into a digital workflow. The assessment of the accuracy of traditional impression materials has primarily been performed using linear or 3D measurements. The accuracy deviations that were found in those studies have been expressed in µm or percentages. [14, 15, 16]

When considering accuracy one is inclined to consider only what we can refer to as “local accuracy” where the scan of a small geometrical form is compared to the original form and the difference between the two forms can be considered as the accuracy of the scanner. This would hold true for accuracy needed for single crown units in dentistry. This accuracy has

been determined for intra-oral scanners by several authors.[17, 18, 19] Another form of accuracy would be the accuracy over more units across the dental arch, which could be referred to as "general accuracy", resembling the accuracy necessary for the production of multi-unit fixed partial denture on natural teeth or implants. This form of accuracy is especially interesting if one considers full arch impressions for implant framework. In those cases the accuracy of the full-arch impression and the distance between the implants leaves less room for errors due to the rigidity of the bone-implant interface.[11] Although the dichotomy between "local" and "general" accuracy may seem immaterial at first, the rationale behind it is that all the intra-oral scanners build their 3D models by combining several 3D images made of the same section of the model but from different angles. The composition of the different 3D patches inevitably leads to registration errors that may vary in magnitude depending on the scanning technology and the registration algorithms used.[20, 21, 22] Even though other studies have tried to establish the accuracy of some of the intra-oral digitizers,[17, 18, 19] no consensus exists on how to assess the accuracy of intra-oral scanners. Some have looked at single teeth,[18] several teeth in a row[17] or at quadrants.[18] One study has looked at full arch scans.[19] In order to simplify the comparison, the dataset comparison was always reduced to a single number depicting the difference between the dataset of the scanner and the golden standard. In our study we wanted to consider the accuracy necessary for multi-unit framework on implants and a single number does not indicate possible error fluctuations over a longer span in those cases. We have therefore chosen to measure the distance and angular changes over a longer span between simulated implants generating multiple numbers that can be compared.

The objective of this study was to assess the " general accuracy" of three commercially available intra-oral scanners, that employ different scanning technologies to obtain the 3D images, for the application in the digital workflow in implant prosthetics.

Materials and methods

The model

Three high precision PEEK (polyether ether ketone) cylinders were manufactured by Createch Medical (Createch Medical, Mendaro, Spain) with an accuracy of 2 µm. PEEK was chosen for its excellent mechanical and chemical properties and to avoid a reflective surface that a metal cylinder would provide, as all intra-oral scanners have problems scanning reflective, shiny surfaces. On a full arch stone model of a volunteer, the teeth 36, 46 and 41 were ground to gingival level. Subsequently a hole was drilled in the stone and implant analogues were placed in the

prepared cavities and embedded in stone. The high precision cylinders were then screwed on the implant analogues.

The intra-oral scanners

The intra-oral scanners used in the study were the CEREC AC with the CEREC bluecam (Sirona Dental Systems Gmbh, Bensheim, Germany) with software version 3.85, the Cadent iTero (Cadent Inc, Carlstadt, USA) with software version 3.5.0 and the Lava COS (3M Espe, St. Paul, USA) with software version 2.1). All 3D scanners measure the distance from the scanner's sensor-tip to the object with different technologies to convert the optical data to a 3D model. The CEREC AC system employs light stripe projection and active triangulation (figure 1) to generate 3D images.[23]

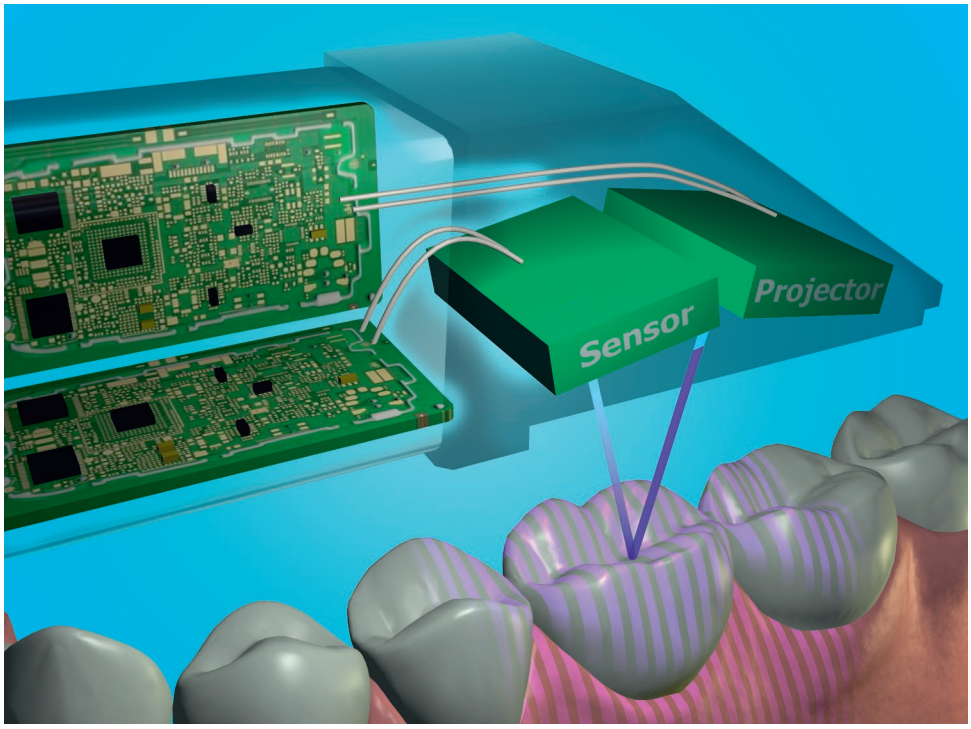

Figure 1: The technical principle of the CEREC scanner. The Cerec projects a light stripe pattern on the object. As each light ray is reflected back on the sensor, the distance between the projected ray and reflected ray is measured. Because the fixed angle between the projector and sensor is known, the distance to the object can be calculated through Pythagoras theorem, as one side and one angle (the fixed angle) of the triangle are now known. Hence the name "triangulation".

The Cadent iTero scanner employs a parallel confocal imaging technique[24] for capturing 3D images (figure 2).

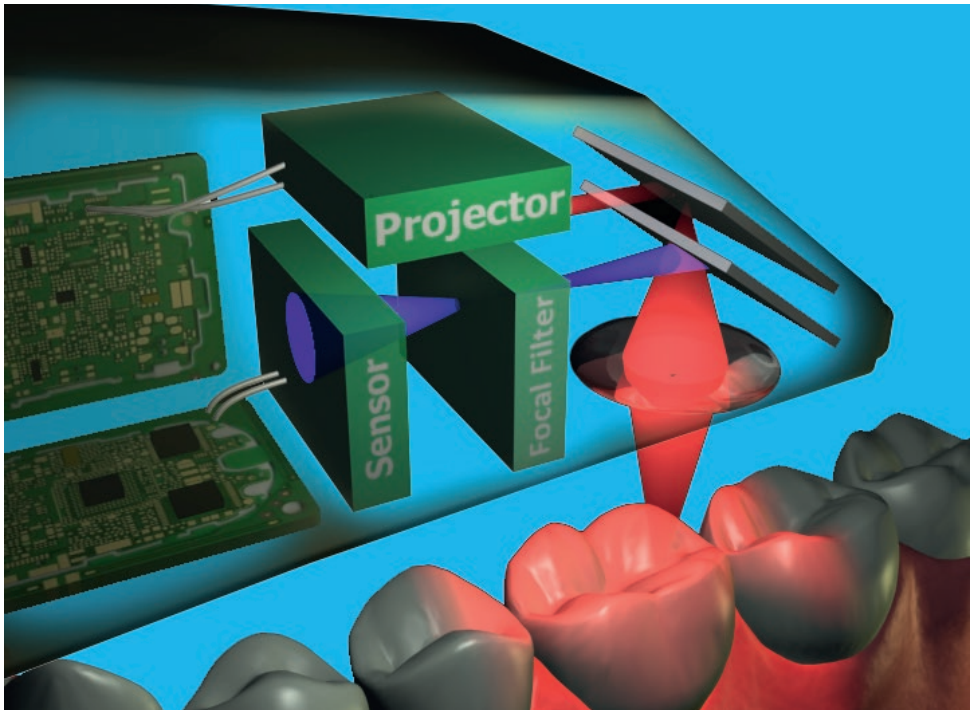

Figure 2: The technical principle of the iTero scanner. The iTero scanner uses confocal laser scanning in which a laser beam (red) is projected on an object. Via a beam splitter, the reflected beam (purple) is led through a focal filter so that only the image that lies in the focal point of the lens can project on the sensor. As the focal distance is known, the distance of the scanned part of the object to the lens is known (the focal distance). To scan the whole object, the lens is moved up and down, each time projecting a part of the object onto the sensor.

The Lava COS uses active wavefront sampling[25] to obtain a 3D model of the dentition (figure 3). Both the CEREC AC and the Cadent iTero capture single 3D frames that are stitched with other frames to compose a complete 3D model in a short registration cycle. After each cycle the user can proceed to scan the next part of the model. After the scanning procedure the

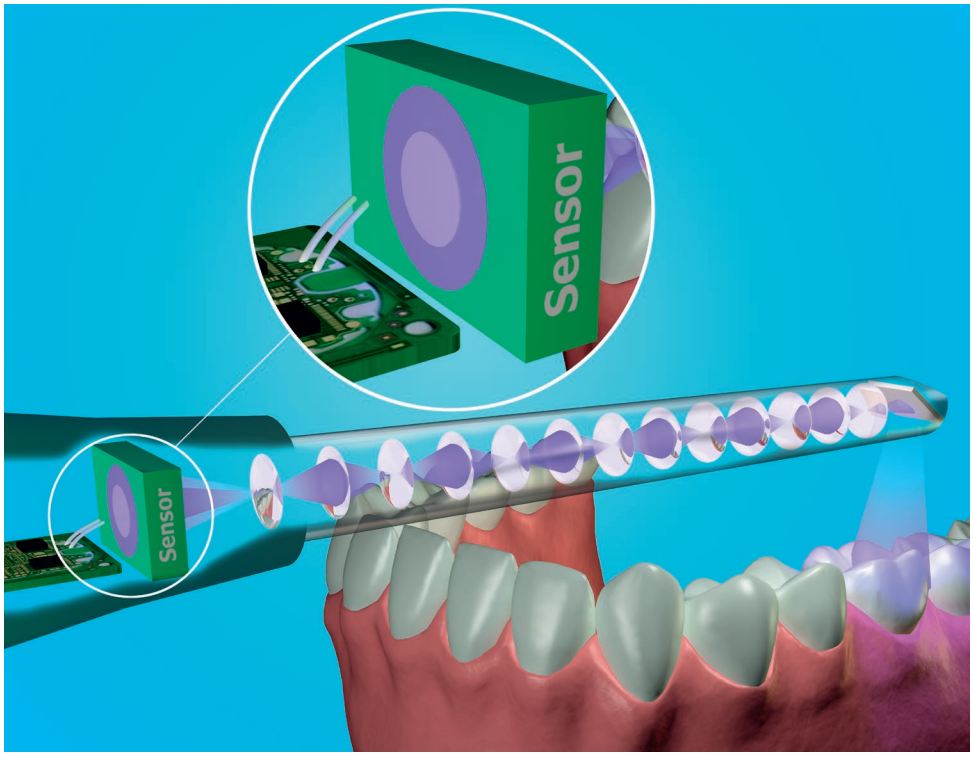

Figure 3: The technical principle of the Lava COS scanner. The Lava COS uses “active wavefront sampling” to calculate the 3D model of the teeth. For this the image reflected from the teeth is led through a lens system and eventually projected onto a sensor. If the image is in focus, the distance of the object coincides with the focal length of the lens. If the image is out of focus, the distance from the lens to the object can be calculated from the size of the blurred image through a simple mathematical formula.

model can be uploaded to respectively CEREC or iTero for post processing. The Lava COS is a 3D video system that captures 20 3D frames per second, which are registered real-time. After the scanning procedure a post processing cycle is necessary to recalculate the registration and compensate for potential errors, resulting in a high resolution model that is uploaded to 3M.

Dusting or powdering

The iTero scanner does not need special preparation of teeth to be scanned. Before scanning with the Lava COS, teeth need to be dusted with Lava Powder (3M Espe, St. Paul, USA), a titanium-oxide powder. The latter has to do with the technology the scanner employs. The dust particles on the teeth are used for registration of the 3D patches obtained during scanning. When employing the CEREC AC, a matte finishing needs

to be applied to the surface to be scanned to prevent reflections. For this purpose the surface is covered with a thin layer of Optispray (Sirona Dental Systems GmbH, Bensheim, Germany). To correctly mimic the clinical situation, the models were prepared according to the manufacturer's instructions with the appropriate powder before scanning the model. To avoid possible errors due to powder contamination, the order of scanning was decided to be

1. the iTero, as it required no powder
2. the Lava COS, as it required only light dusting
3. the CEREC, as it required the complete surface to be covered with a thin layer of Optispray.

3D scanning

The model was attached to a table and scanned 10 times with three different intra-oral scanners: the iTero (Cadent Inc, Carlstadt, USA), the Lava COS (3M Espe, St. Paul, USA) and the CEREC (Sirona Dental Systems GmbH, Bensheim, Germany). The manufacturers were asked for the protocol for high accuracy scanning as would be used for scanning implant locators and for special considerations for this type of scanning, e.g. calibration of the scanning unit or modification of the scanning protocol. The iTero and the CEREC had only one scanning protocol for all cases and did not distinguish between normal scanning and high accuracy scanning. The Lava COS had a high accuracy scanning protocol and subsequent calibration protocol. The normal Lava scanning protocol consists of a calibration with small calibration block before the intra-oral scan starts followed by scanning of the teeth according to a non-prescribed scan path. The high accuracy scanning protocol for scanning implant abutments consists of a calibration with the aforementioned calibration block followed by a slow zig-zag scanning of the dentition. After the scan the calibration with the calibration block is performed for a second time (figure 4).

Figure 4: the hi-res scanning protocol for the Lava COS scans. The scanning protocol for the scans for the Lava COS is the normal scanning protocol, except that the scan-path is a slow zigzag scan and that at the end of the scan a second calibration is performed.

The calibration measurements are used to calculate and compensate for errors that have occurred during scanning. All the scans were performed according to the instructions of the manufacturer by a dentist proficient with the specific intra-oral scanner. As only the iTero scanner does not require dusting or powdering of the model, the iTero scanner was used first to scan the model 10 times with a 10 minute interval between the scans. After this the model was dusted according to the instructions for the Lava COS with Lava Powder (3M Espe, St. Paul, USA) and the model was scanned 10 times with this scanner with a 10 minute interval between the scans. After the model was cleaned with a soft brush, the model was sprayed with Optispray (Sirona Dental Systems GmbH, Bensheim, Germany) according to the instructions of the manufacturer and 10 consecutive scans were performed with a 10 minute interval. All the scans of the different scanners were uploaded to the respective companies and returned after post-processing.

The physical model was cleaned with a soft brush and sent to Createch Medical (Mendaro, Spain) where it was scanned under strictly controlled conditions (temperature, humidity and vibrations) with a ultra-precision contact scanner with a precision of 0.1 µm (Leitz PMM 12106). The latter digital model formed the reference data set.

3D measurements

The distance and the angle between the centres of the high precision cylinders were used to assess the accuracy of the different scanners (figure 5). For this each of the scans was imported in industrial reverse engineering software Rapidform (Rapidform, INUS Technology Inc, Seoul, Korea), where each of the cylinders was isolated as a separate object.

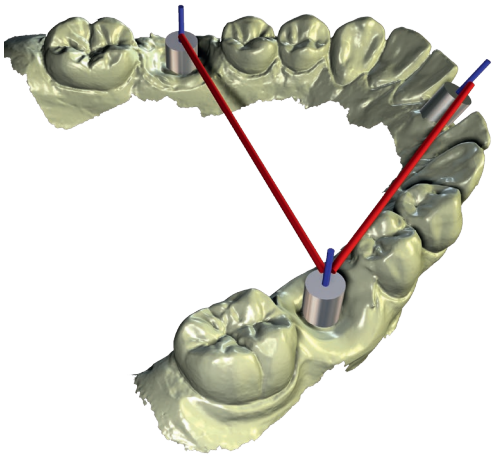

Figure 5: the measurements were made between the centers of the high-precision cylinders.Three 3D CAD models of the cylinders in the model were imported and registered with each of the scanned equivalents. The distance between the centre-lines was measured in the software using a linear measurement tool. The angular deflection of the cylinders was measured with an angular measurement tool, using the cylinder at the location of the lower right molar as the baseline.

Three 3D CAD models of the cylinders were subsequently imported and registered with each of the scanned equivalents. This was done to enable the proper construction of the centre-line of each cylinder.

To validate the precision of the registration algorithm a CAD cylinder, like the one used in the study, was imported in the Rapidform software. There it was duplicated and the second cylinder was subsequently moved to another location in the 3D space. The two cylinders were then registered and the difference between surfaces of the two cylinders was calculated by the software. As the cylinders are perfectly identical, the surfaces of the cylinders should ideally match perfectly. The experiment was repeated ten times and the mean of the registration error was calculated. The mean error of the registration procedure was 1.4 nm (+/- 0.9 nm).

The distance between the centre-lines was measured in the software using a linear measurement tool. The angular deflection of the cylinders was measured with an angular measurement tool, using the cylinder at the location of the lower right molar as the baseline. The measurements were not broken down in x-, y- and z-components as the objects coordinate system could not properly be matched with a world coordinate system. As there is no true common coordinate system, the different models could only be registered in a virtual common coordinate system. As the registration is based on the surface of the models and as these will show minor errors, the positions of the models will differ slightly. This will introduce an error in their relative positions and makes it unreliable to compare measurements broken down in x-, y- and z-components. The measurements were noted in a table and compared to the same measurements made on the reference data set. A one-way ANOVA was performed to compare the differences between the 3 systems ($P<0.05$). The results are summarized in Tables 1 and 2.

Results

	CEREC		iTero		Lava COS	
	ABS Error 1-2	ABS Error 1-3	ABS Error 1-2	ABS Error 1-3	ABS Error 1-2	ABS Error 1-3
MEAN	79.6	81.6	70.5	61.1	14.6	23.5
SD	77.1	52.5	56.3	53.9	12.7	14.2
CI (95%)	31.8-127.4	49.1-114.2	35.5-105.4	27.7-94.5	6.7-22.4	14.7-32.3

Table 1: Absolute errors in the distance between the cylinders in micrometers.

The mean of the distance errors of both the measured distances of the Lava COS, respectively 14,6 µm (95% confidence interval: 6.7 µm – 22.4 µm) for the distance 1-2 and 23.5 µm (95% confidence interval: 14.7 µm – 32.3 µm) for the distance 1-3. These values were the smallest compared to the CEREC and the iTero scanner. The confidence interval for the Lava COS was the smallest demonstrating that the variations were the smallest. The distance errors of the CEREC were the largest, respectively 79.6 µm (95% confidence interval: 31.8 µm – 127.4 µm) for the 1-2 distance and 81.6 µm (95% confidence interval: 49.1 µm – 114.2 µm) for the 1-3 distance. All of the scanners had errors both in the positive and the negative range.

CEREC	iTero		Lava COS			
	ABS Error 1-2	ABS Error 1-3	ABS Error 1-2	ABS Error 1-3	ABS Error 1-2	ABS Error 1-3
MEAN	0.6303	0.4378	0.3451	0.4192	0.2049	0.4722
SD	0.5499	0.3211	0.3382	0.1667	0.0440	0.1436
CI (95%)	0.2894-0.9711	0.2388-0.6367	0.1355-0.5547	0.3159-0.5226	0.1776-0.2322	0.3831-0.5612

Table 2: Absolute errors in the angle between the cylinders in degrees.

The absolute distance errors ranged from 2.2 µm (Lava COS) to 287.5 µm (CEREC) (figures 6 and 7).

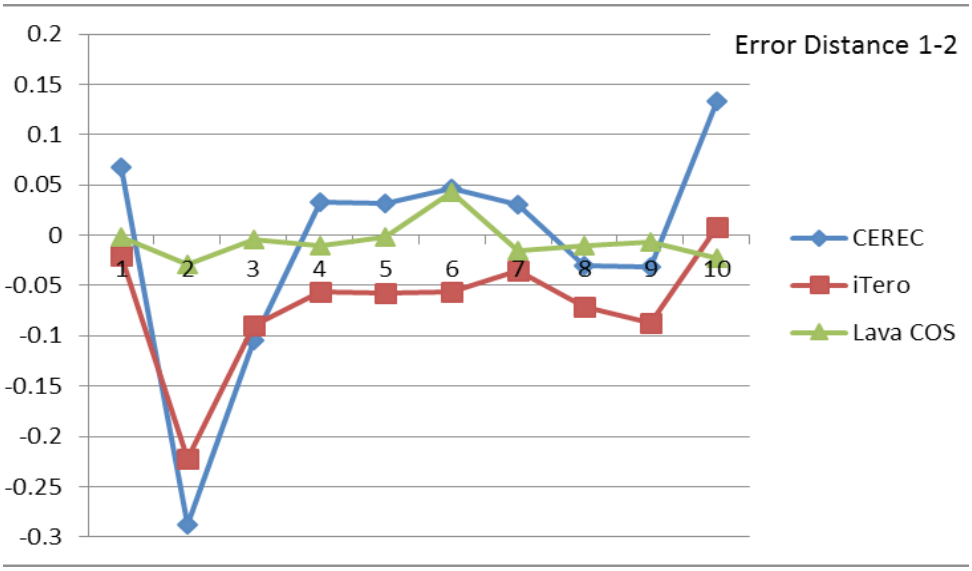

Figure 6: the distance errors between the cylinders 1 and 2 in millimeters for the three intra-oral scanners. The smallest distance error between cylinders 1 and 2 was -22.0 µm (Lava COS), while the largest error was -287.5 µm (CEREC). The Lava COS scanner showed the smallest mean distance error and also showed the smallest variations.

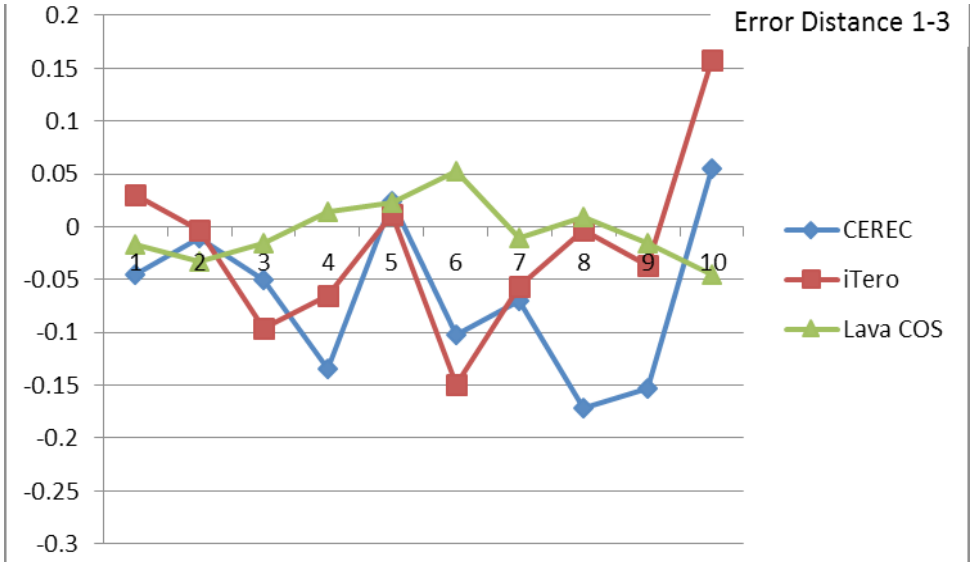

Figure 7:the distance errors between the cylinders 1 and 3 in millimeters for the three intra-oral scanners. The smallest distance error between cylinders 1 and 3 was -32.0 µm (iTero), while the largest error was -171.1 µm (CEREC). The Lava COS scanner showed the smallest mean distance error and also showed the smallest variations.

The angulation errors are shown in the **figures 8** and **9**.

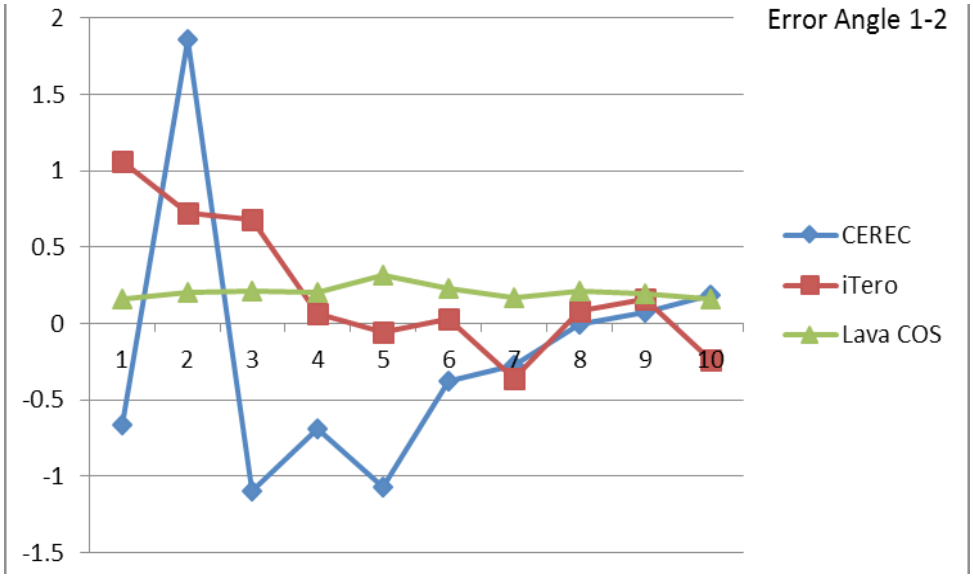

Figure 8: the angulation errors between the cylinders 1 and 2 in degrees for the three intra-oral scanners. The angulation errors were small and ranged from -0.0061° (CEREC) to 1.8585° (CEREC). The Lava COS showed the smallest mean angulation error and also the smallest variations. The Lava COS also showed only positive errors.

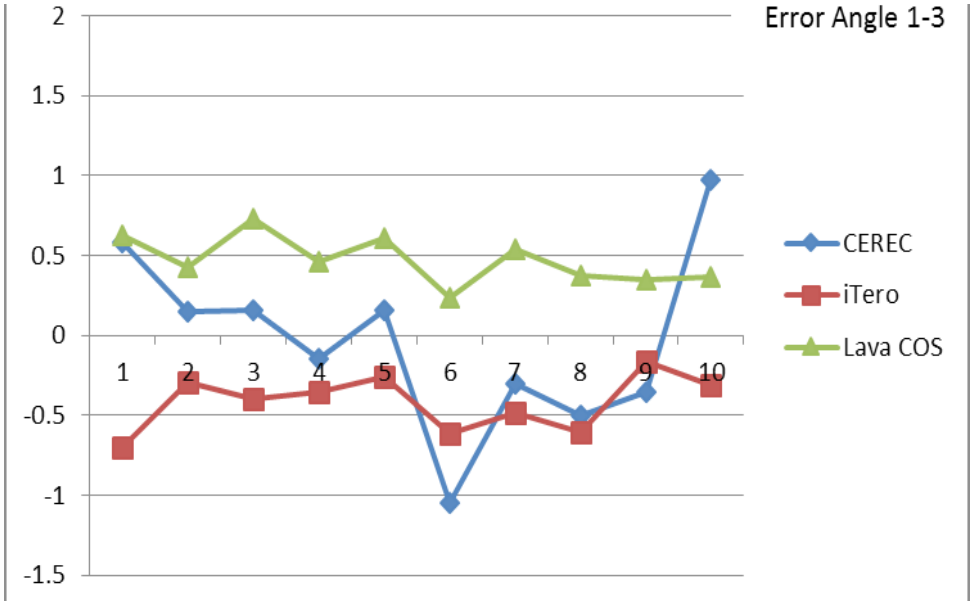

Figure 9: the angulation errors between the cylinders 1 and 3 in degrees for the three intra-oral scanners. The angulation errors were small and ranged from -0.1447° (CEREC) to 1.0456° (CEREC). The iTero showed the smallest mean angulation error. The Lava COS showed the smallest variations. The Lava COS showed only positive errors, while the iTero showed only negative errors. Only the Lava COS showed consistent positive errors in all cases, this could be regarded as an offset which may be compensated.

The mean of the absolute angulation errors ranged from 0.0061° (CEREC) to 1.8585° (CEREC). The mean absolute angulation errors for the cylinders 1-2 was the smallest for the Lava COS: 0.2049° (95% confidence interval: 0.1776° - 0.2322°) and the largest for the CEREC: 0,6303° (95% confidence interval: 0.2894° - 0.9711°). For the cylinders 1-3 the smallest mean absolute angulation error was provided by the iTero : 0.4192° (95% confidence interval: 0.3159° - 0.5226°) and the largest by the Lava COS: 0.4722° (95% confidence interval: 0.3831°- 0.5612°). The confidence interval for both the angulation errors 1-2 and 1-3 was the smallest for the Lava COS, indicating that the Lava COS had the smallest variations in its angulation errors. The CEREC had angulation errors in both the positive and negative range between the cylinders 1-2 and 1-3. The iTero showed a similar distribution for the angulation errors 1-2, but showed only negative values for the 1-3 measurements. The Lava COS was the only scanner that showed errors in the positive range for all measurements. No statistical difference was found between the three groups.

Discussion

To our knowledge, this is the first study that compares three different intra-oral scanning technologies. The present study analysed the accuracy of three intra-oral scanners by determining the distance and angulation errors *in vitro*. The results show that the Lava COS has the smallest mean distance errors and the least variations in the measurements. In the angulation errors, the Lava COS showed the smallest mean error between cylinder 1-2 and the CEREC the largest mean error. The difference between the smallest and largest error was very small (0.4254°). Between cylinders 1-3 the iTero showed the smallest mean error and the Lava COS the largest mean error. The difference between the smallest and the largest error was even smaller: 0.053°. The Lava COS had the smallest confidence interval in angular and linear measurements, indicating that this scanner has the lowest variation in its measurements. The Lava COS was also consistent in the angular errors as their range was small and all the values were positive. Only one other study has compared different intra-oral scanners. Ender and Mehl[19] have compared the Lava COS and the CEREC to determine which scanner is more accurate compared to the cast of an Impregum impression . In their study, the accuracy was defined by the terms "trueness": the deviation of the model with respect to the true size of the object, and "precision": the fluctuation of the different measurements. The "trueness" of the Lava COS was better than that of the CEREC and both were better than an Impregum impression. The "precision" of the CEREC was better than the Lava COS which was comparable to the Impregum impression . The high accuracy scanning protocol was not used in that study. Special software was used to superimpose datasets and the difference between the two models based on measuring points was calculated. This resulted in one value for the accuracy of the scanner.

The various scanners used in our study use different technologies to determine the spatial coordinates of the scanned object. Differences found between the three scanners may be related to measurement errors inherent to the technology employed. To improve the resolution of the 3D scan, CEREC has switched from white to blue light which has a shorter wavelength leading to a higher accuracy.[18] Apart from the differences in the technology of data acquisition, the CEREC and iTero scanners are point-and-click systems, while the Lava COS is a video system. This may explain both the similarities between the CEREC and iTero measurements and the differences with the results of the Lava COS. In the point-and-click systems, the 3D surfaces should be scanned with at least a one-third overlap of the adjoining surface. The registration of the neighbouring surfaces will occur on the basis of this overlap. In the video system with a frame rate of 20 images per second, the overlap of the images will most likely be larger than the aforementioned one-third which could lead to a better

surface registration. Differences in the results may also occur due to the registration of the 3D images and in the rest of the post-processing procedure. The Lava COS uses powder particles as markers as an extra tool for the computer to join the different pieces of the 3D model. How the registration takes place and what algorithms are used in the different scanners is not shared knowledge. But algorithms that involve registration based on surface overlap are most likely. As registration errors, however minute, will always occur in registration procedures[26], one expects an additive effect of these errors over the length of the arch. When comparing intra-oral scanners in full arch impression procedures, it would be interesting to involve the influence of the length of the span to assess the expected additive effect of the registration errors that may occur. The aforementioned effect could be observed in our experiments for the CEREC and the Lava COS when considering the distance accuracy and for the iTero and the Lava COS when considering the angular accuracy. The differences however were very small and statistically not significant. Mehl et al found a decreasing accuracy when comparing single tooth images to quadrant images for the CEREC Bluecam intra-oral scanner[18] which could be explained by an accumulation of registration errors . In the study of Ender and Mehl[19] an increase in the deviations between the models in certain areas were noted, but these can be explained by the registration procedure. The algorithm most likely tried to register the surfaces in such a way that the overall mean deviation between the surfaces is the smallest and this may conceal an increase in deviations between the surfaces and makes interpretation of deviations difficult. A best fit algorithm on basis only of the area where the scanning was started may have shown a possible increase in deviations in their study.

In the study of Ender and Mehl[19] a mean “trueness” of 49 ± 14.2 µm was found for the CEREC and 40.3 ± 14.1 µm for the Lava COS. The difference from our data is most likely resulting from a different research model in their study and a high accuracy scanning protocol for the Lava COS in our study. In their study a 3D comparison was made between the models, where the computer calculates the difference between the surface points of the models. These measurements are usually expressed in a mean value for the error between the surfaces. In our study the linear and angular measurements were made as the accuracy of the distance and the angulation between implants can show the error that will be introduced at the inlet of a digital workflow. Other methods, like the aforementioned 3D comparison of digital models, will also generate a number that will generally reflect the accuracy of a model. However this number will not express the exact error between implant positions nor will it show errors in angulation that may occur or a possible increase in the distance and angular errors over distance.

In future studies other video-scanners should be involved as we have compared two point-and-click systems (CEREC and iTero) with one video system (Lava COS) in the present study. Differences in outcome could be explained with differences between the technologies as explained above. The amount of cylinders on the model should be increase to gain a better insight in possible increase in deviations over the length of the span. The number scans may be increased to increase the reliability of the study. Also a comparison with a traditional impression material, like Impregum, should be added to enable a comparison with the traditional workflow. A comparison between the normal scanning protocol and the high accuracy scanning protocol should also be included.

Conclusions:

1. The Lava COS in combination with a high accuracy scanning protocol resulted in the smallest and most consistent errors of all three scanners tested when considering mean distance errors in full arch impressions for both measured distances.

2. For the mean angulation errors of the three scanners tested, the Lava COS had smallest errors between cylinder 1-2 and the largest errors between cylinder 1-3, although the absolute difference with the best mean value (iTero) was very small (0.0529°).

3. In the Lava COS the angulation errors were very consistent with a small confidence interval value.

4. An expected increase in distance and/or angular errors over the length of the arch due to an accumulation of registration errors of the patched 3D surfaces could be observed in this study design, but the effects were statistically not significant.

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3

Reliability and Validity of Measurements of Facial Swelling With a Stereophotogrammetry Optical Three-Dimensional Scanner

This chapter is an edited version of:
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Abstract

Aim: Volume changes in facial morphology can be assessed using the 3dMD DSP400 stereo-optical 3-dimensional scanner, which uses visible light and has a short scanning time. Its reliability and validity have not to our knowledge been investigated for the assessment of facial swelling. Our aim therefore was to assess them for measuring changes in facial contour, *in vivo* and *in vitro*.

Materials and Methods: Twenty-four healthy volunteers with and without an artificial swelling of the cheek were scanned, twice in the morning and twice in the afternoon (in vivo measurements). A mannequin head was scanned 4 times with and without various externally applied artificial swellings (in vitro measurements). The changes in facial contour caused by the artificial swelling were measured as the change in volume of the cheek (with and without artificial swelling in place) using 3dMD Vultus® software.

Results: *In vivo* and *in vitro* reliability expressed in intraclass correlations were 0.89 and 0.99, respectively. In vivo and in vitro repeatability coefficients were 5.9 and 1.3 ml, respectively. The scanner underestimated the volume by 1.2 ml (95% CI -0.9 to 3.4) *in vivo* and 0.2 ml (95% CI 0.02 to 0.4) *in vitro*.

Conclusion: The 3dMD stereophotogrammetry scanner is a valid and reliable tool to measure volumetric changes in facial contour of more than 5.9 ml and for the assessment of facial swelling.

Introduction

Changes in facial contour may occur as a result of craniofacial surgery, orthognatic surgery, inflammation, trauma or ablative surgery, for example. Several methods have been used during the past 60 years to measure the various types of facial deformity, mainly contact methods.[1] Later, non-contact technology increasingly replaced them, although these newer methods often required complicated equipment for measurement to allow for standard orientation of the head for photography and radiography.[2] Mathematical methods were then applied to describe the changes in facial morphology.[3] Others used early (non-digital) stereophotogrammetry to make linear measurements on landmark-based points.[4,5]

With the availability of 3-dimensional scanning technology, these scanners have evolved to become the first choice in research on measurements of volume and their comparison. Among other things, these scanners have been used to assess volumetric changes in acute oedema of burns,[6] breast symmetry,[7] and post-operative facial swelling.[8-11] The most commonly used optical 3-dimensional scanners are the laser scanner, the structured light scanner and the stereophoto scanner.

The reliability and validity of the 3dMD DSP400 system have been assessed in landmark measurements on an animal skull,[12] a phantom head,[13,14] a human face,[15,16] the human torso,[17] and breast.[18] They have proved to be more than sufficient for clinical needs and better than direct anthropometry or 2-dimensional photography.[13] It is often hard to compare studies, as only a few authors actually define the properties that they have assessed.[12,13,15,19,20]

The 3dMD DSP400® stereo-optical 3-dimensional scanner (Atlanta, GA 30339, USA) has not to our knowledge been used to measure postoperative swelling, but could be an alternative to laser scanners, as stereo-optical 3-dimensional scanners are usually less expensive, easy to use, and have a recording time of milliseconds. The latter is a great aid in the prevention of motion artefacts, which may easily happen in the head and neck region. The aim of the current study was to assess the reliability and validity of the 3dMD DSP400® stereo-optical 3-dimensional scanner of volumetric changes in facial morphology by making repeated analyses of the volume of the cheeks when an artificial swelling was in place at 4 separate moments during the day, and analysing repeatedly the volume of an artificial swelling attached to the head of a mannequin. In this study “reliability” was defined as the degree to which the measurement is free from measurement error, and “validity” was defined as the degree to which an instrument truly measures the construct it purports to measure.[21]

Materials and methods

Subjects

To assess in vivo reliability we enrolled 24 healthy volunteers (12 women and 12 men), who were coworkers at the department of orthodontics in the University Medical Centre, Groningen. Their mean (range) age was 29 (19–63) years. Informed consent was obtained from each volunteer before the study.

The artificial swelling

For each volunteer an artificial swelling was made by mixing a similar amount of base paste and catalyst paste of an impression material (Provil Novo Putty®, Heraeus Kulzer GmbH, Hanau, Germany), by forming it into a small bolus. The volunteers were asked to keep their teeth gently occluded. The artificial swelling (bolus) was then placed in the molar region of the subject's mouth on the buccal side of the teeth and pressed gently against the teeth, which made small impressions in the artificial swelling. These impressions enabled reinsertion of the artificial swelling in the same position again for further measurements later in the day. After the material had set it was removed. It was disinfected with alcohol, as the impression material is not affected by short term disinfection.[22] Each artificial swelling was stored in a marked bag.

To assess the in vitro reliability and validity of the scanner, 6 artificial swellings were made with the same impression material to cover the full volume range of the artificial swellings that were used in vivo. These artificial swellings were placed on the exterior surface of a Styrofoam mannequin head, which was measured 4 times with the stereo-optical scanner, with and without each artificial swelling in place.

Measurement of the volume of the artificial swelling

Each artificial swelling was weighed on a high-precision scale (MettlesPJ360,Mettler- Toledo GmbH, Griefensee, Switzerland). The density of the impression material was taken from the Material Safety Data Sheet of the material (Provil Novo Putty®, Material Safety Data Sheet, Heraeus Kulzer GmbH, Hanau, Germany). The volume of each of these constructed swellings was calculated by dividing the weight of the artificial swelling by its density (1.60g/cm3).

The scanner

Three-dimensional scans were made with the 3dMD DSP400® stereo-optical 3-dimensional scanner by one observer who was proficient with the scanner. The3dMDsys- tem uses a synchronised digital multicamera configuration, with 3 cameras on each side (1 colour, 2 infrared) that capture photorealistic quality pictures. The system can capture full facial images from ear to ear and under the chin in 2ms at the highest resolution. The geometrical accuracy of the facial system used in the study as claimed by the manufacturer is <0.2mm.

Data capture technique

A custom-built studio was used with standardized lighting conditions. The natural head position was used, as it is clinically reproducible.[23] The subjects sat on a self-adjustable chair and were asked to level their eyes horizontally, and the mid-line of the face was aligned towards the camera. Adjustments to seating heights were made to assist the subjects in achieving natural head posture. In order to create a standard head and jaw position, the subjects were instructed to swallow and to keep their jaws in a relaxed position while occluding gently during scanning. The total scan time was approximately 2 milliseconds. Scans with and without the artificial swelling were taken on two occasions; in the morning and in the after-noon. After the subjects had been scanned with the artificial swelling in place they were asked to remove the artificial swelling, to stand up and walk around for half a minute, and then to sit down again for a 3-dimensional scan without the artificial swelling (first session). The procedure was then followed immediately by a second measurement session. The afternoon session was identical to the morning one.
The mannequin head was placed on a tripod to stabilise it during the scans. The head was scanned 4 times, with and without the artificial swelling in place, for each of the 6 artificial swellings.

Data processing

To calculate the changes in contour that were caused by the artificial swelling, the corresponding 3-dimensional models of each session (with or without the artifi-cial swelling in place) of each patient were loaded in the 3dMD software (3dMD Vultus® software version 2.2.0.18, 3dMD, Atlanta, GA 30339, USA). In the soft-ware, the two corresponding 3- dimensional models (with and without the artifi-cial swelling both for the mannequin head and the 20 test subjects) were aligned

and recorded on the basis of the forehead and bridge of the nose as suggested by the manufacturer. These areas were used because they are assumed to be 3-dimensionally stable. After the two corresponding models had been recorded, the volumetric change in facial contour exerted by the artificial swelling was calculated by selecting the area of the swelling and subtracting the two surface models (with and without artificial swelling) (figure 1).

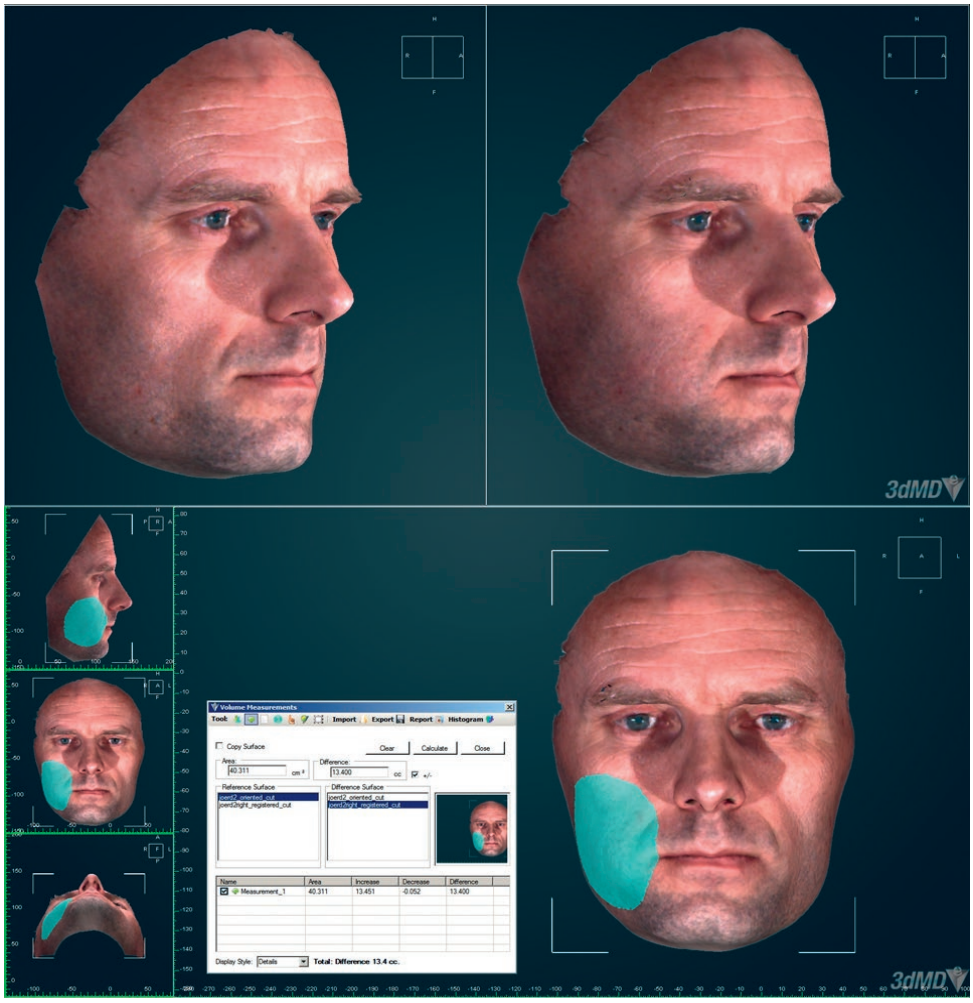

Figure 1. Measurement of volumetric changes in facial contour. The two 3-dimensional scans with and without swelling are recorded, and the region of the swelling selected (blue). The difference between the two surfaces is caused by the artificial swelling, and this volume is calculated automatically by the software.

Statistical analysis

To verify whether the variation in the results of measurements was related to the magnitude of the facial swelling, we made a scatter plot of the mean (of 4 sessions) of the facial swelling of each participant against the SD of that participant.

To analyse differences between measurements, a repeated measures ANOVA was calculated on the outcomes of the scanning of the artificial swelling with time of day (morning or afternoon) and session (1st, or 2nd) as factors, as factors, for participants and the mannequin's head. Intraclass correlations (two-way mixed model, absolute agreement) were calculated for the participants and the mannequin's head. A within subjects ANOVA was used to calculate a repeatability coefficient for participants as well as for the mannequin's head.[24] In the ANOVA the total variance in the results of measurements is partitioned in variation because of the subjects and a residual variance (measurement error). From this residual variance the repeatability coefficient was calculated, as follows: 1.96 x √ 2 x √residual variance. A paired t-test was calculated to assess the significance of differences between the results of the first measurement session and the volume inserted in the mouth of the participants or attached to the head of the mannequin.

Results

We found no significant correlation (r = - 0.022, p = 0.91) between the mean (of 4 sessions) of the facial swelling of each participant and the SD of that participant (figure 2).

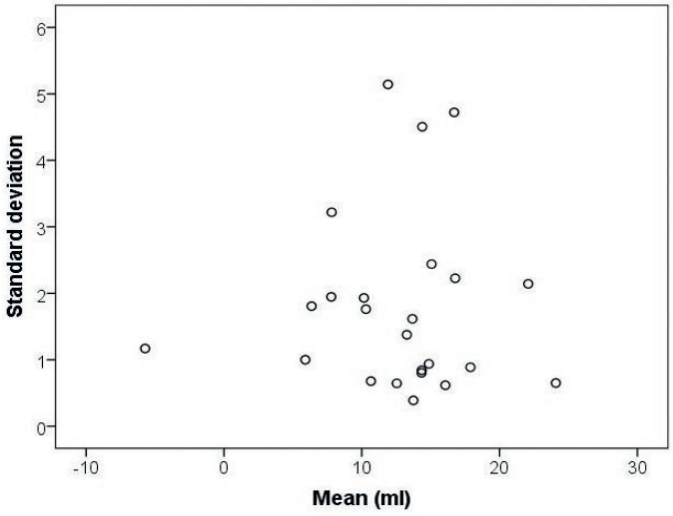

Figure 2. Plot of the mean of 4 sessions / participant against the SD of that mean.

The mean volume inserted in the mouth of the participants (n=24) was 14.0 ml (sd 2.2, range 8.4 – 19.4) and attached to the mannequin head was 15.1 ml (sd 6.1, range 6.3 – 22.5) (Table 1).

Measurements did not differ significantly between morning and afternoon or between session 1 or 2 (Table 1). The intraclass coefficient for the participants was 0.89 and for the mannequin head 0.99. For participants the between-subject variance was 137.79 and the residual variance 4.53.

Table 1 Results of measurements for participants (n = 23) and mannequin head and p values for differences between morning and afternoon and sessions1 and 2. Data are mean (SD) except where otherwise stated

Variable	Participants	P value	Mannequin's head	P value
Volume (ml) (95% CI)	14 (2.2) (8.4 to 19.4)		15.1 (6.1) (6.3 to 22.5)	
Measurements (ml)				
- Morning, session 1	12.6 (5.6)	0.49 *	14.8 (5.7)	0.57*
- Morning, session 2	12.0 (5.9)		14.7 (6.1)	
- Afternoon, session 1	12.9 (6.5)	0.053**	15.0 (6.3)	0.54**
- Afternoon, session 2	12.7 (6.8)		14.8 (6.2)	
Reliability: intraclass coefficient (95% CI)	0.89 (0.81 to 0.95)		0.99 (0.98 to 0.99)	
Reliability: Repeatability coefficient	5.9		1.3	
Validity: Difference (95% CI)	1.2 (-0.9 to 3.4)	0.243#	0.2 (0.02 to 0.4)	0.04#

The results of 1 participant were not used in the repeated measures ANOVA because the measurements for the afternoon sessions were not available.

* p value for differences between morning and afternoon

**p value for differences between session 1 and session 2

95% CI : 95% confidence interval

p value for differences between volume measured and volume inserted / attached.

For the mannequin head these values were 147.79 and 0.23, respectively. The repeatability coefficient for participants was larger than that for the mannequin (Table 1). The 3dMD DSP400® stereo-optical 3-dimensional scanner underestimated the volume inserted by a mean of 1.2 ml (95% CI -0.9 to 3.4) (p = 0.24) in participants, and in the mannequin head with a mean of 0.2 ml (95% CI 0.02 to 0.4). (p = 0.04).

Discussion

The reliability of the stereo-optical 3-dimensional scanning system for measuring facial swelling is higher in vitro than in vivo, but both intraclass coefficients were above 0.85, indicating that the system can be used clinically.[21] The 3dMD DSP400® stereo-optical 3-dimensional scanner systematically underestimated the volume, but this underestimation was clinically small (0.2 ml) relative to the volume of the swelling (mean 15.1 ml) for the in vitro experiment. For the in vivo experiment the underestimation was somewhat larger (1.2 ml), but not significantly so. The repeatability coefficient of the in vivo scan was 5.9 ml, which indicated that the system could detect changes in facial volume of 5.9 ml or more between 2 measurement sessions.

The difference in reliability in vivo and in vitro can be explained by the influence of changes in the soft tissues between scans in participants. Another source of error would be changes in the subject's facial expression.[25] This effect was apparent in our study. One participant smiled during measurements without the artificial swelling in the mouth, and had a neutral facial expression while the artificial swelling was in the mouth. This resulted in the face having a larger volume when the artificial swelling was not in the mouth (figure 2: circle on the left side).

However, as that behavior was consistent, the SD was small (< 2 ml). The lack of correlation between the mean volume measured and the SD of these measurements within participants indicate that the measurement error is not dependent on the size of the swelling.

The difference in validity between the in vivo and in vitro measurements can be explained by the deformation of the soft tissues, as swelling will have its effects both inward and outward in the mouth. Measurements of the external surface will inadvertently lead to underestimation of the true volume, as inward deformation will not be taken into account when volume changes are measured by external surface measurements. In other words, the method is applicable for reliably detecting volumetric changes in the facial contour, but is not applicable for estimating the true increase in tissue volume that underlies the externally visible change in facial contour.

The 3DMD system that we used has been assessed by comparing 3-dimensional landmark measurements on a mannequin head with those taken by calipers.[13,14] The differences ranged between 0.1 and 0.5 mm[13] and between -0.8 and 0.5 mm.[14] The intraclass coefficients ranged from 0.98 to 1.00.[14]

In a study similar to ours but using a different 3- dimensional scanning system, it was claimed that the system was accurate and reliable for assessing volumes in studies of facial swelling.[20] However, limits of agreement, or repeat- ability coefficients, were not reported

in that study. In another study that used a handheld laser scanner to assess facial swelling[26] it was reported that the measurements of swelling on an artificial mannequin head the measurement error was 4%, but when testing the device in volunteers the variation in results was larger, up to 7.6 ml (a value close to our repeatability coefficient of 5.9 ml) as a result of repositioning of the participants. The findings of our study agree with the other studies that have assessed the validity of the 3DMD system.[13,14]

Clinically, the 3DMD system can be used to measure facial swelling and changes in volume in the facial region reliably, and to assess the effects of interventions (such as operation, treatment of oedema, or medication). The changes must, however, be greater than 5.9 ml to indicate a true difference. Changes of less than 5.9 ml cannot be interpreted clinically because they could be the result of measurement error of the 3dMD DSP400® stereo-optical 3-dimensional scanner, alignment errors of the observer, and variations in facial expression or posture of the subjects scanned. The true volume (validity) that underlies a swelling cannot be assessed accurately with this system. For assessing the true change in volume that underlies the swelling, transmissive technology such as magnetic resonance imaging should be used.

Conclusion

The 3dMD stereophotogrammetry scanner is a reliable and valid tool for measuring volumetric changes in facial contour larger than 5.9 ml and for the assessments of facial swelling.

Conflict of interest statement

The authors have no commercial interest in the products used in the study.

Acknowledgements

The authors have no commercial interest in the products used in the study. The authors thank Kelly Duncan for making the 3dMD system and software available for us to acquire the images and collect the data used in this study.

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Treatment planning

Chapter 4	3D Computer Aided Treatment Planning in Endodontics. *Journal of Dentistry 2016 Feb;45:67-72.*
Chapter 5	3D Technology in Maxillofacial Prosthodontics. Submitted
Chapter 6	Digitally Designed Surgical Guides for Placing Implants in the Nasal Floor of Dentate Patients: a Series of Three Cases. *International Journal of Prosthodontics 2012 May- Jun;25(3):245-51.*
Chapter 7	Digitally Designed Surgical Guides for Placing Extra-oral Implants in the Mastoid Area. *International Journal of Oral and Maxillofacial Implants 2012 May- Jun; 27(3):703-7.*
Chapter 8	Digital Planning of Cranial Implants. *British Journal of Oral and Maxillofacial Surgery 2013 Jul;51(5):450-2.*

4

3D Computer Aided Treatment Planning in Endodontics

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Abstract

Aim: Obliteration of the root canal system due to accelerated dentinogenesis and dystrophic calcification can challenge the achievement of root canal treatment goals. This paper describes the application of 3D digital mapping technology for predictable navigation of obliterated canal systems during root canal treatment to avoid iatrogenic damage of the root.

Materials and Methods: Digital endodontic treatment planning for anterior teeth with severely obliterated root canal systems was accomplished with the aid of computer software, based on cone beam computed tomography (CBCT) scans and intra-oral scans of the dentition. On the basis of these scans, endodontic guides were created for the planned treatment through digital designing and rapid prototyping fabrication.

Results: The custom-made guides allowed for an uncomplicated and predictable canal location and management.

Conclusion: The method of digital designing and rapid prototyping of endodontic guides allows for reliable and predictable location of root canals of teeth with calcifically metamorphosed root canal systems.

Introduction

The objective of root canal treatment is adequate control of the resident microbiota through proper shaping, disinfection and obturation of the root canal system to achieve periapical healing. Calcification of the pulp chamber and root canal system can compromise access and thus complicate the root canal treatment. The process of calcification is called obliteration or calcific metamorphosis and is associated with injury to the pulp. The injury is commonly through disease process (caries, tooth surface loss), dentoalveolar trauma, or operative procedures such as pulp capping, pulpotomy and rarely orthodontic treatment[1]. Although canal obliteration does not inevitably lead to pulp necrosis or periapical disease[2,3], when it does, canal location and negotiation are significantly more difficult. The degree of difficulty is dictated by natural tooth morphology, the nature and extent of superimposed calcific alteration, extent of dentinal sclerosis and access to the tooth in the mouth.

In most cases, the calcific metamorphosis appears to be severe coronally, tapering off towards the root apex, leaving the dentist with the tantalising technical prospect of reaching it through spatial and drilling skills. Many clinicians have fallen foul of the temptation to achieve apical patency in such cases, only to have been sobered by the complications of excessive and uncontrolled dentine destruction or worse: root perforation[4].

Access to such calcified teeth has traditionally relied on the ability to drill truly in the direction of the anticipated canal opening based on knowledge of anatomy, 3D mental visualisation and a steady hand able to hold bur orientation[5]. A contemporary aberration of this approach is to use an operating microscope, which requires experience with treating challenging cases as it can further compromises any loss of orientation. Another development, cone beam computed tomography (CBCT), has the potential to aid the operator in enhancing the information for 3D visualisation by providing 3D depiction of the radiographic data. Not only does the CBCT dataset give a clear 3D representation of the tooth involved, it also seems to provide the operator with a more reliable way to detect root canal anatomy[6]. When comparing measurements made on traditional radiographs and CBCT datasets the latter seem to be more accurate[7] and the errors seem to be small and clinically insignificant[8]. The mere availability of 3D information, however, still leaves the operator with the task of interpreting it, creating a *mental* 3D map along which to execute the practical task free-hand as before.

This paper describes a novel way to create a directional guide for anterior teeth with obliterated root systems on the basis of CBCT data which guides the clinician while removing dentin to locate the canal opening.

Materials and Methods

A small field CBCT data set (3D exam, KAVO, Amersfoort, The Netherlands) is made of the patient's upper or lower jaw, depending on the tooth to be treated. The patient is asked to open their mouth slightly to ensure that the maxillary and mandibular teeth are separated. The CBCT machine is set to a voxel size of 0.3 mm. This resolution surpasses the 0.5 mm resolution prescribed for planning implants using Nobelguide (Nobelbioresearch, Gothenburg, Sweden) or Simplant (Materialise, Leuven Belgium). These settings are chosen to obtain the lowest dose possible for the patient while maintaining the best imaging result to accomplish optimal planning. The CBCT dataset is converted to a surface model with "Devide" freeware (TU Delft Graphics group, Technical University of Delft, The Netherlands) using an optimal threshold to depict bone, teeth or the pulp. In addition, digital registration of the dentition is performed with the aid of the Lava COS intra oral scanner (3 M Espe Zoeterwoude, The Netherlands). Three separate entities, viz., bone, pulp and teeth are imported into 3ds Max software (Autodesk, San Rafael, California, USA) (figure 1).

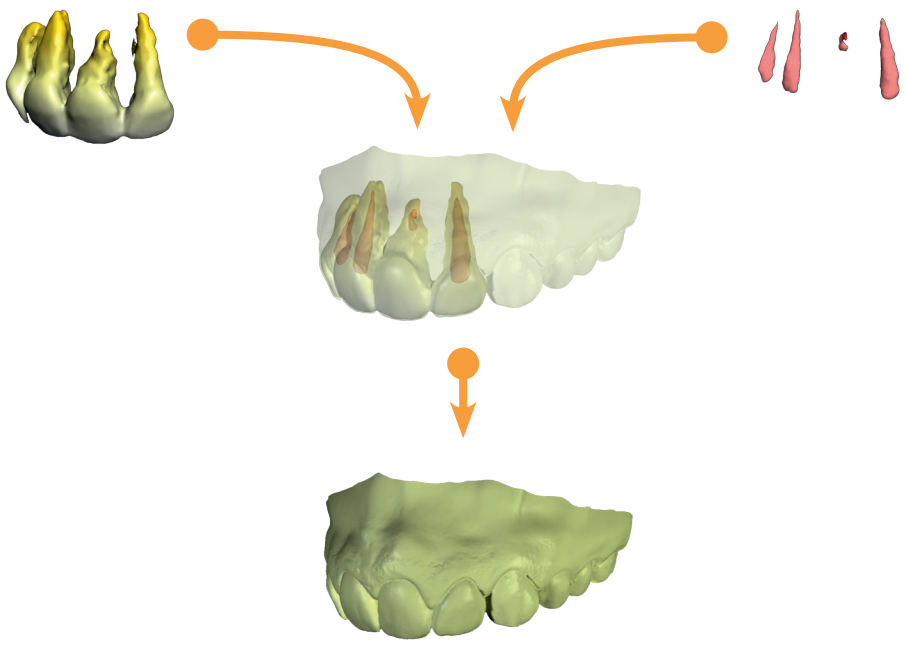


Figure 1: 3D datasets of the teeth, pulp and digital impression of patient 3 combined in one 3D model.

As the planning requires a 3D model of the roots of the teeth (the CBCT dataset) and a precise 3D model of the crowns of the teeth (the digital impression), these two models are aligned and registered in GOM inspect free software (GOM mbH, Braunschweig, Germany). In 3ds Max software, a virtual cylinder is created, which is aligned with the line between the centre of the remaining root canal and the centre of the palatal surface of the crown of the tooth. Around this central cylinder, a second 3D cylinder is designed with a diameter 2 mm larger than the central cylinder, by cloning the first cylinder and then increasing the diameter. This cylindrical zone depicts the safety zone around the central shaft within which drilling can be performed safely. A third cylinder is then created with a diameter similar to that of the consuetudinary drills used for the purpose. This cylinder is used to construct a hole for the metal sleeve that will prospectively guide the drill. The aforementioned cylinder is aligned with the first cylinder using the “align”-tool available in the software (figure 2).

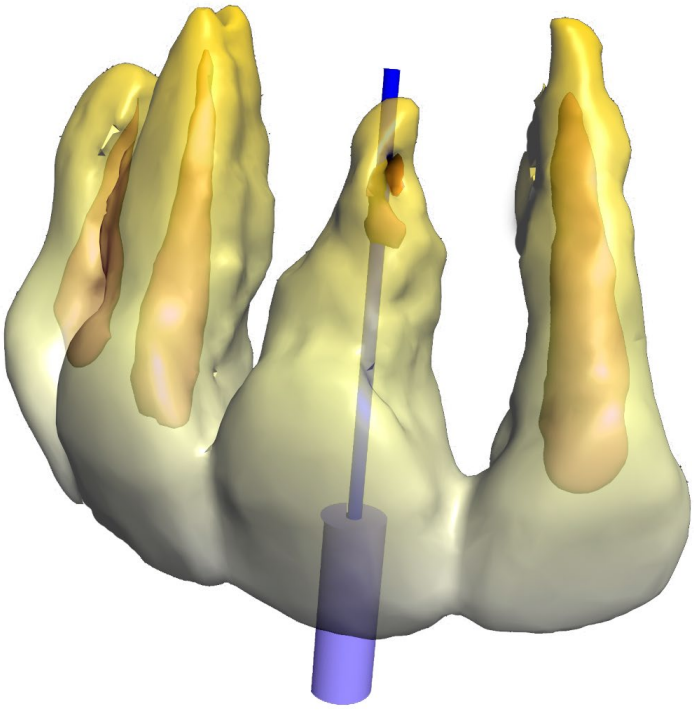


Figure 2: Planning of the directional guide for patient 3. A cylinder is used to depict the direction of the drill necessary to locate the root canal system. Other cylinders are automatically aligned with the directional cylinder. Those cylinders are used for the design of the directional guide.

Based on the planning, a surgical guide is digitally designed in the 3ds Max software. The guide will use the dentition for stable anatomical fixation and extends from the left first premolar to the right first premolar. The surgical guide is made to fit the dentition by first expanding the digital dentition by 0.1 mm using a “shell”- command and then digitally subtracting the dentition from the guide design using a Boolean operation. Expansion of the dentition is performed to compensate for the polymerization shrinkage that occurs in almost all 3D printing technologies, thus ensuring a proper fit. Similarly, a hole is modelled with an outside diameter of 3.0 mm in the surgical guide in which a metal tube with an inside diameter of 2.40 mm could be placed. This metal tube will eventually serve to guide the endodontic drill (figure 3).

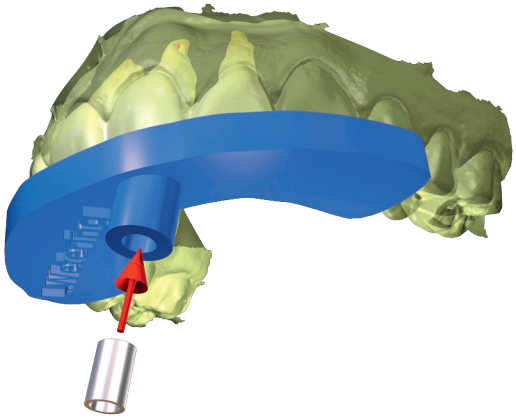
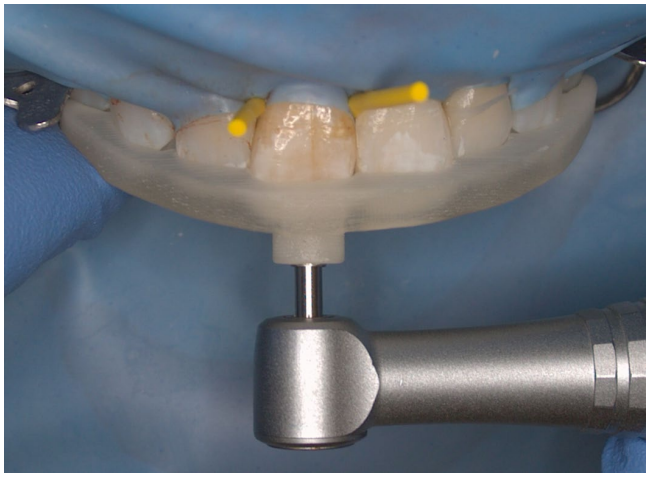


Figure 3A: The final directional guide design. After the rapid prototyping of the guide a metal tube is placed in the corresponding hole. The metal tube has an inner diameter that is slightly larger than the bur used during the location of the root canal system.

Figure 3B.The directional guide in place, while a bur is used to gain access to the canal system. As can be seen the direction of the bur is not exactly parallel to the long axis of the tooth during preparation. This coincides with the 3D planning.



The distance from the top of the guide to the beginning of the root canal system is measured and noted on the patient chart. The working length is also determined from the 3D dataset and noted on the patient chart. An overview of our digital planning process is given in figure 4.

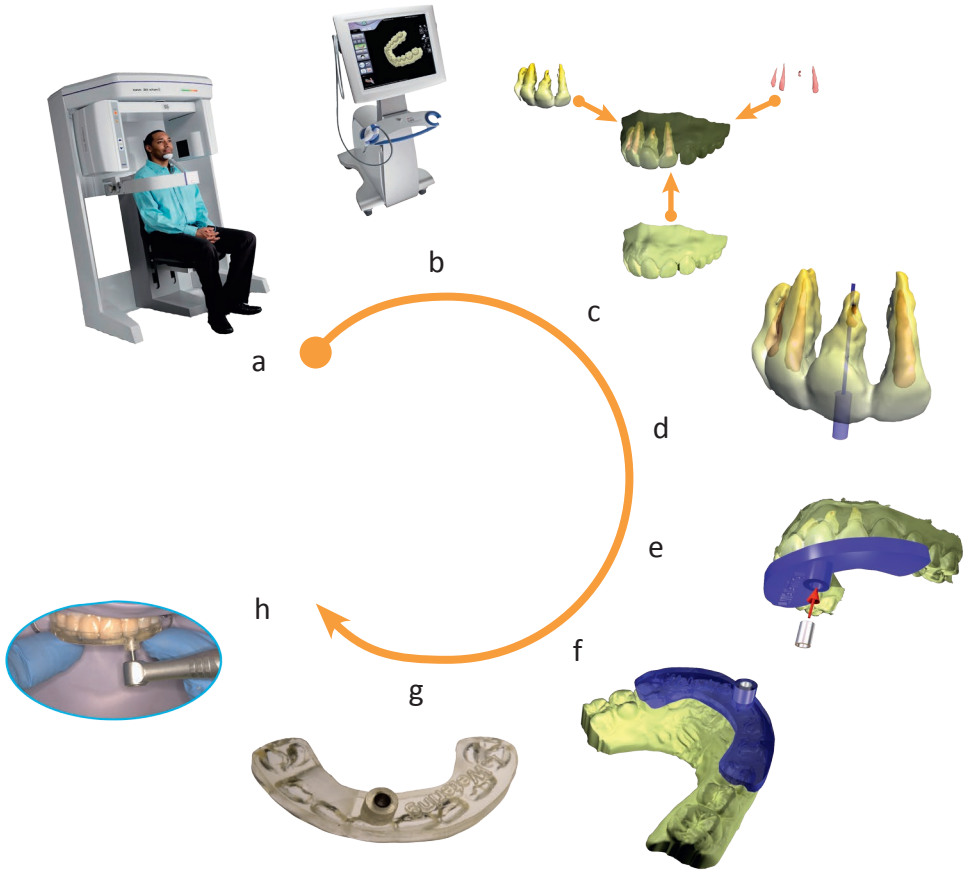


Figure 4: An overview of the 3D planning for the endodontic directional guide and its application in the patient. A cone-beam CT is made (a) of the teeth involved in the planning. An impression of the dentition is made with an intra-oral scanner (b). In GOM inspect software the datasets of the teeth, pulp, bone and digital impression are registered (c). In 3D software the planning of the direction of the access is made (d) and a guide is designed with space dedicated for the metal guiding sleeve (e). When the final design is ready (f), it can be sent to a dental lab or a rapid prototyping facility. The printed guide (g) for use in the mouth of the patient (h). With this guide the route canal system is identified and prepared.

The digitally designed surgical guide is prepared for export using the “stl check” command and exported as stl file and sent to a 3D printer. If a 3D printer is not available, the file can also be sent to a dental laboratory that is able to produce rapid prototyping models. With the aid of rapid prototyping the stl file is converted to a physical model.

The digital planning procedure and the directional guide were tested in three patients who required endodontic treatment on maxillary anterior teeth with obliteration of the root canal system. The patients were informed about the risk associated with endodontic treatment of calcified root canals and an informed consent form was signed by the patient. The Medical Ethics Review Board of the University medical Center, Groningen ascertained that the study was not deemed a clinical research project with test subjects as described in the Medical Research involving Human Subjects Act (WMO) and that formal ethics committee approval was not necessary as normal clinical procedures were followed with addition of an aid to increase the safety and decrease the risk of complications for the patients.

Before the endodontic treatment, the anterior teeth were isolated by rubber dam from the right to left first premolar, to allow the endodontic directional guide to use these teeth for stability. The fit of the guide was confirmed using “fit checker” (GC Europe NV, B-3001 Leuven, Belgium). A standard endodontic opening was created in the involved tooth in each patient and the guide was placed in position. A Munce bur number 2 (CJM Engineering Inc., Santa Barbara, CA 93101, USA) was used to slowly gain access to the root canal system. The metal tube in the guide fitted tightly around the shaft of the bur, ensuring proper guidance in the right direction, while only the tip of the bur was able to cut the dentin. Once the full length of the shaft was reached, the bur was replaced with one with a longer shaft. After the root canal system had been reached, it was negotiated with endodontic hand files with intracanal use of a lubricant to the working length as indicated by an apex locator while irrigating copiously.
When the number 15 handfile was reached, a radiograph was taken to confirm the determined working length (figure 5). The root canal system was further prepared using a WaveOne (Dentsply Maillefer, Ballaigues, Switzerland) instrument. This phase was accomplished with the continuous intracanal use of a lubricant and a 2.5% solution of sodium hypochlorite. After a final rinse of 17% EDTA solution, the prepared canal was disinfected with a 2.5% solution of sodium hypochlorite and subsequently dried and prepared for obturation.

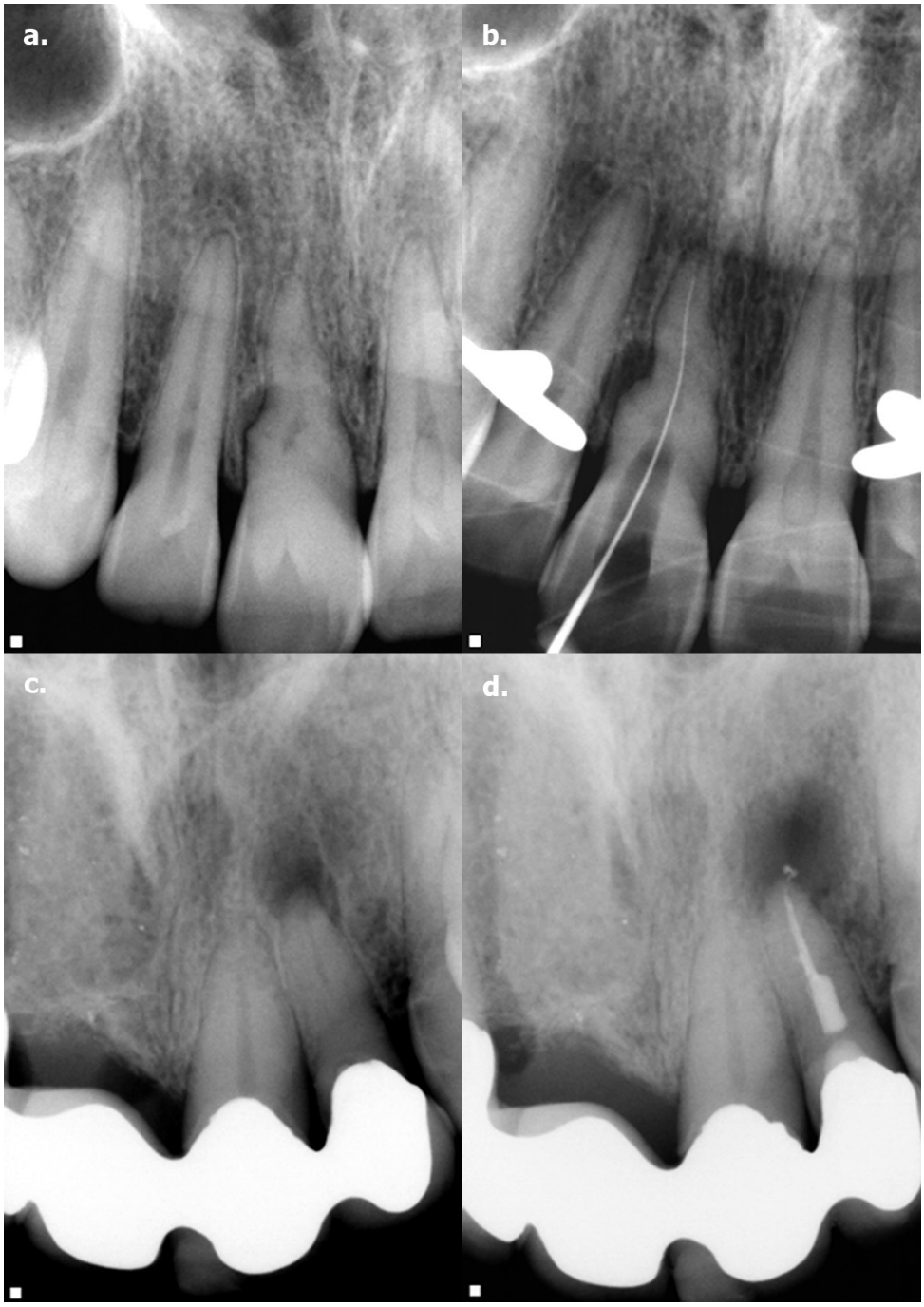


Figure 5: The pre-operative radiograph (a) and working length radiograph of patient 1, after the root canal system had been located with the aid of the directional guide (b) and the preoperative (c) and immediate postoperative radiograph (d) of patient 2

Results

Location of the root canal system proved straightforward in all three cases with the aforementioned directional guide. In the first case, after every millimetre advance of the bur, the guide was removed and the access cavity checked through the microscope to ensure that the proper angulation was maintained, by looking for traces of the original canal. The canal opening was reached as anticipated at the target length. In the subsequent cases, the microscope verification was abandoned without incurring any problems. Because the root canal systems could be rapidly located using the directional guide, the canal preparation of all cases could be finished in one visit.

Discussion

The digital planning procedure and the resulting directional guide simplified difficult root canal treatment in obliterated teeth meanwhile decreasing the risk of iatrogenic damage to the root due to excessive dentine destruction and/or root perforation.

In the traditional approach to calcified pulp chambers, if the canal orifice or pulp chamber has not been located after 3–4 mm of penetration into the teeth, it is recommended that the buccopalatal orientation of the bur is rotated so that it is parallel to the long axis of the tooth. In most cases, the problem is that the long axis of the tooth had not been followed; the commonest error being that the bur is angled labially, leading to a perforation of the labial root surface below the gingival attachment[9]. To facilitate more predictable location of the root canal system, it has been suggested that the access cavity is prepared close to or through the incisal edge of the tooth[9,10] . This approach also facilitates better planing of the root canal system walls by the endodontic files[11]. Although this approach enables easier maintenance of bur alignment with that of the long axis of the tooth, it still requires the clinician to have an accurate mental map of the root canal system and the anatomy of the tooth. Even the availability of CBCT alone, merely enhances 3D visualisation, lacking the necessary coupling of the data set to clinical execution.

The developed method provides coupling between the CBCT dataset and physical execution of the task of drilling to the minerally-receded canal opening; it eliminates the unpredictability of drilling in the correct direction and makes a challenging clinical problem relatively simple to manage. The digitally designed directional guides worked in all respects to facilitate root canal treatment as anticipated and shortened treatment time considerably. The tentative sectional drilling and checking process is replaced by one that is uninterrupted and allows drilling directly to the receded canal. A major advantage of digital planning is that it is possible to preoperatively visualize the root canal location and plot the naviga-

tion in detail without having to mentally transfer the planning to the clinical situation. The described technique has the potential to substitute the 3D visualization skill, specialized training and/or clinical experience necessary to treat these difficult cases. This will enable many dentists to achieve predictable results without needing extensive endodontic skills.
The disadvantage of the method described is that multiple teeth have to be isolated during the procedure as the guide needs to rest on the teeth directly to ensure the stability of the guide. It is possible to use a smaller number of teeth for support of the guide, but still multiple teeth need to be isolated. Another disadvantage is that the guide restricts the visual access to the endodontic access cavity even though the guide is made of a transparent plastic, necessitating removal of the guide to ensure that the proper path is still being followed during the procedure. Modification of the guide to facilitate inspection of the access cavity is an issue for future developments. Moreover, an ultrasonic tip can be used with the guide in place, but this is not advised as the guide restricts the visual access. It is, therefore, advised to remove the guide before using an ultrasonic tip.
When considering the accuracy of this 3D planning technique, a slight mismatch between the planning and execution may be expected. One reason for this is system error, i.e., a summation of all the errors present in the different phases, is accumulated in the final outcome. In the data acquisition phase, the resolution of the CBCT dataset should be taken into account even though the CBCT can be considered to be very accurate.[7] As the voxel size is 0.3 mm, the accuracy of the system as a whole is unlikely to surpass 0.3 mm. Then there is an error in the data acquisition of the dentition. The manufacturer of the Lava COS claims an accuracy of 11 mm, but this value has not yet been validated externally. Furthermore, the 3D model of the dentition was automatically registered with the dentition in the CBCT dataset to obtain a combined 3D model, which would give rise to registration errors. [12] During the final stage of rapid prototyping, the SLA or 3D printing material may show a slight dimensional change during polymerization. If the guide is not seated exactly as planned on the dentition, a small angulation of the Munce bur may occur resulting in magnified differences between the planned and final angulation of the bur. Furthermore, the bur used to remove the dentin is very thin and may show a slight bending under pressure. A meta-regression analysis of Schneider et al. on computer-guided template-based implant dentistry[13] revealed a mean deviation of the implant of 1.07 mm at the entry point and 1.63 mm at the apex. However, some of the studies included in the meta-analysis involved edentulous subjects, in whom, the stability of the surgical guide may be less than optimal. Even though there is a difference between the procedures for placing implants and locating root canal systems, the procedure followed shows many similarities and a slight mismatch can be expected for

the endodontic directional guide. The proposed method has a number of advantages. It is a predictable technique that replaces mental visualisation and technical execution skills while it reduces treatment time. Furthermore, 3D planning can be relatively cost-effective and may be contracted out to a proficient 3D software operator with input from the clinician. Finally, the proposed method has flexibility of application to other teeth and for preparation of endodontic surgery (although not demonstrated in the presented cases). The cost of the developed technique is potentially minimal. The 3D planning as described, may entirely be performed with expensive 3D software applications but to minimize the cost, we have used only one commercial software application, 3dsMax. To reduce the costs it is possible to perform the entire workflow using only freeware applications. The conversion of the CT data was already performed with the freeware application "Devide". The GOM inspect software, used to register the different 3D surface models, is also available free of charge. The 3D visualizations and designs were performed in 3ds Max software, but this can also be done in "Blender", a free 3D modelling and animation tool (www.blender.org). For the digitization of the dentition, the Lava COS intra-oral scanner was used, but a traditional impression poured in stone may also be used. Many dental laboratories offer the service of converting plaster models to digital models using 3D scanners at a small additional cost. The rapid prototyping of the directional guide may be performed with one of many available techniques. The SLA production of a directional guide costs currently around 130 euros, while the same guide design printed with a 3D polyjet printer ("Objet", Objet Ltd., Rehovot, Israel) costs around 30 euros. The guides produced with these technologies fit equally well. This means that the cost of the aforementioned method can be brought down to the cost of the production of the guide. With the prices of 3D printers reducing rapidly, the approach comes within reach for a clinician to print their own directional guide provided that the resolution of the printer is sufficient. Future developments with regard to 3D computer aided treatment planning in endodontics include the use of the device for locating obliterated canals in posterior teeth. A limitation in this respect is the needed minimal thickness of the guide that might restrict its application in limited posterior spaces. Another development would be the fabrication of a set of sequential burs with a very small head with increasing lengths of the shaft. Such a design ensures a proper fit of the shaft in the metal cylinder and enables early use of the series of very thin burs. This approach would ensure preservation of coronal dentin and prevent unneeded weakening of the root.

Conclusions

Endodontic treatment of an anterior tooth with severe pulp system obliteration requires experience and skills of the clinician and can be very challenging. By using a 3D digitally designed directional endodontic guide produced with computer-aided additive production techniques, the treatment of compromised cases can be performed by less specifically experienced or skilled clinicians. The cost of such 3D planning and the production of the directional guide are considered to be low and will further reduce in the future. In addition, use of the developed tool, may reduce the treatment time while increasing the predictability and success of the treatment of calcifically metamorphosed teeth.

Acknowledgement

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5

3D Technology in Maxillofacial Prosthodontics

This chapter is an edited version of:
van der Meer WJ, Vissink A, Raghoebar GM, Visser A
3D Technology in Maxillofacial Prosthodontics.
Submitted.

Abstract

Aim: To provide an overview of the current status of three dimensional (3D) technology in the prosthetic rehabilitation of maxillofacial defects (ear, nose, orbital).

Materials and Methods: MEDLINE, COCHRANE and EMBASE databases were systematically searched for articles pertinent to the use of 3D technology in maxillofacial prosthodontics up to December 31, 2015. Eligible papers described the use of 3D technology in the workflow of maxillofacial prostheses.

Results: Eighty-two out of 1900 identified papers were considered eligible. Although 3D technology is increasingly used in maxillofacial prosthetics, almost all eligible papers were technical notes and case reports describing how certain steps in the traditional workflow of making maxillofacial prosthesis could be replaced by 3D technology. No clinical trials comparing different techniques are yet published neither papers assessing time efficiency or costs. Moreover, none of the included papers described a 100% 3D workflow due to lack of appropriate software and limited options for rapid prototyping, e.g., printing silicone prostheses with matching coloring and or details like hair. It is assumed that in the near future techniques needed for 3D technology in facial prostheses will become easier to apply and cheaper with time as well as that a 100% 3D workflow for facial prostheses will become available.

Conclusion: 3D technology in maxillofacial prosthodontics is evolving and has shown its potential in replacing certain steps in the traditional workflow of designing and fabricating facial prostheses, but yet no full 3D workflow is available.

Introduction

Trauma, treatment of cancer and congenital diseases can result in maxillofacial defects that are demanding from an aesthetic perspective and are in need of a challenging prosthetic treatment.[1, 2] These maxillofacial defects can be restored by either surgical reconstruction or with silicone facial prostheses.

Surgical reconstruction of maxillofacial defects is difficult to perform. Outcome has not been described in large patient numbers and the results are often unsatisfactory.[3, 4] Because of the often satisfactory results, maxillofacial defects are usually reconstructed prosthetically. Moreover, the satisfaction of the patients with a prosthodontic reconstruction of their maxillofacial defects is high.[3]

Manufacturing of a silicone maxillofacial prostheses is traditionally a labor-intensive work in which three phases can be distinguished:

1. *Preparation phase*: planning of the prosthetic rehabilitation and collecting data by taking impressions and making photographs of the affected and healthy contra lateral region.

2. *Production phase:* creating a try-on model, often made out of wax, by using plaster models of the defect to be reconstructed. The try-on model is fitted on the patient and adjusted to the patient's needs and wishes. The final try-on model is converted into a silicone prosthesis, usually by using plaster molds and individual colored silicone materials.

3. *Placement phase*: the silicon prosthesis is placed on the patient and finalized chair-side by making color adjustments and adding lifelike details, like eyelashes.

It has been shown that the aforementioned traditional workflow is reliable with a usually very satisfactory final outcome for both the prosthodontist and patient.[5] A major disadvantage of the traditional workflow is the large number of often laborious and for the patient not always comfortable intermediate steps that has to be taken before maxillofacial prostheses can be finalized. It would be a great achievement when the workflow would become less laborious and less demanding for the patient.

As mentioned, the traditional workflow from taking an impression of the maxillofacial defect until finalization of the maxillofacial prosthesis is time-consuming, even though digital technology can be used for obtaining better results in, e.g., matching skin colors[6] or adding details.[7] For long, there was no alternative to this approach, but since the advent of three dimensional (3D) scanners, 3D software and rapid prototyping technology, the traditional impression, modelling and production techniques can probably be replaced by

digital equivalents. Therefore, the aim of this paper was to systematically review literature in order to search for the current status of 3D technology used in prosthetic rehabilitation of maxillofacial defects (ear, nose, and orbital).

Materials and methods

Search of the literature

A search of MEDLINE, COCHRANE and EMBASE databases (*last accessed on 31/12/2015)* was conducted using (a combination of) search terms: facial prostheses, facial prosthodontics, maxillofacial prosthodontics, maxillofacial prostheses, craniofacial defects, maxillofacial defects, silicone prosthesis, 3D, CT, MRI, digital, ear prosthesis, orbital prosthesis, nasal prosthesis, extra-oral prostheses, rapid prototyping and stereolithography. No language restriction was applied. The search resulted in 1900 papers that met the search terms according to the search engines. Additional references were taken from the bibliography of the references identified through MEDLINE and EMBASE searches.

Inclusion and exclusion

The identified 1900 studies were subjected to preliminary analysis (figure 1). Eligible papers were papers that showed how to use 3D technology in at least one of the three phases of the fabrication of facial prostheses (eye, nose, ear), with or without comparison with traditional technology. Excluded were 1) reviews 2) papers that described 3D technology for other medical purposes than the fabrication of facial prostheses, e.g., cranioplasty or to aid surgical reconstructions, and 3) papers exclusively dealing with implant placement for the retention of facial prosthesis. Titles and abstracts were scanned and the relevance of each study to the 3D technology in prosthodontics was determined. Title and abstracts identified through electronic searches were reviewed by 2 authors independently (WJM, AV). In case information from the title and abstract was not adequate in determining the article's relevance, the article was automatically included in subsequent analysis. The full texts of articles that passed the first check were obtained and reviewed. Additional references were taken from the bibliography of the references to identify other potentially relevant papers (a backward search).

Data analysis

Most of the eligible papers lacked a description of the category of the paper. Two reviewers (WJM, AV) independently evaluated each of the papers that lacked such a description for the assessment of the category. Cases of disagreement were discussed together until agreement

was reached. Based on the content the papers were divided into one of the categories: original article, technical note or case report.

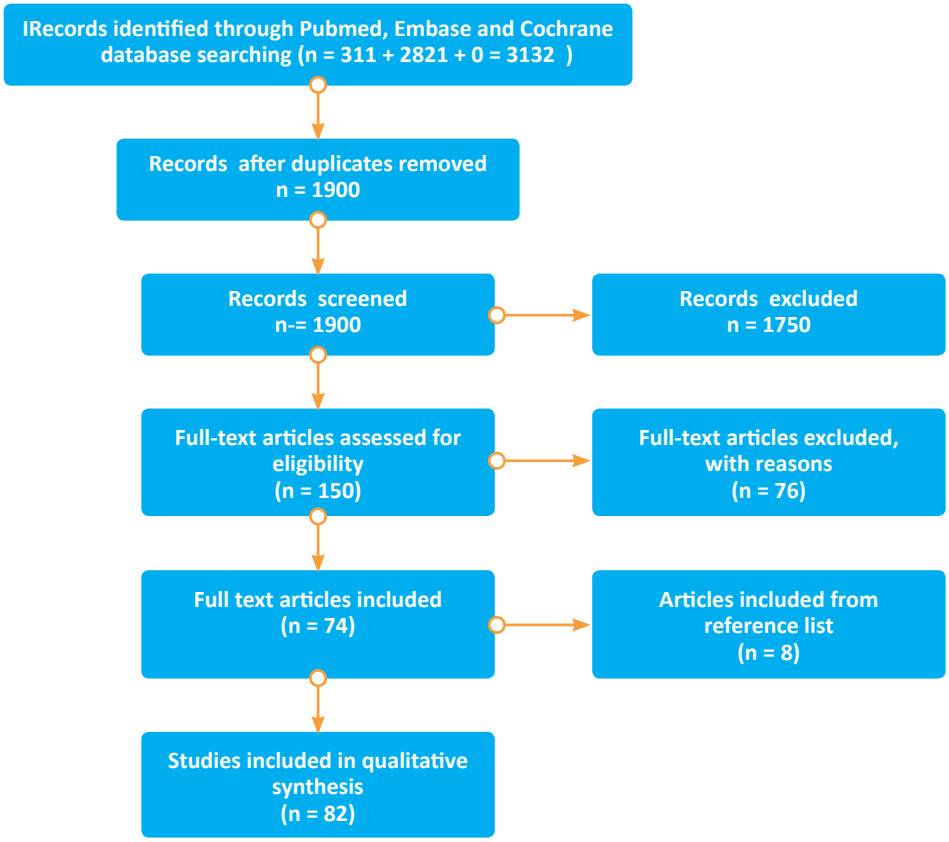

Figure 1: Prisma Diagram: search strategy and results

Results

The systematic review of the literature resulted in 82 eligible papers of which 8 were a result of backward search of the reference lists of the included papers (figure 1). None of the 82 papers were clinical trials or papers comparing digital technology with traditional methods in terms of cost-effectiveness or patient management. Fifty-two papers were technical notes describing the technical procedure to produce a facial prosthesis. In 32 of these technical notes, the technical procedure was illustrated by adding one or more cases. Fifteen papers were case reports demonstrating how 3D technology was used to replace parts of the traditional workflow. Another 15 papers were defined as original articles dealing with different

aspects of facial prosthetics such as testing of scanning technology to obtain a digital model for constructing a facial prosthesis[8, 9, 10] , testing of landmarks on digital models to determine where the prosthetic reconstruction should be positioned[11, 12, 13], testing different algorithms on a CT dataset[14], the use of rapid prototyping technologies to create a facial prosthesis[15, 16], the 3D accuracy of the manufactured facial prostheses[17], the immediate construction of a facial prosthesis[18, 19, 20] or the construction of a digital database facilitating the production of facial prostheses.[21] One paper describes a survey of maxillofacial prosthetists' and technologists' attitudes and opinions on the application of digital technology in facial prosthetics.[22] Almost all papers describe how to replace one or more steps in traditional workflow of facial prostheses. This workflow, as also mentioned earlier in the introduction, consists of a preparation phase, a production phase and a placement phase. 3D technology might particularly be an aid in the first two phases, viz. with regard to collection of the data, designing the prosthesis and rapid prototyping the prosthesis or a mold for the prosthesis.

1. Digital data collection

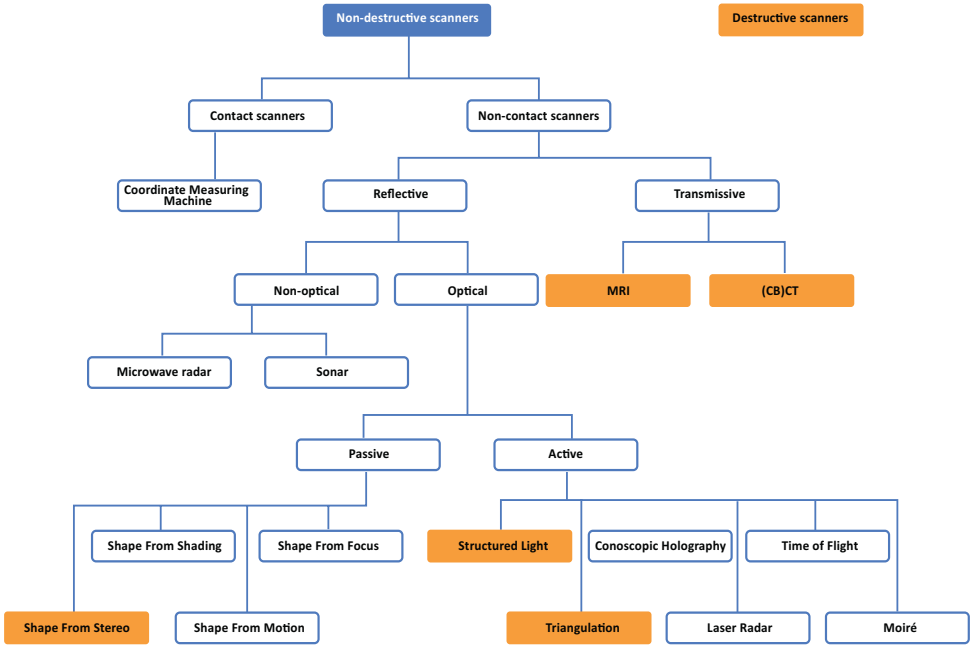

Figure 2: Overview of 3D acquisition technologies for facial prostheses: the technologies used in the reviewed articles are marked in yellow.

The first step in the digital workflow is to replace the traditional impression by a detailed 3D scan. For acquisition of maxillofacial defects, a variety of 3D scanning technologies is available (figure 2).[23] Amongst these technologies, transmissive scanning technologies, like (cone beam) computed tomography ((CB)CT) and magnetic resonance imaging (MRI) have been used with success to replace a traditional impression for a facial prosthesis.[8, 14, 16, 17, 20, 24 - 38] (CB)CT scans can be used for imaging of hard tissues and with limitations for soft tissues as (CB)CT scans have a restriction in resolution. An increase in resolution coincides with an increase in effective radiation dose. Furthermore, (CB)CT images suffer from scatter when metal parts, like filling materials, crowns or bridges or implants, are present. However 3D-(CB)CT scans can be very helpful in the workflow for facial prostheses as datasets of healthy contralateral sides have been successfully used to reconstruct auricular[16, 24, 26, 28, 30 - 35, 38 - 40], orbital.[14, 27, 30, 33] (CB)CT scans have also been used as a basis for constructing nasal prostheses.[36, 37]

Next to (CB)CT scans, MRI scans can be made. MRI scans are able to depict soft tissues in great detail. [41, 42] Therefore, MRI scans have been used for fabricating auricular prostheses [16, 25] and orbital prostheses.[20] MRI scans however are not suitable when bony structures have to be imaged simultaneously as well as that MRI is not applicable in claustrophobic patients, obese patients, and patients with ferromagnetic metals in their body.

Even though transmissive technologies (CBCT, MRI) are of added value in the data collection as they are an asset in the design of maxillofacial prosthodontics[8] the most commonly used scanning technologies are optical scanners, as these are safe (no radiation), relatively cheap and can obtain a higher resolution than *in-vivo* transmissive scanners (CT or MRI scanners). The optical 3D scanners mostly used for facial scanning are the laser scanner, the stereo-photo scanner and the structured light scanner.

Laser scanner

The laser scanner consists of a laser line that is moved relative to the object being scanned. The resultant distortion of the light pattern on the subject is viewed from an offset angle and captured on a charged couple device (CCD) device. The 3D co-ordinates of the object's surface are calculated by triangulation. Laser scanners have proven to be accurate[43, 44] and have been used successfully in digital acquisition for the production of auricular[30, 45 - 56], nasal[18, 47, 57, 58, 59] and orbital prostheses.[20, 30, 50, 60 - 63]

Stereo-photo scanner

Stereophotogrammetry uses multiple images of the same object taken from different view-points to reconstruct a 3D model. Common points are distinguished on each image and a virtual ray is constructed from each camera location to these points on the object. Because the distance between the cameras and the angle of the cameras are known, the distance to the specific points can be calculated via the principle of triangulation. A fundamental limitation of stereophotogrammetry is that obtaining correspondence between points on consecutive images is extremely difficult, commonly mentioned as the "correspondence problem".[64]

Photogrammetry scanners have been proven to be accurate when used for measurements of distances between anatomical landmarks on the face of a subject[65] but the resolution of the 3D model produced by most photogrammetry scanners is too low to reproduce fine skin details.[66] 3D models produced from a photogrammetry scan were shown to be less accurate than 3D models produced with CBCT.[67] Photogrammetry scanning has been used for nasal[68, 69] and orbital[70] prostheses.

Structured light scanners

Structured light scanners solve the previously mentioned correspondence problem by projecting a known light pattern onto the object to be scanned. Photo- or video cameras capture the image of the object with the projected pattern. Structured light scanners can employ several algorithms for the range measurement of the 3D scanning process. Mostly the technology behind the scanner will employ triangulation to calculate the distance of projected light point or line(s) on the object to the sensor.[64] Structured light scanners have also been proven to be accurate for measuring facial landmarks, ie distances and angles on the face of a subject.[71] Structured light scanners have been used for auricular[15, 39], nasal[19, 72, 73, 74, 75] and orbital prostheses.[29, 76 - 81]

2. Computer aided design

For 3D designing soft tissue reconstructions a variety of approaches is used:

a) When possible, it is preferable to capture the healthy facial surface preoperatively to get the most natural shape of the anatomy to be reconstructed[57, 69, 74, 75];

b) Mirroring of the healthy side to the affected site can be performed when a healthy side is present and when the facial defect does not cross the midline[15, 16, 18 - 20, 24 - 33, 35, 40, 45, 48, 49, 51, 52, 54, 55, 56, 60, 61, 63, 76, 77, 80 - 84];

c) Using a virtual "donor", e.g., a family member. The anatomical part that needs to be reconstructed is scanned on the "donor" and combined with the anatomical surface of the patient.[47, 68, 81, 85] An alternative is the application of a database of facial parts which enables the user to select the appropriate part from a multitude of shapes and to adapt it individually to the patient [8, 21, 36,37, 58, 53, 59, 72, 74, 79] ;

d) Reconstruction of the defect using a statistical model of the human face that generates a complete face of the patient including the reconstructed defect, based on the 3D datasets of 200 human faces[73];

The functionality of the software used for producing a model of the prosthesis or a mold can be divided into a number of categories: 1) functions to convert the output of the 3D scanner or MRI/(CB)CT scanner to a 3D model, 2) functions to produce a new body part (mirroring, library/donor, statistical model, freehand modelling), 3) functions to conform the new body part to the existing anatomy (most often using Boolean operations) and adding details[86], and 4) functions to produce a model that can be sent to a rapid prototyping machine. Currently, these functions are not combined in one software program. For the conversion of (CB)CT or MRI data, "Mimics" (Materialise, Belgium) is mostly used. For conversion of datasets from 3D scanners, software like "Geomagic" (Geomagic GmbH, Stuttgart, Germany) and "Rapidform" (Geomagic GmbH, Stuttgart, Germany) are used. For modelling, "Freeform" software (Geomagic GmbH, Stuttgart, Germany) and "Rhino" (McNeel North America, Seattle, USA) are currently the most widely used applications.

3. Rapid prototyping

In the traditional workflow, the production of facial prostheses is a time-consuming process that requires numerous steps with wax and plaster models that all are prone to technical errors. In a digital workflow the production phase of the prosthesis can be performed by rapid prototyping.[15, 87 - 92] Rapid prototyping is the way of producing the digitally designed model. There are two ways for rapid prototyping, viz., subtractive[26, 60, 61, 75] or by additive manufacturing.[10, 14 - 21, 24, 25, 27 - 40, 46, 47, 49, 51 - 59, 63, 67 - 70, 72 - 74, 76 - 82, 84, 88, 93 - 96] In subtractive manufacturing, computer controlled mechanical tools are used to cut away (milling) material to achieve a desired model. This technology is also known as "computer numerically controlled (CNC) machining". However, not all desired materials can be easily and precisely milled, e.g., plaster materials. Furthermore, subtractive manufacturing produces a lot of, often quite expensive, waste material. The use of additive manufacturing (building a model dot

for dot or layer for layer) is therefore more widespread and has largely replaced the use of subtractive manufacturing.

The American Society for Testing and Materials (ASTM) has defined additive manufacturing as the process of joining materials to make objects from 3D model data, usually layer upon layer. There are many different additive manufacturing technologies available that can be used in the digital workflow for fabricating facial prostheses. A variety of materials is used for this purpose such as acrylics and wax.

With one of the aforementioned technologies a model or mold can be produced:

- *Model of the facial defect:* a model of the defect is occasionally used in the production phase[70], and is used in the traditional workflow.
- *Direct try-on model of the facial prosthesis:* a try-on model for a direct fit can be made with subtractive or additive techniques. Subtractive techniques were employed by milling a standard block of wax or polyurethane in the desired shape to form the computer aided designed facial prosthesis and directly fitting and adjusting the part on the patient.[27, 45, 60] Such a try-on model can also be produced by a variety of additive manufacturing technologies, viz. selective laser sintering (SLS)[72, 73, 79, 80, 81], thermopolymer printing[15, 21, 29, 34] and stereolithography (SLA).[77]
- *Indirect try-on model of the facial prosthesis:* another option is to produce a model of the prosthetic part by a rapid prototyping technique and converting this part to a try-on model through traditional techniques. This is sometimes done e.g. because of the somewhat brittle nature of the thin edges of the prototyped prosthesis.[39]
- *Mold for producing the facial prosthesis:* fused deposition modeling[18, 53, 54, 58, 59, 95], 3D printing[40, 52, 57, 63, 68, 96], SLS[20, 47], laminated object manufacturing[47] and SLA[36, 82] have been used to directly produce a mold for a facial prosthesis.
- *Direct production of the final facial prosthesis:* direct printing of the final facial prosthesis has been accomplished, but the end-result lacked the necessary aesthetic and mechanical properties.[97]

The most advocated production technology in digital workflows for facial prostheses are powderbed 3D printers[10, 32, 33, 35, 40, 49, 52, 55, 56, 57, 63, 68, 70, 74, 96, 97]. These printers lay down a layer of powder on which on specific points a binder is applied to set the powder. A new layer of powder is then laid down and the process is repeated until the 3D model is completed. These printers were claimed to be accurate enough for facial prostheses.[10] However, the minimum feature size a powderbed 3D printer (Zprinter 650) can produce is 100 µm, which is actually not sufficient for a facial prosthesis. The reason that, notwithstanding the limitation in feature seize, powderbed 3D printers were extensively used in the workflow of facial

prostheses is probably that the technology these printers use was much more affordable than rather expensive technologies like SLA in the early days of rapid prototyping. Currently, the highest resolution of 3D printers using PolyJet technology is about 16 µm which suffices. However, no biocompatible materials with the proper mechanical and aesthetic properties are yet available for those printers.

Discussion

This systematic review describes the options for the current 3D techniques that can help in the workflow for producing facial prosthesis (figure 3). Although there are several ways to obtain digital data, design prostheses and print 3D try on models/molds, this hasn't led to a full 3D workflow for fabricating all facial prostheses. Furthermore, the various techniques described in the result section all have their own advantages and limitations as discussed in the next sections.

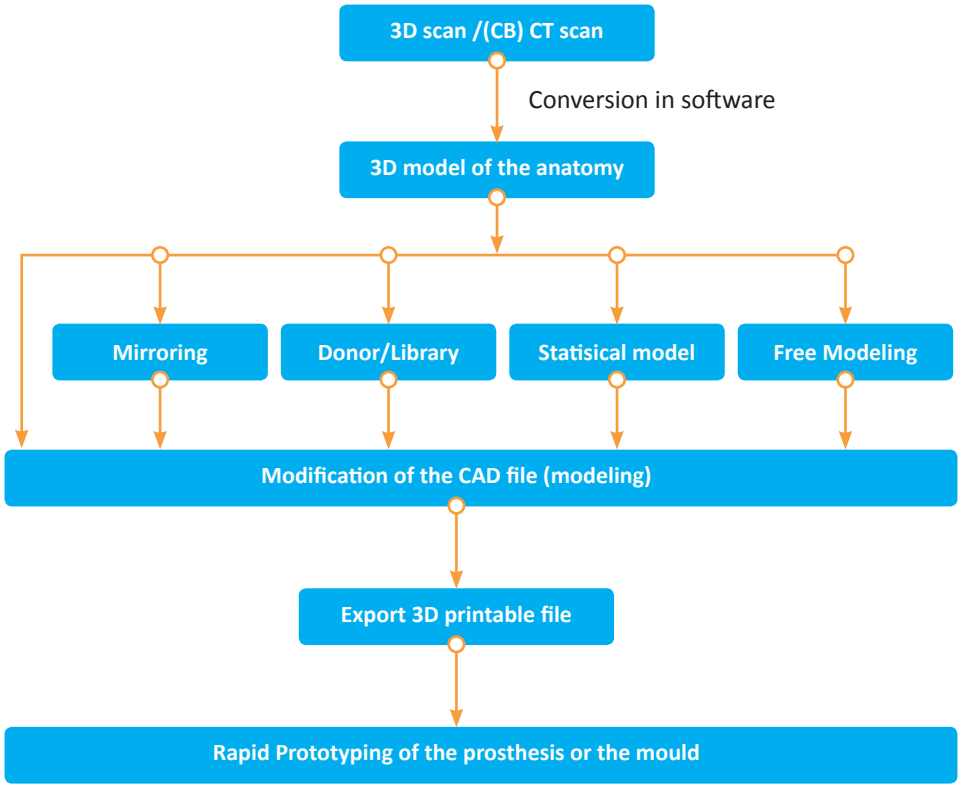

Figure 3: Overview of the various 3D workflows thatare in use to produce a facial prosthesis.

Obtaining data with scanners

3D Data collection with scanners is comfortable for both the practitioner and patient, overcomes the hazard of deformation of soft tissues by impression materials, but is less accurate than impression materials. Traditional impression materials (alginate, silicones) can reproduce details of 20 µm, which should be the desirable resolution for 3D scanners to reproduce skin details.86 This accuracy is unfortunately not yet reached with 3D scanners (laser, CT, MRI, photo, structured light) (figure 4).

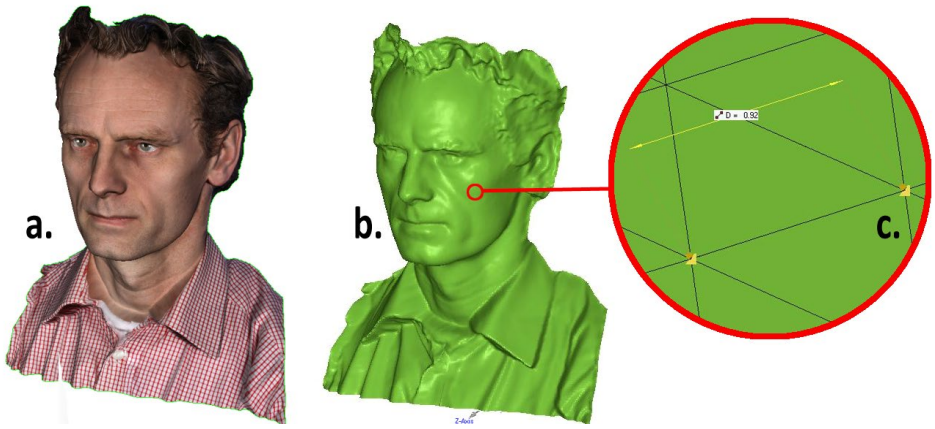

Figure 4: A 3D scan made with a high performance photogrammetry 3D scanner (Di3D, Dimensional Imaging Ltd., Glasgow, UK) (a). When looking at the non-textured surface model, the lack of surface details becomes apparent (b). When zooming in on the mesh, the distance between the surface points (vertices) can be measured. The distance between the surface points is 0.92 mm (c). (Scan was published with permission of the patient).

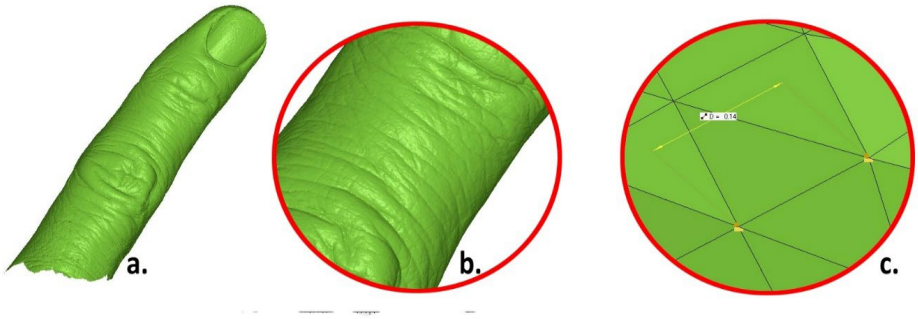

Figure 5: A 3D scan of a finger was made with an intra-oral scanner (Lava COS, 3M Espe Zoeterwoude, the Netherlands) (a). When looking at the un-textured surface model, surface details like wrinkles becomes apparent (b). When zooming in on the mesh, the distance between the surface points (vertices) can be measured. This distance was 0.14 mm (c).

Transmissive scanners (MRI or (CB)CT) can be used for parts that don't require a lot of skin detailing and contain many undercuts, like ears. Apart from their limitation in resolution, these scanners unfortunately also have other disadvantages to consider, as previously mentioned. Some 3D scanners, like intra-oral scanners, have a higher resolution (figure 5) and would be able to depict important skin details. Unfortunately, these scanners have a limited field-of-view which means that many scans have to be taken and combined to scan a larger surface which increases the likelihood of movement artifacts. However, technology is developing quickly and modern high resolution 3D scanners can already obtain an accuracy of 25 µm which is close to the ANSI/ADA standards for traditional impression materials.44 The application of improved scanning techniques and printers will also result in more detailed 3D models of surface structures (figure 5). The future 3D scanners should also have a large field of view and a short acquisition time, so they are able to capture all detail of the target area within one second to avoid movement artefacts.

Designing facial prostheses with computer software

For the computer aided design phase, comprehensive software is needed to design a final model of the facial prosthesis that can be rapid prototyped. 3D planning and design of facial prostheses, particularly with regard to the soft tissues, is yet still largely limited due to the lack of user-friendly software. As the market is small and therefore not commercially attractive for software companies, development of optimal software will probably progress slowly. As long as such software is not available, a combination of commercially and free available software can be used for the necessary conversions and adding the necessary detail to the 3D model, like is done in the process for designing cranial implants (van der Meer et al, 2013 Cranial implants paper), surgical guides (van der Meer et al, 2014 endo guides paper) or applying texture relief.[86]

Production of facial prostheses

For the production phase, the use of printable silicon materials with the proper mechanical properties would be the first choice as these materials are the most widely applied materials for facial prostheses.98 Silicones can be matched with skin colors by adding pigments, have an excellent detail reproduction capacity and can reproduce details up to 20 µm.99 However, very few printers are yet available that can directly print silicone. The recently developed Hyrel System 30 (Hyrel 3D, Atlanta, Georgia, USA) is such a 3D printer, but this printer has not yet been tested with silicone materials used for facial prostheses as well as that currently no skin matching colors are available. Zardawi FM et al97 were able to

produce a 3D printed soft tissue prosthesis using a Z-corp 3D printer and subsequently infiltrated the porous structure with medical grade silicone. Further results of this approach are eagerly awaited. The commercially available "Picsima" 3D printer (Picsima Ltd, Sheffield, UK) can also be used for this purpose. However, a major disadvantage of this approach is the restricted resolution of the printers due to the particle size of the printing powder as well as that the color of the silicon material is hard to match the skin color of the patient.

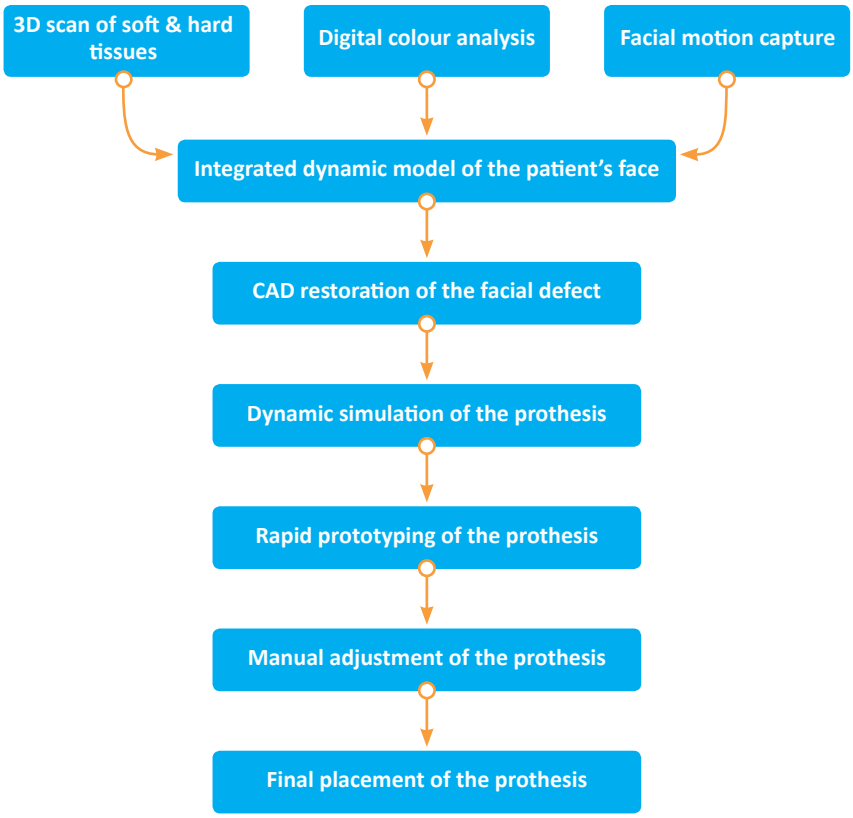

Figure 3: Ideal 3D workflow as expected to become available within the next decade. An ideal digital workflow is composed of scanning of the face with a combination of technologies to combine information of hard and soft tissues and to incorporate the color and dynamics of the soft tissues. Thus, the maxillofacial defect can be restored by either using digital data of the original anatomy (if available), mirroring the healthy anatomy, by using a digital anatomical library, or by using algorithms that are able to restore the defect based on the anatomy of the rest of the face. Eventually the prosthetic part can be printed out directly when the printers are able to print the necessary materials in the proper resolution, and in the desired color and anatomic details. During the final fit, the prosthodontist may refine the prosthesis and may adjust the fit before placement.

Full digital workflow

The in the previous sections mentioned current limitations in 3D technology (software and hardware) to allow for a full digital workflow to design and make a facial prosthesis are likely to be solved within the next decade. The resolution of 3D scanners and printers will continue to increase and appropriate materials will become available for direct 3D printing of facial prostheses. Moreover, dedicated software will become available with time for the intuitive production of facial prostheses, to modify the design and to introduce characteristic details that are representative for the face of the patient. When all these issues have become available, an ideal full 3D workflow as outlined in figure 6 will become reality. Such a workflow has the potential to make the (re)production of facial prostheses easier, cheaper and faster than the traditionally workflow. In addition, this workflow is presumed to be more convenient to the patient and to result in an improved aesthetic end product.

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6

Digitally Designed Surgical Guides for Placing Implants in the Nasal Floor of Dentate Patients: a Series of Three Cases

This chapter is an edited version of:
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Abstract

Aim: Insight into the bone volume and position of natural teeth is essential when placing implants to retain nasal prostheses. This paper describes a series of three cases in which a new method was applied for implant placement in the nasal floor of dentate patients using digital planning techniques.

Materials and Methods: With the aid of computer software, digital planning of implants in the nasal floor based on cone beam computed tomography was performed. Next, surgical guides for implant placement were digitally designed and fabricated using rapid prototyping.

Results: In all three patients, implants could be placed and nasal prostheses could be manufactured as planned. All anterior teeth remained vital. Analysis of planning and post–implant placement cone beam computed tomography scans revealed high accuracy of implant placement.

Conclusion: The applied method allows for reliable implant placement in close proximity to the preoperatively planned implant position.

Introduction

Midfacial defects (e.g., nasal defects) can be caused by genetic disorders, trauma, and ablative tumor surgery. Patients with nasal defects can suffer from esthetic and psychologic problems.[1] Treatment options to rehabilitate such patients include surgical reconstruction with a radial forearm free flap, titanium mesh, or a para-median forehead flap. However, surgical reconstruction of a defect affecting the entire nasal cavity is a significant challenge to reconstructive surgeons and is currently only performed with good results in a few specialized medical centers worldwide.[2] For this reason, nasal defects are usually covered with maxillofacial prostheses made of silicone. These prostheses can be attached to the patient's skin with glue or be attached to glasses[3], or the prosthodontist can try to find mechanical retention for the nasal prosthesis in the remaining nasal cavity.[4] The latter approach runs the risk of compromising normal nasal airflow. Because of limitations in all of these retention systems, dental implants are currently the preferred treatment modality to retain nasal prostheses.[5,6] Implant-retained nasal prostheses have been shown to be reliable, and from a patient's perspective, are a highly appreciated treatment option.[7-10]

Implants to retain nasal prostheses are usually placed in the in the nasal floor. An additional implant can be placed in the glabella region, but success rates for implants in the glabella region have been reported to be lower than those for implants placed in the nasal floor, probably resulting from poor blood supply and bone density in this region.[11,12] Planning and placement of implants in the nasal floor is often complicated when the patient has natural teeth in the anterior part of the maxilla or when there is a deficiency of paranasal bone. For placement of intraoral implants in compromised areas, special software such as NobelGuide (Nobel Biocare) and Simplant (Materialise) is available to aid the surgeon and prosthodontist in digital planning. With this software, computed tomography (CT) or cone beam CT (CBCT) data are used to visualize the implant area and plan the desired implant position, after which a digitally designed surgical guide is fabricated. The surgical guide directs the surgeon to place the implants in the preoperatively planned and prosthodontically preferred positions, thereby avoiding damage to vital anatomical structures (e.g., nerves, roots of the teeth) and attempting to safeguard a sufficient volume of bone at the implant site.

Since specific planning software for extraoral implants is not yet available commercially, the authors used an alternative method in three cases to digitally plan the placement of implants to retain nasal prostheses by using commercially available computer aided design/computer-assisted manufacturing software, thereby avoiding implant placement too close to the patients' maxillary anterior teeth.

Case series

Patients

Three patients, all with nasal amputation as part of ablative surgery (Table 1), had been provided previously with an adhesive-retained silicone nasal prosthesis but experienced discomfort. Cancer and prosthetic treatment had been performed at the Head and Neck Oncology Center of the University Medical Center Groningen, The Netherlands. Patients had not been provided with nasal implants to retain a nasal prosthesis because of the high risk of damaging the roots since no proper three-dimensional (3D) information was available regarding the volume of bone available for implant placement, thereby avoiding the roots of the maxillary anterior teeth.

All patients were scheduled for prosthodontic rehabilitation with an implant-retained nasal prosthesis applying a newly developed method. Patients were informed about the risk of damaging the roots of the teeth in the anterior portion of the maxilla. Vitality of the anterior teeth was tested before surgery, and an informed consent form was signed by the patients.

CBCT based implant planning and surgical guide design

CBCT data (3D eXam, KaVo) were obtained for all three patients and converted to a surface model using Mimics software (Materialise) with an optimal threshold to depict

Patient (M/F)	Year of amputation	Tumour	Radiotherapy (cumulative dose*)	Hyperbaric Oygen Therapy ◊	Year of implant placement
1 (M)	1996	adenoid carcinoma	Yes (66Gy)	Yes	2010
2 (M)	2008	adenoid carcinoma	Yes (66Gy)	Yes	2010
3 (M)	2009	Vestibulum nasi carcinoma	Yes (66Gy)	Yes	2010

Table 1. Characteristics of the patients.

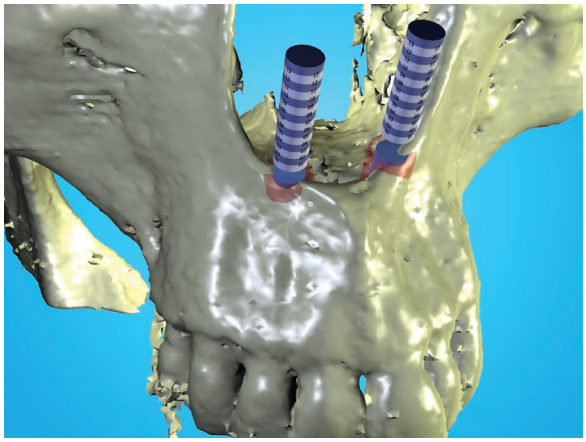
M = male; F = female

* Cumulative dose received at the implant region in Gray.

◊ 20 sessions before and 10 sessions after implant placement.

bone, teeth, or skin. The CBCT machine was set to a voxel size of 0.3 mm, which results in a resolution that surpasses the 0.5-mm resolution prescribed for planning implants using NobelGuide or Simplant. In addition, digital registration of the dentition was done with the aid of the Lava COS intra oral scanner (3M Espe Zoeterwoude, the Netherlands).

Figure 1A: Implant-planning in patient 1. The planned implants (blue cylinder, diameter 4 mm) are in the center of the preferred implant position (red circle, diameter 6 mm). Components such as soft tissue, bone, and teeth were made transparent so an optimal virtual planning of the implants could be achieved.



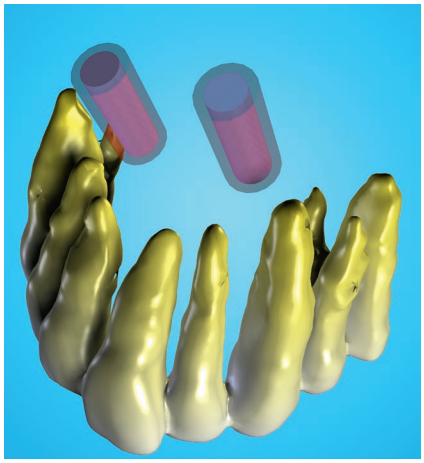


Figure 1B: The planned position of the implants does not interfere with the roots of the maxillary anterior teeth. The software provides the clinician with a window in which the implant can be moved virtually in case preferred implant position interferes with the available bone volume or position of the roots of the anterior teeth. This way, alternative implant positions can be viewed while still allowing for fabrication of an adequate suprastructure and nasal prosthesis. If no adequate position can be selected, this method helps the clinician decide whether it is suitable to perform reconstructive surgery before implant placement.

Three separate entities for the bone, skin, and teeth were imported into 3ds Max (Autodesk). Since the planning required a 3D model of the roots of the teeth (the CBCT dataset) and a precise 3D model of the crowns (the digital impression), the two models were combined in a separate software.

The 3D model obtained from scanning of the dentition was imported into Geomagic Studio software (Geomagic 8.0, Geomagic) together with that of the teeth obtained from the CBCT.

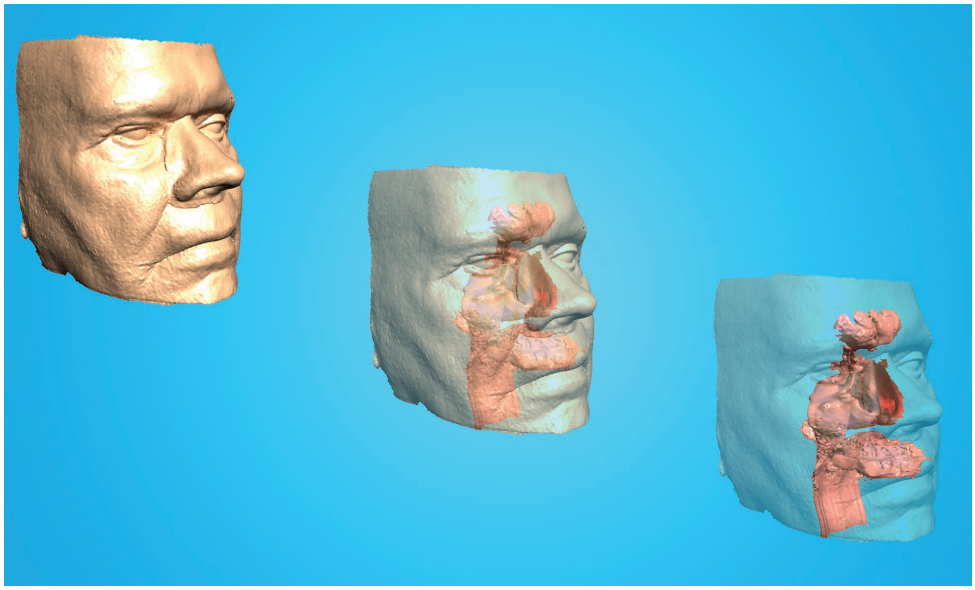


Figure 1C: Besides bone, soft tissue, a d teeth, the software also provides the clinician with a window in which the airways can be visualized.

The two models of the dentition were aligned and registered with a manual registration algorithm available in the software. In this process, the coordinate system of the CBCT model was fixed to prevent movement of the CBCT model of the teeth. This procedure was introduced to ensure that the spatial coordinates of the scanned plaster cast coincided with those of the teeth in the CBCT model. The 3D model and its coordinates were exported as an stl file and imported into 3ds Max. In the 3ds Max software, a library with a variety of dental implants was made with lengths and diameters corresponding to dental implants that are customarily employed extraorally to retain maxillofacial prostheses. Around the implants, a 3D cylinder was designed with a diameter of 6 mm, which was 2 mm larger than the implants (implant diameter: 3.75 mm). All components such as soft tissue, bone, and teeth can be made transparent so optimal virtual planning of the implants can be achieved (figure 1a). This cylindric zone depicted the zone within which the implants could be placed safely and allowed the prosthodontist to fabricate the maxillofacial prosthesis as planned.

An experienced maxillofacial surgeon, an experienced maxillofacial prosthodontist, and an information technology specialist proficient with the aforementioned software planned the preferable implant positions while taking the prosthodontic and surgical needs and the implant characteristics and safety zone around the implants into consideration.

The software provided the planning team with windows in which the amount of bone, the location and angulation of the roots of the teeth (figure 1b), and the airway (figure 1c) could

be visualized in 3D to ensure proper implant planning. The implant can be moved virtually within these windows to a preferred position or angulation. Based on the planning, a surgical guide was digitally designed in the 3ds Max software (figures 2a to 2d). The guide used the dentition as a stable anatomical fixation. To allow proper placement, the guide was designed as two parts. The parts were designed to interlock and could be secured with a locking pin, thereby ensuring proper fit (figures 2a to 2c). At the implant locations, the guide was designed to fit the bone surface with the aim of good fit and stability. At the site of the virtual implants, a hole was modelled in the surgical guide in which a metal

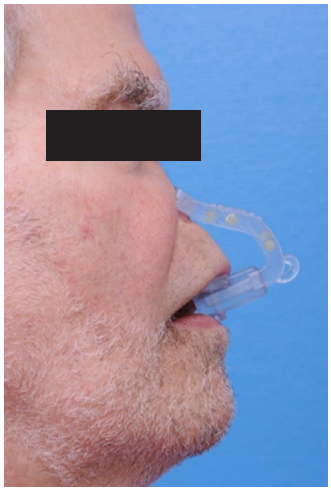


Figure 2A to 2C: Surgical guide to place implants in the nasal floor. Both parts interlock and can be secured with a locking pin. The natural dentition is used as a reference to stabilize the guide and to allow checking of its fit.Fig 2D: Fit of the surgical guide checked on the patient before surgery.

tube with an inside diameter of 5 mm could be placed. This tube fit the metal insert that served as a guide for the first twist handpiece. The surgical guide was made to fit to the bone surface by digitally subtracting the bone from the guide design, a so-called Boolean operation. A second Boolean operation was performed by subtracting the soft tissues from the guide design. The resulting guide would therefore fit the bone at the implant site and the soft tissues at the corresponding points. To ensure proper fit of the guide onto the teeth, a third Boolean operation was performed by subtracting the spatial properly positioned 3D scan of the plaster cast from the guide.

The digitally designed surgical guides were exported as stl-files and sent to DSM Desotech, where they were converted to physical casts with the aid of a stereolithography (SLA) machine and a biocompatible SLA resin (BioSure™; DSM Desotech, Elgin, IL 60120, USA). The fit of the guide was checked on the patient before surgery (figure 2d).

Surgical treatment

Implant placement was accomplished under general anesthesia using the digitally designed surgical guides. An incision was made through the nasal mucosa. Then, the skin and mucosa were elevated and the bone surface was exposed. The surgical guide was brought into place. The guides were easy to position and had good fit and stability. Implants were placed according to a two-stage procedure.[1,13,14] The implants (3.75-mm diameter, 12-mm length; Brånemark, Nobel Biocare) were placed in the digitally planned positions with the aid of the surgical guide. Next, the implants were covered with skin. Perioperatively, patients received broad-spectrum antibiotics.

The healing time was 4 months to ensure adequate osseointegration. Patients could wear their adhesive prosthesis in the meantime. Stage-two surgery was completed under local anesthesia and consisted of exposing the implants, thinning the subcutaneous tissue, and placing abutment cylinders of appropriate height (3 or 4 mm) and healing caps on the implants. After placing the healing caps on the abutments, gauze soaked in ointment (Terra-Cortril, Pfizer) was wrapped around the abutments to promote skin healing.

Prosthodontic treatment

Fabrication of the implant-retained nasal prosthesis was started 2 to 3 weeks after abutment connection. The nasal prostheses were made of silicone elastomers (VST50 silicone, Technovent) and intrinsically pigmented with silicone paste and fabric fibers to achieve a good match to the skin (figure 3a).

Clips and magnets were used for retention (figures 3b and 3c). Furthermore, the prostheses and bar suprastructures were designed and fabricated in such a way that adequate airflow during breathing was guaranteed (figure 3d). Patients were instructed to clean the suprastructures and surrounding skin daily with either a very soft toothbrush and Super Floss (Oral B) or a small shoestring in combination with water and gentle soap.

Evaluating the method

The surgical guides enabled the surgeon to place all implants at the preoperatively planned positions without damaging the roots of the teeth (figure 4). No changes in vitality of the teeth occurred. The guides were easy to position and had good fit and stability. None of the implants were lost during the 6-month follow-up, and no inflammation of the skin around the implants occurred. All patients functioned well with their nasal prostheses (figures 3a to 3d).

To assess the reliability of the developed method, a postoperative CBCT scan was taken of all three patients using the same CBCT machine as used for the preoperative

planning scan. These scans were used to compare the actual implant position with the pre-operatively planned implant position (figure 4). Therefore, postoperative data were imported

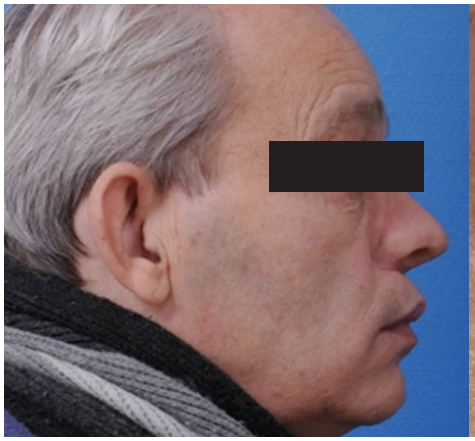


Figure 3a: The patient is supplied with his implant retained silicone nose prosthesis.

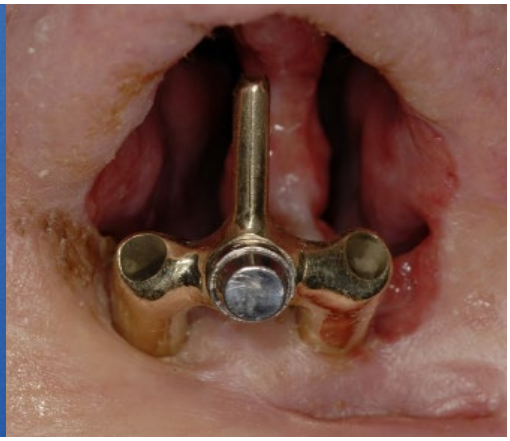


Figure 3b: Individually designed suprastructure to retain the nasal prosthesis. The suprastructure was placed directly on the implants.

Figure 3c: In the nasal prosthesis itself, a metal clip and magnet are embedded to retain the nasal prosthesis onto the suprastructure.

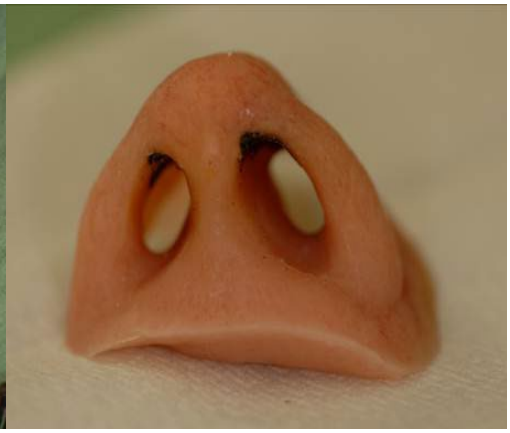


Figure 3D: One patient, a smoker, reflected the uncompromised airflow by the presence of nicotine deposits on the inside of the prosthesis.

into Geomagic Studio software and matched with the preoperative planning data using an iterative closest-point registration algorithm. Linear measurements were made between the neck/tip of the planned implants and their actual postoperative positions. Lines were constructed through the center of the implants, and the angle between the planned and actual implant position was measured through angular measurement.

Analysis of the differences between the actual and planned positions of each implant revealed that all implants were placed well within the limits needed for fabrication of an optimal prosthesis both from a surgical and prosthodontic perspective (figure 4).

Discussion

The digitally designed surgical guides facilitated placement of extraoral implants at the preferred implant positions in the nasal floor of dentate patients. A major advantage of digital planning is that the desired implant locations can be preoperatively visualized and the clinician can plan and place the implants in the most preferable position from a prosthodontic as well as surgical point of view (avoiding the roots of the teeth, minimizing invasive surgical treatment, guaranteeing an undisturbed airway, and confirming that there is enough bone volume for placing the implants).

This is a great achievement when comparing the present method with that applied by Guttal et al,[17] who, to the best of the authors' knowledge, described the only case reported

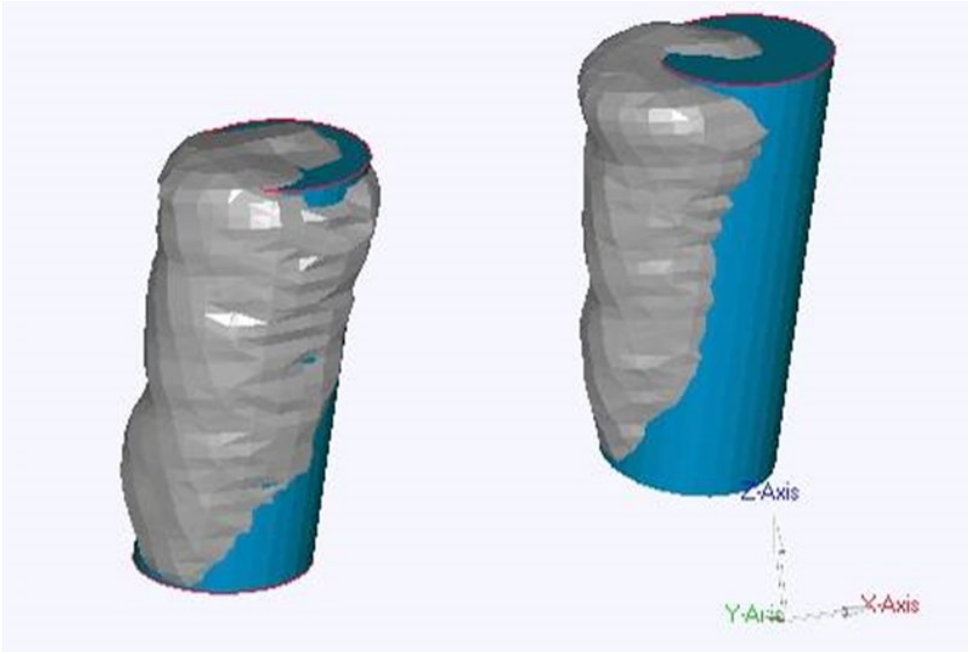


Figure 4: Comparison of planned and actual implant position by superposing pre-operative and postoperative CBCT data. The planned implants (blue cylinders) could be placed as shown in close proximity with the pre- operatively planned locations (grey cylinders). The deviation of the neck and the tip of the implant as well as that of the angulation of the implant is depicted and was well within the limits as reported by Van Assche et al16 and Schneider et al16. (left) Top: 0.496 mm , tip: 0.702 mm, angle: 0.98 degrees. (right) Top: 1.924 mm, tip: 0.9441 mm, angle: 4.66 degrees.

in the literature of an implant-retained nasal prosthesis in a dentate patient. In that case, implant placement was accomplished without the help of special devices or tools to guide the surgeon to place the implants in the preferred position. The authors did not describe how they managed the risk of coincidentally damaging the roots of the maxillary anterior teeth, but they might have solved this problem by placing the implants deep into the nose, as is obvious when looking at the photographs accompanying their paper. This rather dorsal placement of implants can be an option for avoiding root damage but compromises both cleaning of the implants by the patients themselves and fabrication of the suprastructure. Furthermore, dorsal placement of the implants runs a higher risk that the suprastructure fabricated on these implants may interfere with nasal airflow.

Although all implants were placed in the prosthodontically and surgically preferred positions, the actual implant positions did not coincide 100% with their planned positions. This slight mismatch may be caused by several factors. One reason is system error, ie, a sum of all the errors present in the different phases. In the data acquisition phase, the resolution of the CBCT dataset should be taken into account. Since the voxel size is 0.3 mm, the accuracy of the system as a whole is unlikely to surpass 0.3 mm. Then, there is an error in the data acquisition of the dentition. The manufacturer of Lava COS claims an accuracy of 11 µm, but this value has not yet been validated externally.

Furthermore, the 3D model of the dentition was registered with the dentition in the CBCT dataset to obtain a combined 3D model, which gives rise to registration errors. During the final stage of rapid prototyping, the SLA material will show a slight dimensional change during polymerization. In case the guide is not seated exactly as planned on the dentition, a small angulation of the final implant placement might occur, resulting in differences between the planned and final implant positions (figure 4).

The three cases showed that the applied digital method to place implants in the nasal floor to retain a nasal prosthesis is reliable, thereby avoiding the roots of maxillary anterior teeth when present and allowing for fabrication of a nasal prosthesis. Although the software for the aforementioned application can be quite costly if it cannot be purchased under an academic license, there are freeware applications for all of the necessary functions. Conversion of CT data can be performed with freeware such as Osirix, while the 3D visualization and design can be done in Blender, a free 3D modeling and software program. For digitization of the dentition, the authors used a Lava COS intraoral scanner, but a traditional impression that is poured in plaster can be used as an alternative since many dental laboratories offer the service of converting plaster casts to 3D digital models. This means that the software cost of the aforementioned method can be reduced to a minimum.

However, since not all dentists have a special interest and skill in information technology, there might be a need to ask a specialist for help, which may bring some additional costs. Notwithstanding the aforementioned limitations of this method with regard to potential costs, the method has a number of advantages. Traditionally, implants in the nasal floor to retain nasal prostheses are placed without any insight into the implant area. As mentioned previously, one risks damage of vital structures and loss of implants because of insufficient bone volume. Planning in 3D with all the necessary anatomical structures taken into account facilitates a predictable prosthetic end result. With the aid of a computer, every individual desired shape of a surgical guide can be made. Furthermore, printing of the designed surgical guide is not dependent on local facilities; the stl file can be sent to specialized centers all over the world for printing. The only limitation is that the clinician has to be interested in digital technology and have some skills in using computers.

Conclusion

Digitally designed surgical guides for placement of extraoral implants in the nasal floor are of great help in dentate patients to avoid the roots of the anterior teeth and place the implants in a preferred position from a prosthodontic point of view.

Acknowledgements

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7

Digitally Designed Surgical Guides for Placing Extraoral Implants in the Mastoid Area

This chapter is an edited version of:
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Digitally Designed Surgical Guides for Placing Extraoral Implants in the Mastoid Area.
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Abstract

Aim: When planning implant therapy, knowledge of the bone volume in the implant area is needed to plan and place implants in the most appropriate locations from the prosthetic and surgical perspectives. Commercial software for digital planning of implants in the craniofacial region is not yet available. This article describes a method that enables digital planning of extraoral implants in the mastoid region utilizing commercially available computer-aided design (CAD) software and rapid-prototyping techniques to manufacture a corresponding surgical guide.

Materials and methods: With the aid of CAD software designed for reverse engineering and three-dimensional animation, digital implant planning based on cone beam computed tomography (CBCT) scanning was performed. On the basis of this planning, surgical guides were digitally designed to facilitate the placement of dental implants in the mastoid area. The guides were fabricated using rapid prototyping. The appropriateness of the digitally designed surgical guides for placing extraoral implants was tested on six human cadaver heads with simulated bilateral ear defects. After implant placement, a second CBCT scan was performed to compare preoperative planning with the actual postoperative implant positions.

Results: Twenty-four implants were placed. The surgical guide helped the surgeon to place the implants at the preoperatively planned positions. Comparison of the CBCT scans revealed that adequate accuracy of implant placement was achieved, both for deviation of the neck (1.56 ± 0.56 mm) and the tip (1.40 ± 0.53 mm) of the implant, and for deviation of the angulation of the implant (0.97 ± 2.33 deg).

Conclusions: The presented method for digitally planning extraoral implants in the mastoid area and designing surgical guides allows for placement of implants in the mastoid area in close proximity to the preoperatively planned implant position. The actual implant positions were satisfactory both surgically and prosthetically.

Introduction

Maxillofacial defects can be caused by genetic disorders, trauma and ablative tumour surgery. Patients with such defects can suffer from aesthetic and psychological problems.[1] To rehabilitate such patients, these defects are usually covered with maxillofacial prostheses made of silicone. In the past, these prostheses were usually attached to the patient's skin with glue.[2] Nowadays, implants are often used to retain maxillofacial prostheses.[3,4] Prostheses for the ear, nose, and orbit retained by implants have been shown to be reliable, and from a patient's perspective they are highly appreciated treatment options for the restoration of these defects.[5-7]

Most often, maxillofacial implants are placed in the upper and lower orbital rim (orbital prostheses), in the mastoid area (ear prostheses), and in the nasal floor (nose prostheses). For the placement of intraoral implants, particularly in compromised areas, special software programs, for example, NobelGuide (Nobel Biocare) and SimPlant (Materialise), are currently available to help the surgeon and the prosthodontist to digitally plan the placement of intraoral implants. With this software, computed tomography (CT) or cone beam CT (CBCT) data are used to plan the implant position via computer, with which a digitally designed surgical guide is fabricated. The surgical guides for implant placement in the mandible or maxilla obtained with this method enable the surgeon to place the implants in the preoperatively planned and prosthodontically preferred positions, thereby ensuring a sufficient volume of bone at the implant sites.

Recent advances in computer technology have allowed maxillofacial prostheses to be designed digitally.[8, 9] Various tools have been developed that can help the surgeon with digital planning of extraoral implants, eg, robot-assisted placement of craniofacial implants, placement of implants with image guidance.[10,11] The latter technique is based on a calibrated image guidance system and a corresponding stereotactic burr handpiece. The handpiece is used to identify the implant site as its position is projected into the existing CT dataset. The implant site is determined by tattooing the periosteum with a methylene blue dye, applied by a tattoo needle penetrating through the skin, after which the maxillofacial surgeon can place the implants . Although the accuracy of image-guided systems has been claimed to be very high, this technique is dependent on a variety of cumulative and interactive factors involved in data acquisition and surgery. Another example of using digital technology is described by Schlieper et al 2001.[12] In their study patients were scanned with conventionally fabricated templates in situ. The templates incorporated titanium pins in the preferred implant positions. The acquired CT data were used to evaluate the chosen implant positions. Few case reports on the use of digital technology for planning extraoral

implants are available.[13,14] Furthermore, no commonly available tools have been described that are specifically designed for pre-operative digital planning of extra-oral implants and the corresponding bone-supported surgical guides. This statement is supported by the conclusions of Widmann and Bale[15] in their review of the accuracy of computer-aided implant surgery. In 2006, these authors stated that long-term clinical studies are needed to examine all aspects of treatment success to confirm the value of the strategies and to justify the additional radiation dose, efforts and costs. In other words, a full digital workflow and the exact realization of accurate planning and placing of extra-oral implants is not yet possible with the routine surgical guides, as was already mentioned some years before.[10,12] As a result, in most cases, planning of extra-oral implants to support maxillofacial prostheses is still performed according to conventional planning with the risk that implants may be placed in areas with insufficient bone volume to guarantee implant stability.[16,17] As a consequence, the surgeon may be directed during surgery toward a prosthetically less appropriate implant position. Furthermore, conventional methods cannot be used when placing implants during ablative surgery, as ablation is not very precise, while the surgeon must have good insight into the actual bone volume of the planned (and from a prosthetic perspective, still acceptable) implant position, which can be hazardous when implant placement is performed in the mastoid and/or orbital areas. In the mastoid area, for example, the bone contains air compartments, which limit the areas where implants can be placed. With digital planning, CT or CBCT data are used, providing detailed data about the actual bone volume at the most prosthetically preferable spots, whereas with conventional planning it is likely that the implants will not be placed in prosthetically ideal positions because of a lack of knowledge of the bone volume in the designated implant areas.

Another important problem with “conventional” surgical guides is related to placing the surgical guide in the correct position during surgery owing to their inaccurate fit. Placement of a conventional surgical guide can be difficult, as such guides are made on plaster casts. Plaster casts do not mimic the resilience of the soft tissues, although the guide must be applied on soft tissue during implant surgery. Therefore, it would be beneficial if digital planning of extraoral implants could be performed in a similar fashion as dental implants in compromised intraoral conditions. If information about the actual bone volume and soft tissue configuration were available, digital planning and placement of extraoral implants would be more predictable. For example, a surgical guide that is placed directly on the bone and has a stable fit can ensure that the surgeon places the implants in the preoperatively planned positions, thus improving the prosthetic outcome. Because specific planning software for extraoral implants is not yet commercially available, the authors have developed

an alternative method to digitally plan the placement of implants to retain maxillofacial prostheses through the use of commercially available computer-aided design/computer-assisted manufacture (CAD/CAM) software. The present article aims to describe a reliable method that enables digital planning of extraoral implants in the mastoid region utilizing commercially available CAD software and rapid-prototyping techniques to manufacture a corresponding surgical guide.

Materials and Methods

CBCT based implant planning and surgical guide design

CBCT data (3D Exam, KAVO) of six edentulous cadaver heads, all with unaffected soft tissues, were converted to surface models with Mimics software (Mimics, Materialise, Leuven, Belgium) using an optimal threshold to depict either the bone or the skin and imported into 3ds Max (Autodesk, San Rafael, California, USA). To mimic the clinical situation, the CBCT machine was set to a voxel size of 0.3 mm which results in a resolution higher than that prescribed for planning implants using Nobelguide (Nobelbioresearch, Gothenburg, Sweden) or SimPlant (Materialise, Leuven Belgium).

In the 3dsMax software, a library with a variety of dental implants was made, with lengths

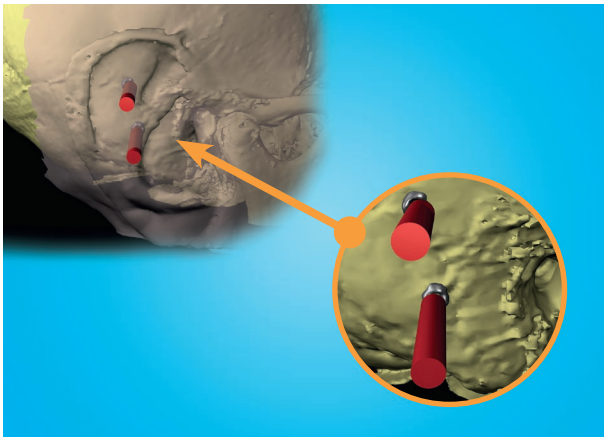

Figure 1: Preoperative implant planning on one of the human cadaver heads. The planned implants (red cylinders, diameter 4 mm) are centered in the preferred implant positions (blue circles, diameter 7 mm). The actual implants (grey) were placed within this area in the most preferable locations, ie, right underneath the cartilage edge of the external ear.

and diameters corresponding to dental implants that are customarily employed extraorally to retain maxillofacial prostheses. Around the implants, a three-dimensional (3D) cylinder was designed in the software with a diameter of 6 mm (ie, 2 mm larger than the 4-mm diameter of the implants) **(figure 1)**. This cylindric zone depicted a safety zone within which the implants could be safely placed from a surgical point of view; this also allowed the prosthodontist to fabricate the planned maxillofacial prosthesis. An experienced maxillofacial surgeon, an experienced maxillofacial prosthodontist, and a specialist proficient with the

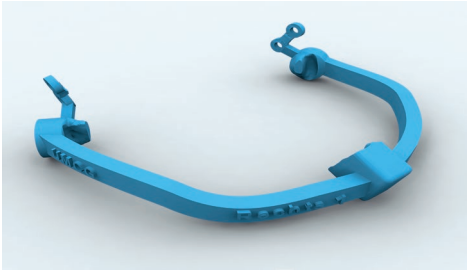

Figure 2a: Digitally designed surgical guide that was fabricated via rapid prototyping to place implants in the mastoid area.

Figure 2b: Three reference points were used when designing the guide: the bridge of the nose (nasion), the tragus, and the external meatus (skin contact point). At the implant locations, the guide makes full bone contact.

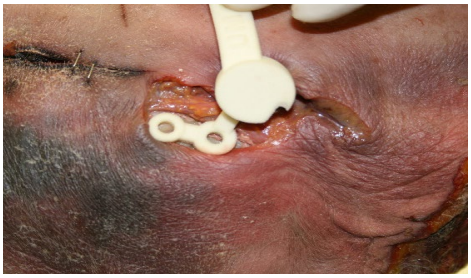

Figure 2c: Testing the fit of the surgical guide on the head of the cadaver.

aforementioned software planned the preferred implant positions, taking into consideration the prosthetic and surgical needs, as well as the implant characteristics and safety zone around the implants. The virtual implants were exported as .stl files. These files could then be imported into the Mimics software to ensure that the planned implant locations coincided with bone. Based on the planning, a surgical guide was digitally designed in the 3ds Max (figure 2). At the implant locations the guide was designed to fit the bone surface, aiming for good fit and stability, whereas the remainder of the guide was designed to fit to three points on the skin surface: the region bordering nasion on the head, the external meatus, and the tragus of the former ear (figure 2). These anatomical points are easy to locate and demonstrate typical characteristics that ensure a good fit and enable reproducible positioning of the guide during surgery in accordance with the digital planning. Because the skin in the implant locations was not firmly attached to the underlying bone, predictable flapless surgery was not possible. It was therefore decided that the bone would be used to stabilize the surgical guide during osteotomy preparation.

At the site of the virtual implants, a 5.1-mm hole was modelled in the surgical guide. A

5.0-mm metal insert could be placed in this 5.1-mm-diameter hole to serve as a guide for the first twist drill. The guide was made to fit to the bone surface by digitally subtracting the bone from the guide design, a so-called Boolean operation. A second Boolean operation was performed by subtracting the soft tissues from the guide design. The resulting guide would therefore fit the bone at the implant site and would fit the soft tissues at the corresponding points.

The digitally designed surgical guides were exported as .stl files and were sent to Tridentica, a company that converts digital 3D models into physical models. At Tridentica, the digital 3D guide was converted into an actual surgical guide using rapid prototyping and infusion technology.

Testing the method

To test the method of planning the extraoral implants and designing the corresponding surgical guide in 3D animation software, the aforementioned six human cadaver heads were used. Preoperatively, all heads were scanned and digital surgical guides for the placement of two mastoid implants on each side of the heads were fabricated, as detailed earlier. After the fabrication of the surgical guides, bilateral removal of the ears was performed by an experienced oral and maxillofacial surgeon. The bone of the mastoid area was uncovered, and the surgical guides were placed. A total of 24 implants (Southern Implants), all 4.0 mm in diameter, were placed in the digitally planned positions with the aid of the surgical guide (figure 3).

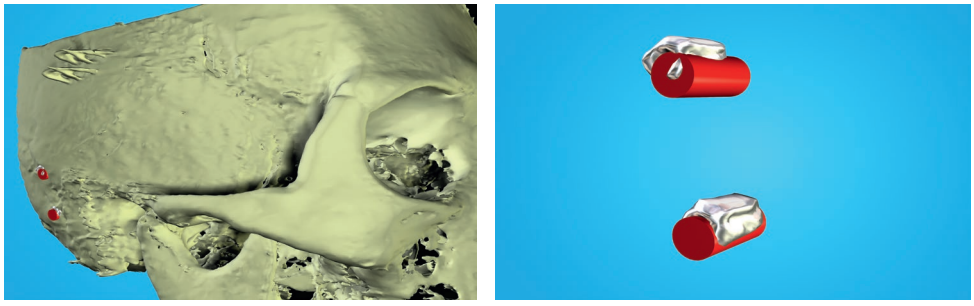

Figure 3: Comparison of planned and actual implant positions. (a) By super-imposing the preoperative and postoperative CBCT data, the pre-operative implant positions (red) can be compared with the actual implant locations. (b) The implants (grey) were placed in close proximity with the preoperatively planned locations (red).

Analyzing the results

Postoperatively, CBCT scans were made of the cadaver heads using the same CBCT machine that had been used for the preoperative scans. These scans were employed to compare the actual implant positions with the preoperatively planned implant positions using the same threshold values used in the preoperative scans (figure 3b). The postoperative data were imported into Geomagic Studio software (Geomagic Gmbh) and matched with the preoperative planning data using an iterative closest point registration algorithm. Linear measurements were made between the neck and tip of the planned and actual implant positions. Lines were constructed through the centers of the implants, and the angle between the planned and actual implant positions was measured.

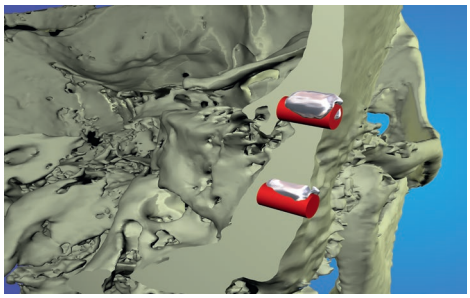

Figure 4: Sectional plane of the mastoid area with the actual implant locations. The implants (grey) are completely surrounded by bone and in close proximity with the preoperatively planned locations (red).

Results

In all, 24 implants were placed. The surgical guides, which were easy to position and had good fit and stability, enabled the surgeon to place the implants at the preoperatively planned positions (figure 4). Analysis of the differences between the actual and planned position of each implant revealed a mean deviation at the neck of the implant of 1.56 ± 0.56 mm (range, 0.66 to 2.76 mm), a mean deviation at the tip of the implant of 1.4 ± 0.53 mm (range, 0.64 to 2.81 mm), and a mean angular deviation of 0.97 ± 2.33 degrees (range, 0.51 to 3.69 deg). From a prosthetic point of view, the implants were in very good positions, and the ear prostheses were fabricated as planned (figure 1).

Discussion

The digitally designed surgical guides facilitated placement of extraoral implants in preferable positions. The fit of the surgical guides was appropriate, and the guides were held in place manually with ease. Because commercial software specifically for digital planning of extraoral implants is not yet available, two commercial software programs were combined to plan the implant locations and design the guides: Mimics to convert the CBCT data to a surface model, and 3ds Max to plan the implant positions and model the corresponding surgical guide.

The advantage of digital planning is that one can visualize the implant locations and plan the implants in the most preferable positions (eg, avoiding air chambers in the bone) from a prosthetic point of view. There are two major advantages of using the described method versus other methods described in the literature. First, this method is relatively inexpensive (sophisticated technology is not needed). Second, it is a simple technique that requires little training. Clinicians without a CBCT scanner can obtain a CT scan in a nearby hospital. Rapid-prototyping services are provided over the Internet by many companies worldwide.
The actual placed implants were between 0.66 and 2.81 mm from their planned positions. Van Assche et al[18] reported deviations of 0.7 to 2.4 mm for intraoral implants, and the meta-regression analyses of Schneider et al[19] revealed mean deviations of the implants of 1.07 mm at the entry point and 1.63 mm at the apex; the results obtained from the present study are comparable.
However, most of the studies included in the meta-analysis of Schneider et al involved fully dentate or partially edentulous subjects, which enhances the stability of the surgical guide. Thus, taking into account that a slight deviation of the actual implants compared to the planned implants in the mastoid region was not accompanied by problems in the fabrication of an optimal implant-retained auricular prosthesis, the observed mismatch between the planned and actual implant positions of the present method is highly acceptable from a prosthetic point of view. It may even call into question whether a comparably accurate result can be achieved with conventional planning.

Conclusions

With the described method, it is possible to digitally plan extraoral implants in the mastoid area. With the aid of a digitally designed surgical guide, the planned implants were placed in close proximity to the preoperatively planned implant positions. These positions were more than satisfactory from the surgical and prosthetic points of view to allow for optimal implant-retained prostheses.

Acknowledgements

The authors are very grateful to the valuable contribution of Dr P.O Gerrits, pathologist, who provided us with the human cadaver heads we used to test the method. We also sincerely thank Mr A.K.Wietsma, dental technician, who helped us to design the surgical guide, and dr. W.D Noorda, maxillofacial prosthodontist, who helped with the method. Finally, the authors would like to thank Southern Implants (Cape Town, South Africa) for providing the extra-oral implants.

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8

Digital Planning of Cranial Implants

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van der Meer WJ, Bos RR, Vissink A, Visser A.
Digital planning of cranial implants.
British Journal of Oral and Maxillofacial Surgery 2013 Jul;51(5):450-2.

Abstract

Aim: Computer-aided techniques can be used in the reconstruction of defects in the skull, although there are limitations for large defects. We describe a technique for the digital design of an implant for cranioplasty using one, easy-to-use, piece of generic industrial software that shows a curvature-based, hole-filling algorithm. This approach is suitable for all kinds of defects, including those that extend across the midline of the skull. The workflow gives the user full control over the design, production, and material used for the implant.

Materials and Methods: A cone-beam CT image is made of a patient with a cranial defect and of two cadaver heads and the resulting datasets are converted to a surface model. The defect is reconstructed using a curvature based reconstruction algorithm and cranial implants are designed in software. The fit of the implants was assessed independently by two maxillofacial surgeons and by comparing the planned CAD file with CAD files of the original skull before the defect was created and the skull with the implant in place.

Results: Implants showed excellent fit and adaptation to the skull.

Conclusion: The suggested digital workflow for designing custom-made cranial implants is an easy-to-use, fast method to produce well-fitting cranial implants if an autologous bone flap is not available or less appropriate.

Introduction

When cranial bone needs to be removed or is lost, subsequent reconstruction of the defect is necessary to protect underlying brain, or correct aesthetic deformities, or both.[1] The bone can be reconstructed with a flap of autologous bone or with alloplastic material. If available, a computed tomographic (CT) dataset of the intact skull can be used for reconstruction of the skull.[2] However, in most cases only a CT dataset of the injured skull is available, which restricts the digital reconstruction to one of these strategies:

1. mirror-imaging the unaffected side (figure 1);[3]
2. size and shape-matching data;[4,5]
3. or mathematical algorithms.[6,7].

The application of mathematical algorithms has the most benefits, but we know of no technically feasible description of the workflow. Here we describe a workflow for digitally designed, custom-made, cranial implants that uses commercially available software to produce a curvature based, hole-filling, algorithm instead of mirroring the unaffected side. This approach can be used for small and large defects, even those extending through the midline.

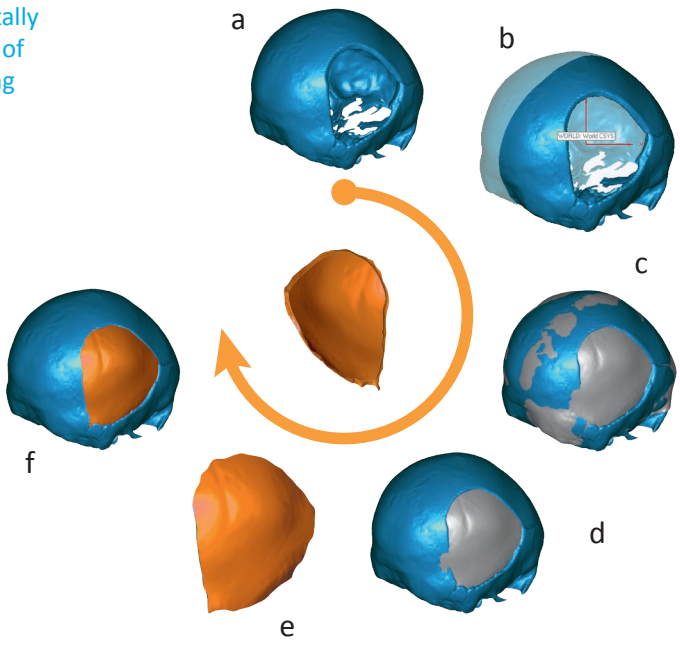

Figure 1: Workflow for digitally restoring unilateral defects of a skull (a= blue) by mirroring the unaffected side (grey) to create an anatomically correct implant (orange). After positioning a mirror plane (b) the unaffected side is mirrored into the defect (c). The mirrored part is registered with the affected side (d) and then the implant can be fabricated after subtracting the two parts (e). Finally, the implant can be placed in the defect (f).

Materials and methods

A cone-beam CT image is made of the patient's head and the resulting dataset is converted to a surface model using the DICOM convertor in Geomagic Studio 12 software (Geomagic 12, Geomagic GMBH, Stuttgart, Germany). In the 3-dimensional model (figure 2) the edges of the defect are selected and removed. Next the "fill holes" procedure in the software

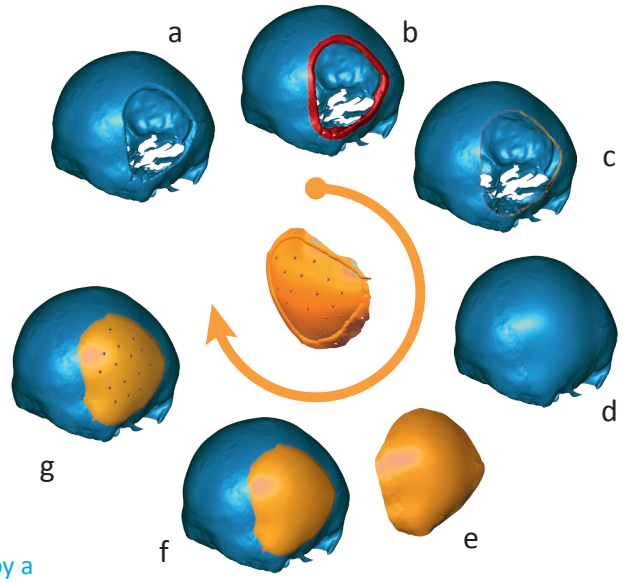

Figure 2: Workflow for digitally restoring a unilateral skull defect (a= blue) by deleting the edges of the defect (red) and closing the existing hole by using a curvature-based algorithm to close the defect and create an implant (orange). Firstly, the edges of the defect are selected (b). Next, the edges are deleted (c), and then the defect is closed by a curvature-based algorithm (d) and the implant can be designed (e). Finally, the implant can be placed in the defect (f). When desired (applies also for the approach shown in figures 1 and 3), the implant can be modified by adding perforations for ingrowth of tissue or holes for fixation screws, or both(g).

is activated to reconstruct the outer surface of the skull using a "curvature based filling" function. This function uses the tangent of the surface next to the defect to reconstruct the surface, which results in a surface that closely resembles the original curvature (figure 3). After the edge of the implant extension has been selected, the residuum of the skull model is deleted. The remaining part is given the appropriate thickness using the "shell" command and is subtracted from the original skull model using a Boolean operation. The design can be modified when needed. It takes about an hour to design the cranial implant from conversion of the CT data to export of the final design. The digitally-designed implant can be produced by rapid prototyping of the implant or the mould for the implant.

To validate the workflow we reconstructed two cadaver heads with large artificial cranial defects using this method. The implant designs were exported as stl-files and sent to DSM

Desotech (Elgin, IL 60120, USA.) where they were converted to physical models with the aid of a stereolithography (SLA) machine and a biocompatible SLA resin (BioSure™; DSM Desotech). The fit of the implants was assessed independently by two maxillofacial surgeons and by comparing the planned CAD file with CAD files of the original skull before the defect was created and the skull with the implant in place (figure 3). Implants showed excellent fit and adaptation to the skull.

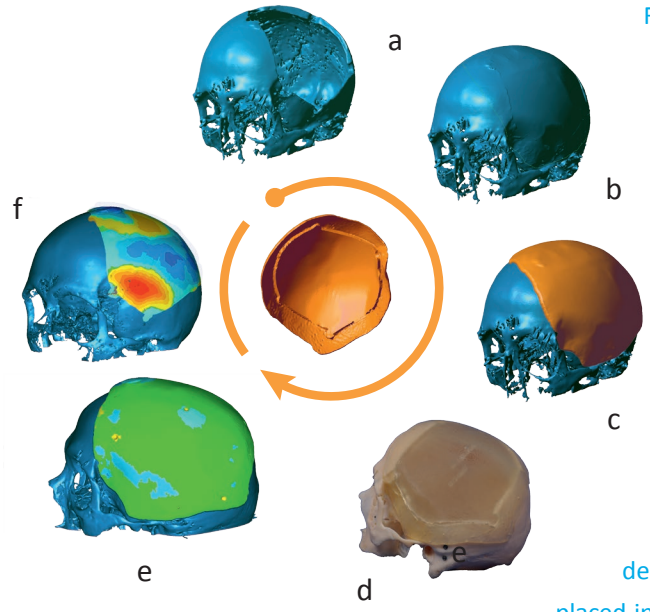

Figure 3: Workflow for restoring large skull defects (a= blue) that cross the midline by using a curvature-based algorithm and so creating an anatomically correct implant (orange). According to the method shown in figure 2, the defect is closed by a curvature-based algorithm (b), where after the implant is designed (c), fabricated, and placed in the defect (d). The surface of the implant was checked against the surface of the skull before the defect was created by superposing the computer-aided design (CAD) file of the original skull with the planned CAD file of the skull defect with the implant in place and by comparing the CAD file of the planned implant with the CAD file of the skull with the implant in place. The computer calculated the distance between the position of the implant and the planned implant (e) and the position of the implant with the original curvature of the skull (f). With regard to the comparison of the planned and actual position of the implant, the difference between these positions is within 0.5 mm for 90% of the surface (the green part of the surface). The difference between the preoperative intact skull and the closed defect (f) showed that overall the algorithm will result in a curvature that lies 0.5 -1 mm below the original outer surface. In case of complex curvature the algorithm might result in a slight outward bulging of the outer surface up to a maximum of 3.5 mm (red).

Discussion

The suggested digital workflow to design custom-made cranial implants is fast, practical. Others have described ways to design and produce cranial implants digitally,[8] but our workflow is the first practical application that has used a curvature-based algorithm and commercially available software. The advantage of curvature- based, hole-filling, algorithms is that it makes designing cranial implants easier for all kinds of defects, either small (**figure 2**) or large (**figure 3**). By using only one type if software we reduce the cost of software and of its annual maintenance. Compared with other methods, the software is easy to use, and the proposed workflow is fast, relatively cheap and results in anatomically well fitting, cranial implants. We used a biocompatible SLA resin, but other rapid prototyping technologies can also be used.[9] The workflow also gives the operator full control over the design of the implant so that important factors such as retraction of skin can be considered in the design.[10] This workflow also is in control of the method of production and materials used and therefore the final price of the implant.

Conclusion

The suggested digital workflow for designing custom-made cranial implants is an easy-to-use, fast method to produce well-fitting cranial implants if an autologous bone flap is not available or less appropriate.

Conflict of interest statement

The authors have no commercial interest in the products used in the study.

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Appliance manufacturing

Chapter 9 Full 3-Dimensional Digital Workflow for Multicomponent Dental Appliances: a Proof of Concept.
Journal of the American Dental Association 2016 Apr;147(4):288-91.

9

Full 3-Dimensional Digital Workflow for Multicomponent Dental Appliances: a Proof of Concept.

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van der Meer WJ, Vissink A, Ren Y.
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J Am Dent Assoc. 2016 Apr;147(4):288-91.

Abstract

Background: The authors used a 3-dimensional (3D) printer and a bending robot to produce a multicomponent dental appliance to assess whether 3D digital models of the dentition are applicable for a full digital workflow.

Methods: The authors scanned a volunteer's dentition with an intraoral scanner (Lava Chairside Oral scanner C.O.S., 3M). A digital impression was used to design two multicomponent orthodontic appliances. Biocompatible acrylic baseplates were produced with the aid of a 3D printer. The metal springs and clasps were produced by a bending robot. The fit of the two appliances was assessed by two experienced orthodontists.

Results: The authors assessed both orthodontic appliances with the volunteer's dentition and found the fit to be excellent.

Conclusions: Clinicians can fully produce a multicomponent dental appliance consisting of both an acrylic baseplate and other parts, such as clasps, springs, or screws, using a digital workflow without the need of a physical model of the patient's dentition.

Introduction

For creating the treatment plan and for producing appliances, a plaster model of the dentition has traditionally been the criterion standard in clinical dentistry. A plaster model is, however, associated with difficulties and problems related to storage and retrieval, damage of the model, reproduction and communication[1]. Therefore, efforts have been made over the years to replace these models with digital equivalents.

Even though many steps in the production of a removable appliance are already digitized[2], a physical model of the dentition was still needed for the production of the end-product as there were, until recently, no printable resins that, once set, can remain in contact with the oral mucosa for a prolonged time.

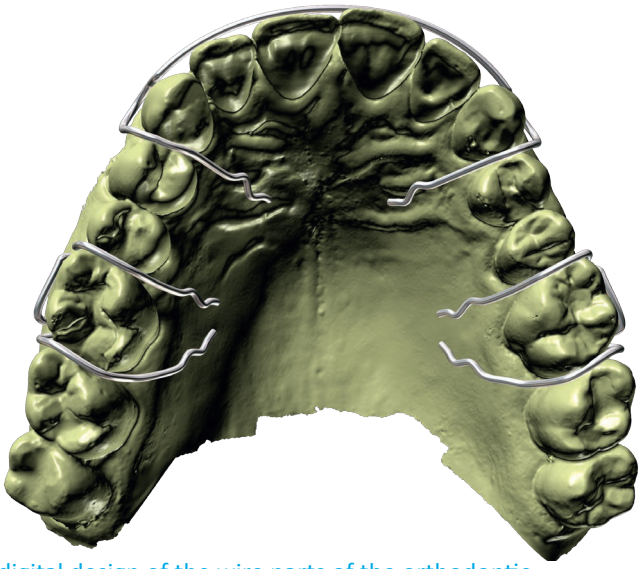

Figure 1: The digital design of the wire parts of the orthodontic

Furthermore, most removable appliances consist of both metal parts and plastic parts that need to fit together seamlessly to ensure a proper fit in the mouth that avoids interference with the occlusion or articulation. These complex interactions of removable appliances are not only challenges in traditional orthodontics and prosthodontics, they have long interfered with adaptation to full digital workflow. Innovative technology is available to address the impression and casting challenges of traditional techniques. A full digital workflow and robotics makes treatment planning, design, and virtual model making that produces an orthodontic appliance ready for patient try-in within reach. The aim of this proof-of-concept study was to assess whether a digital model can be used in a full digital workflow to produce a multicomponent orthodontic appliance.

Materials and methods

Participant

A staff member from the Department of Orthodontics, University Medical Center Groningen, The Netherlands, volunteered to participate in this proof-of-concept study. Informed consent was obtained prior to the study. The Medical Ethics Review Board of the University Medical Center Groningen ascertained that the study was not clinical research with human test participants as described in the Medical Research Involving Human Subjects Act3 and that formal ethics committee approval was not necessary (METc 2014/147).

The impression

We lightly dusted the dentition of the volunteer with titanium dioxide powder to enable the scanner to register the 3-dimensional (3D) images. We scanned the dentition with an intraoral scanner, sometimes referred to as a digitizer (Lava Chairside Oral scanner C.O.S. (3M) according to the manufacturer's instructions and automatically uploaded to digital file storage. We downloaded the digital file of the scanned dentition as a .PLY file from the central sever of the manufacturer.

Production of the multicomponent dental appliance

We used the digital model obtained from intra-oral scanning to produce a multicomponent removable appliance. We constructed two appliance designs for the maxillary model:

- a removable appliance with a with an expansion screw, labial bows, protrusion springs and Adams clasps;
- a retainer plate consisting of a labial bow and Adams clasps.

To construct the maxillary model, we imported the 3D file of the model in a modelling and animation software program (3ds Max, Autodesk) and designed the necessary springs, clasps and acrylic baseplate (figure 1). We modelled a fitting space for the expansion screw and for the extensions of each of the springs and clasps. We modelled small support arms and attached them to the baseplate. We fitted the supports with grooves thus ensuring that the different wire parts would be positioned correctly in respect to the baseplate (figure 2). We exported the baseplate design as a stereolithography format (known as an STL file) and sent it to a 3D printing company (Nextdent). The company converted the 3D file to a physical model in a 3D printable biocompatible material (Nextdent Ortho Rigid, Nextdent) with the aid of a 3D printer (Rapidshape D30, Rapid Shape).

We exported each of the wire designs as an .ASE file which consist of an American Standard Code for Information Interchange (that is, ASCII) ASCII description of the wire part.

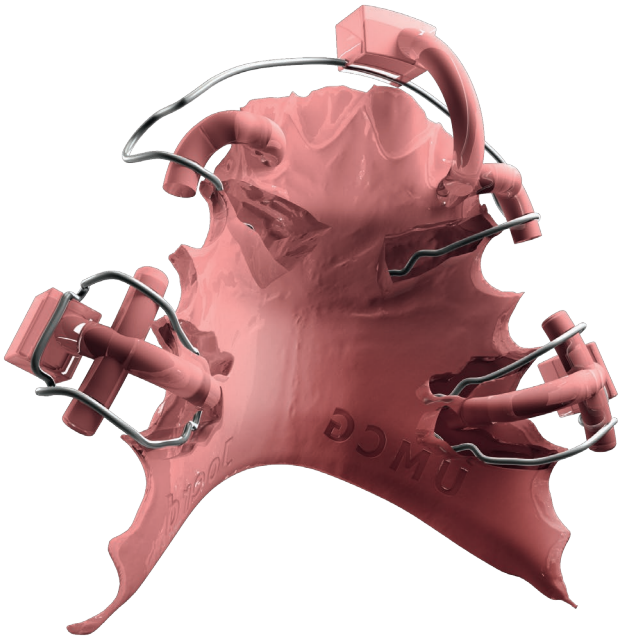

Figure 2: The design for the 3-dimensional printed part with support arms to position the wire parts correctly.

One of the authors (W.J.v.d.M.) wrote a software routine in C++ computer language to convert the ASE files to one that could be used by a wire bending robotic machine (FMU 2.7, Wafios). The files were read in by the bending machine and the labial bows, springs, and clasps were bent from 0.7 and 0.8 mm orthodontic spring wire (Dentaurum) (figure 3). A dental technician positioned the constructed wires on the support arms of the 3D printed baseplate and filled the holes with the biocompatible light curing resin of which

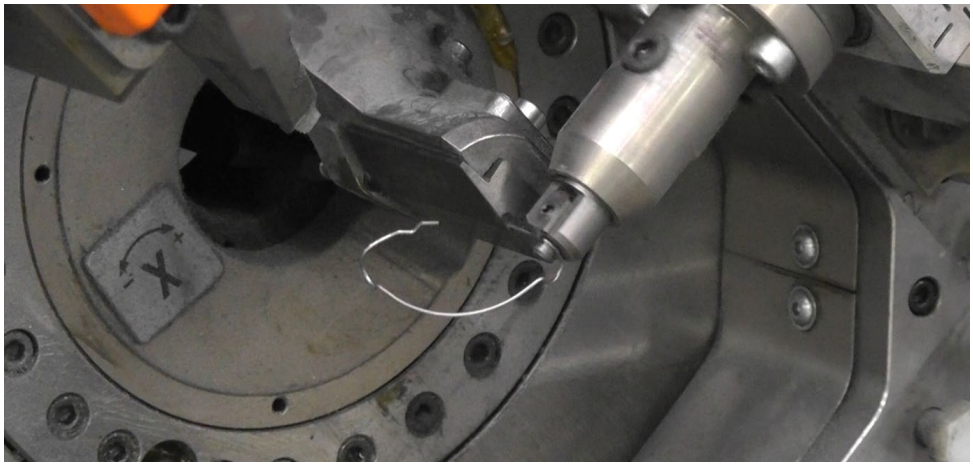

Figure 3: The bending machine constructing one of the wire parts for the removable appliance

the baseplate was constructed and light cured. He removed the support arms from the baseplate and polished the palatal side, rendering a smooth palatal surface (figure 4). Two experienced orthodontists fitted the removable appliances in the mouth of the participant and independently assessed the appliances for proper fit. For assessing the quality of the appliances' fit, the clinicians applied these criteria: pressure necessary to insert the appliance, retention of the appliance, stability of the appliance after being inserted

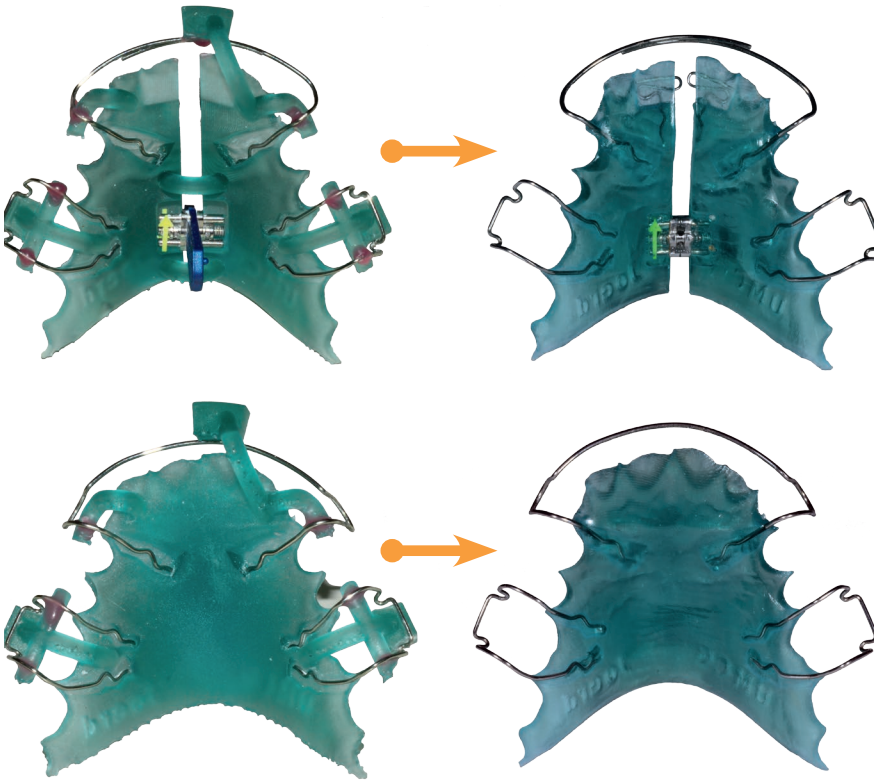

Figure 4: The assembly of the wire parts and the baseplate to construct the appliance without the aid of a physical model of the dentition. Images on the left show the assembled appliance, and images on the right depict the finished appliance in which the support arms have been removed and the surface has been polished.

(no rocking) and ease of removal of the appliance. The participant wore each appliance for two weeks and we inspected the appliance for signs of wear and damage. We also inspected the soft tissues after one and after two weeks for signs of irritation or redness.

Results

The clinicians evaluated the fit of the digitally and robotically created removable appliance; both of the appliances showed a proper fit for both the plastic baseplate and for the wire parts. The appliances designed and fabricated as such could be inserted into place with no need for adjustments to either the acrylic baseplates or the metal wire components. The retention of the appliances was sufficient to withstand normal oral functions such as speaking, drinking, and minor chewing. The volunteer could remove the appliance for cleaning with ease. No signs of excessive wear or damage to the appliances and no signs of tissue irritation or redness could be detected.

Discussion

Digital 3D models seem to promise advantages over traditional plaster models including increased ease of portability, reduced need for physical storage space, and reduced maintenance required for model quality and integrity [4 - 8].

Efforts for a digital workflow have already been made for the production of aligners[9], but a physical model was needed for the production of the aligner, as a biocompatible resin for 3D printing with the proper mechanical properties did not yet exist. The new material that was used for producing the baseplate, is in conformity with International Organization for Standardization documents EN ISO 1641:2009 (Dentistry. Medical devices for dentistry. Materials) and EN ISO 10993-1:2009/AC2010, EN ISO 10993-3:2009 and EN ISO 10993-5:2009 (biological evaluation of medical devices)[10] and products made with this material can remain in the mouth during the complete orthodontic treatment if necessary. The mechanical properties of the material[11] are comparable to a commercially available self-polymerizing acrylic for orthodontic appliances[12].

As a biocompatible resin for 3D printing is available for the production of orthodontic appliances, the next step could be taken - a full digital design and production of a multicomponent appliance without using a physical model of the dentition. Such a workflow has great potential as, when the workflow is fully streamlined, the production of the appliance can be largely automated, even though the fixation of the wires to the baseplate, removal of the support arms and polishing of the baseplate still requires manual actions. Ultimately such a workflow will result in a high, constant quality appliance at lower costs. Thus, we have shown that a multicomponent dental appliance consisting of both a polymer baseplate and other parts, like clasps, springs or screws, can be fully designed and produced.

Conclusion

It is possible to produce a multicomponent dental appliance consisting of both a polymer baseplate and other parts, like clasps, springs or screws with a full digital workflow without the need of a physical model of the patient's dentition. Future studies should consider assessing if the described digital workflow can be extended beyond dentistry to appliances or devices with more complex designs or requiring different materials.

Conflict of interest statement

The authors declare that they have no conflict of interest.

Acknowledgements

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Discussion and future perspectives

10

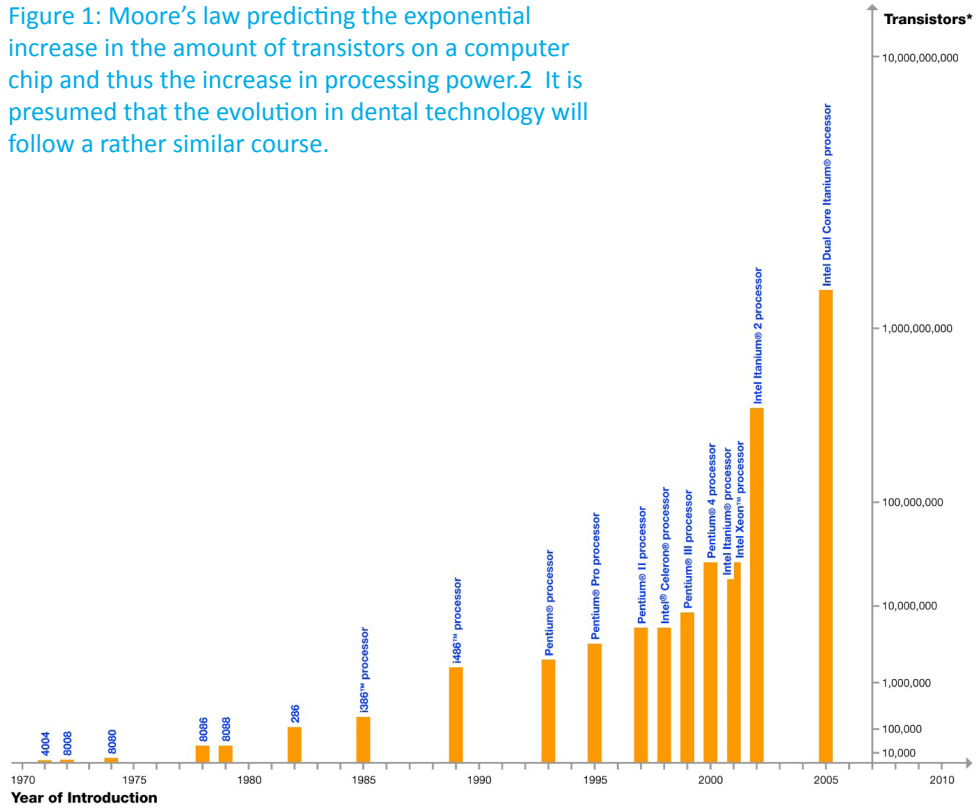
General Discussion

The last century, dentistry has developed from an artisan trade that could relieve pain-stricken visitors from their agony and pain by just extraction of the affected teeth to a science that involves prevention of tissue damage, planned movement of teeth, planned changes in function, planned changes in facial appearance to increase the aesthetic appearance of the requestor and still, occasionally of course, relieve patients from pain. Over the years the educational profile of the dentist had to be modified too to accommodate for developments that had taken place in existing fields of technology or simply because a whole new technology was introduced that expanded the existing armamentarium of the dentist. Such modifications can be expected in every academic field that involves the application of technology.

The "modern" dentist has a highly specialized profile, with expert scientific knowledge and insights in anatomical, biochemical and mechanical interactions of the complex of tissues that make up the orofacial system meanwhile also concerning the complex biochemical and microbial processes occurring in the mouth and the changes that occur during the progress of caries, periodontitis, peri-implantitis, infections of an endodontic origin, osseointegration of dental implants etc.. Apart from this, the modern dentist needs good visual and tactile senses, and highly trained manual skills. The aforementioned skill set enables the modern dentist to determine whether, e.g., a change in the orofacial system needs additional investigation, supervision of change or immediate treatment. These skills are based on pattern recognition in combination with a thorough knowledge of healthy and diseased tissues. This knowledge grows with the years of experience making the dentist a "better" dentist in that he or she is better at both recognizing disease and the challenges that are faced during treatment.

With the advent of digital technology and the introduction of 3D digital workflows, the question rises what changes will occur in current and future workflows, and what is the impact of these changes with regard to the profile of the dentist. The modern dentist should be able to up to date apply the technology in the dental field and to keep up with the changes occurring in that field: modern dentistry has become highly dependent on technology and its dependency will increase over time. As will be for many other fields, also dental technology will follow Moore's law to some extent[1] **(figure 1)**.

Figure 1: Moore's law predicting the exponential increase in the amount of transistors on a computer chip and thus the increase in processing power.2 It is presumed that the evolution in dental technology will follow a rather similar course.



*Note: Vertical scale of chart not proportional to actual Transistor count.

Evolution in diagnostic technology

The patient has always been dependent on the clinical skills of the dentist to assess the condition of the orofacial tissues and to distinguish between healthy and diseased tissues. For example, the clinical environment (temperature, humidity, lighting, etc.) will have an impact how tissues are presented. The dentist has to heavily rely on pattern recognition fed by clinical examples and experience in differentiating between subtle differences in the condition of tissues and the patient's physical condition. This rather subjective skill set is dependent on, e.g., the condition of the dentist on a particular day or even at a particular moment that day. This phenomenon was nicely illustrated by Goldman et al[3,4] who showed that the result of X-ray diagnostics vary between clinicians at the same moment of the day and even in the same clinician over time. When dental technology is able to reduce the subjective component, this will be a great asset for the patient. In this respect the term "Computer Aided Diagnosis" is used for solutions where a computer will analyse a 3D (or 2D) radiographic datasets to facilitate or improve the human aided diagnosis.[5]

Apart from X-ray information other 3D datasets can also be incorporated in the diagnostic process. Consecutive intra-oral 3D scans of the dentition provide a multiplicity of information concerning, e.g., wear and can enable us to differentiate between pathological and physiological wear of the dentition. It has been shown that the intra-oral scanners are very accurate at a local level (Chapter 2), but are not yet as accurate as conventional impression materials for general applications.[6] But for the assessment of wear the local accuracy of the intra-oral scanners can be used in conjunction with software that can assess the severity of pathological wear. These scanners can also be used for monitoring changes in the position of teeth to assess phenomena like crowding of the teeth.

Other Computer Aided Diagnosis applications will involve the monitoring of external changes in tissues with 2D (changes in colour) and 3D (changes in texture of the surface) in combination with pattern recognition algorithms. External changes that involve swelling of the tissues can already be assessed with 3D camera systems, but the accuracy of these measurement is in need of refinement. The camera system tested (Chapter 3) could accurately detect changes >5.9 ml. Important limitations of the tested system were related to the resolution of the system and the applied software algorithms. This was nicely illustrated by the applied software: for the same data set older software algorithms performed worse than newer algorithms showing that optimized software algorithms play a pivotal role in the accuracy of a 3D measurement system. However, the improvement that can be obtained by just applying sophisticated software is limited. Greater improvements are expected from hardware improvements. For example, the resolution of digital photo cameras has increased exponentially over the years (figure 2). However, beyond a certain resolution the difference in image quality that can be perceived by the human eye is reached, therefore it is expected that this curve will level off for consumer cameras, but may continue to follow Moore's law for technical applications such as optical 3D scanning systems.[7]

For the hard tissues underlying the soft tissues, we need imaging systems that "see" through tissues. Yet, radiographic techniques are most applied for this purpose. These can provide information in 2D or in 3D but at the cost of exposure to radiation and with a limited resolution. Other imaging technologies can also be applied in the diagnostic process. Ultrasound imaging is one of these that even though it is yet limited in resolution as the wavelength of the ultrasound signal is still rather large compared to the level of detail we like to depict. Ultrasound has been tested for caries detection and encouraging findings have been reported.[7] High frequency ultrasonic scanners have been tested to solve the aforementioned resolution problem. Even though some of these scanners were primarily designed as an alternative for traditional impression materials, they show

promising results resolution-wise[8, 9] and may be incorporated at some level in Computer Aided Diagnostics. Another technology that has great promise is optical coherence technology (OCT).[10] Unfortunately, the equipment is yet suitable for research purposes only and currently, there are no OCT scanners for intra-oral use available for the dental practice. The availability of new technologies and the increase of diagnostic resolutions will go hand in hand with further software improvements and it can be presumed that many, if not most, diagnostics will be done with automated systems within the next decades.

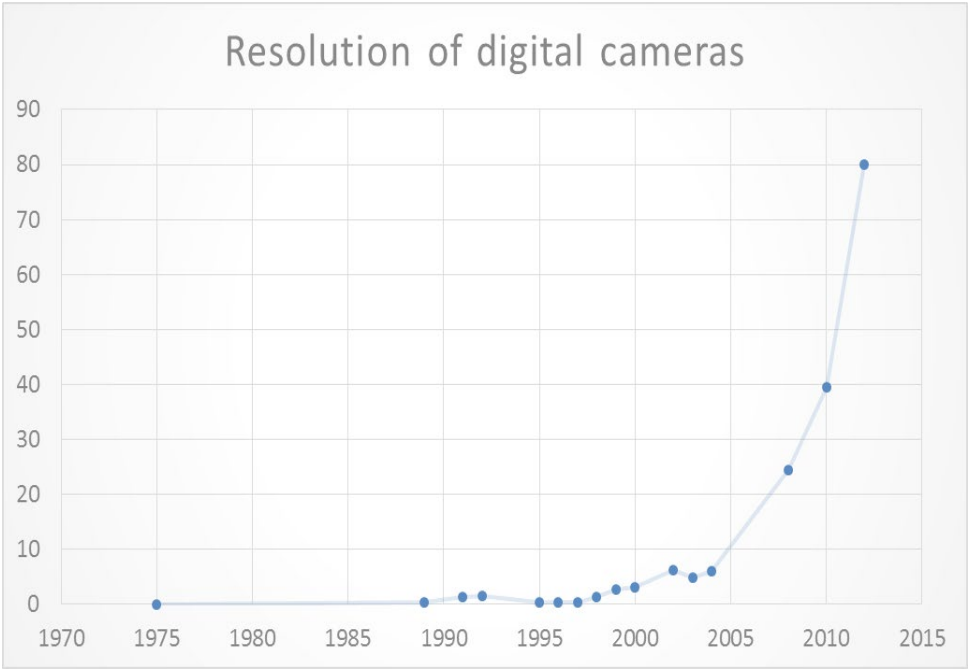


Figure 2: The exponential increase in resolution of digital cameras as a function of time.[11]

Evolution in treatment planning technology

Though some available technology may have limited value from a diagnostic perspective (see previous session), others have already shown their value in the treatment planning process. For some treatment modalities, e.g., implant treatment planning, there is already software available that enables the clinician and dental technician to plan suprastructure and implants position. Even though in some software X-ray data can be combined with digital models of the dentition, it is still not a full functional simulation. Nevertheless, this combination can be used to plan implant treatment and to produce surgical guides to facil-

itate implant placement, particularly for difficult anatomical areas like the floor of the nose (Chapter 4) or the mastoid region (Chapter 5).

To enable a complete simulation of the patient, data collected with different imaging technologies has to be combined in one 3D model which ideally results in a photorealistic model of the patient allowing for a simulation of different treatment modalities. Even though this approach is already feasible[12], there is yet no complete and fully developed solution for a full simulation of the functional and aesthetic aspects of a treatment. When considering the current state of technology and what is needed to achieve a technical solution, it is expected that a full simulation will become available in the next decade.

Most of the current treatment planning technology also deals with the actual production process. The objective of technology in a production process is to establish a high and constant quality while reducing the costs of the end-product. Reducing the costs is usually achieved by minimizing or eliminating the human factor in a production chain. In Chapter 7 a practical way of using technology as an aid for the technician to digitally plan and produce a cranial implant is shown. In Chapter 8 the next step is illustrated by showing that a digital workflow for producing multicomponent dental appliances without resorting to a physical model of the dentition is already feasible. The implications of this proof of concept are profound. Align Technology, Inc. for example, produces about 40,000 parts a day resulting in a total of 8–10 million aligners each year.[13] Such a production process still involves the production of multiple models of the dentition of the patient, however. A digital workflow for the production of full acrylic appliances without having to resort to a physical model of the dentition will significantly reduce the production costs of these aligners and will reduce the production time meanwhile reducing the amount of waste material by not needing physical models anymore.

Another example is the traditional fabrication of multicomponent dental appliances. This production was previously restricted to dental technicians with proper hand-eye coordination and fine motor skills to bend steel dental spring on a plaster model. The introduced digital workflow (Chapter 8) enables everyone with experience with computers to design such appliances. The production of the appliances occurs by machines. The proposed workflow can easily be streamlined further as most 3D software can be scripted, thereby automating certain tasks. A simple script can lead the end-user through the whole process.

The treatment planning will therefore shift from a traditional, labour intensive process that requires the input of multiple specialists to a highly automated, computer aided process that can be executed by a single person with both a dental and a technical background.

Evolution of treatment technology

In Chapter 4 a study is described going beyond the planning and production process of technology pointing to more profound aspects of technology. With regard to tasks that require human involvement, the objective of technology is to make difficult tasks easier and to make impossible tasks possible for human. Examples of the latter are the development of technology that can compensate for inexperience or human flaws and/or is able to expand the human abilities with extra competencies. The study described in Chapter 4 provides the dentist with a solution to treat calcific metamorphosis of the root canals that normally left the dentist with the tantalising technical prospect of reaching the root canal space through spatial and drilling skills without the complications of excessive and uncontrolled dentine destruction or worse: root perforation. Access to such calcified teeth traditionally relied on the ability to drill precisely in the direction of the anticipated canal opening based on knowledge of anatomy, 3D mental visualisation and a steady hand able to hold bur orientation.[14] The proposed method provides a coupling of the CBCT dataset and the actual physical root canal and makes endodontic treatment of such complex cases less challenging meanwhile bringing it within reach of general practitioners. The principle of using a 3D printed device to guide the operator was used to perform the endodontic treatment, but other treatments like apical surgery can be simplified using similar technology and a similar workflow. In these cases the surgeon is left with a similar challenge: mental visualization of the anatomy and the location of the apical anomaly that needs to be treated. By removing the need for visualization the operation will become easier and the end result more predictable. This principle has already been applied successfully in a clinical case.[15] Over time more technology will evolve that compensates for the lack of visualization or fine motor skills and for clinical experience. This implies that the dentist of the future will get better results without having to rely on experience and highly trained fine motor skills as this can be compensated by applying technology, which will have a profound effect on the education and training of the dental professionals.

Evolution of the disruptive nature of 3D technology

“Disruptive technology” or “disruptive innovation” are terms coined by Clayton M. Christensen.[16] Currently, disruptive innovation is defined as a technology that brings a much more affordable product or service that is much simpler to use into a market which allows a whole new population of consumers to afford, to own and have the skill to use a product or service, whereas historically, the ability to access was limited to people who have a lot of money or a lot of skills.[17]

While sustaining innovations build further on known technology, refining and improving technology mainly is based on demands and wishes of current users, disruptive innovations are based on new technologies and have the ability to change the complete market. To become truly disruptive, such technologies must at some point become better and cheaper than the "old" sustaining technologies. When considering the introduction of digital technology as a sustaining innovation then the changes will be minor and can easily be predicted. When digital technology is regarded disruptive, the resulting changes for the dental profession will be huge.

With regard to the current 2D and 3D digital technologies for dental applications, they do not meet that standard yet, but have the potential to become disruptive. Their disruptive potential is driven by two phenomena, viz. the rapid development in technology expanding the possibilities for diagnosis / treatment planning / treatment execution and the influence of the innovations on the cost of healthcare. When digital technology evolves to being disruptive, the disruption will most likely come in two stages. In the first stage, digital technology will make things easier and will make things possible for dentists that have been impossible up till then. At this stage a shift will take place in the tasks that traditionally exclusively belonged to the profile of the dentist as a number of these tasks now can be delegated to differentiated staff as lower level training and education is needed. In the second stage, technology will replace the human factor, leaving the dentist more and more in a supervising position and no longer in an operator position.

Even though the aforementioned will be difficult to accept for everyone, this disbelief relies on the false presumption that there are human competencies that are so unique that they cannot be replaced with technology. When considering key competencies of the dentist for instance, the diagnostic abilities and the fine motor skills are among the most important ones. When we strip down the process of diagnostics, the diagnostic competencies of the dentist consists of diagnostic data being combined and using a decision tree to come to a single diagnosis or simplified set of diagnostic options. However, before reaching such an algorithm, the first issue has to be solved that the diagnostic process often relies on the ability of a dentist to correlate a vast store of diagnostic knowledge with direct and indirect clues given by the patient combined with data from laboratory tests and imaging (X-ray, etc.). Yet, this still seems a task that is too difficult to handle for any computer program. But with the aforementioned definition, it's not any more of a challenge than winning a game of "Jeopardy!", and this task will become within reach with time. Actually, for Jeopardy this has already been accomplished in 2011 by the "Watson" technology from IBM. One might argue that the gathering the data by interviewing the patient cannot be performed

by a computer, but Cortana, Siri and GoogleNow are assistant services for mobile devices that are already able to break down human speech to search terms and the "Watson" technology is able through machine learning to distil other levels of meaning that would normally only be discernible to humans. When we will have an electronic assistant with the ability to respond to diagnostic or therapeutic questions combined with IBM's "Watson" artificial intelligence technology, we already are at the frontier of practicing evidence-based, cost-effective, personalized medicine.

So, are the thoughts mentioned above still a future goal or already within reach? When considering the amount of data that needed for diagnosis in dentistry and even for a multiplicity of medical ailments, we can state that this amount of data is limited. Solving a game of checkers[18] where the computer needs to solve 5×10^{20} board positions or a poker game[19], where the computer needs to handle 3.19×10^{14} information sets can already be performed by a computer at or beyond the level of the most skilled chess and poker players. Regarding that for dentistry we only need a limited amount of information sets, we may expect diagnosis technology like "Watson" to take over most of the diagnostics within 10 years.

Apart from the in-office application of this kind of technology, there will be another level of disruption, viz. home-diagnostics. In its advanced form, the development of diagnostic technology will eventually lead to probes or sensors that can be connected to a communication device like a smartphone, enabling a layperson to assess the oral health of themselves. The 'home-made diagnosis' should also result in a preventive and curative advice and, if necessary, this may be combined with the address of the nearest dental professional. For the medical and dental professional this will mean that the patient of the future won't come as frequently and will come with a demand for specific care and no longer with a demand for a general solution for his or her problem.

What will be harder for patients to accept than replacing humans for the diagnostic process, is replacement of humans at an actual treatment level. However, as described in Chapter 8, some of fine motor skills, like wire bending, can already be replaced by technology while also other competencies like the preparation of a crown can also be performed by a robot using laser technology.[20]

Key competencies of dental specialists also will change with the advent of new technology. For orthodontists, two main competencies are insight in growth and development and insight in the biomechanics of tooth movement. A complete human simulation model already be made by combining 3D data from the dentition, a scan of the face and cone beam CT data. With such a simulation model a computer will become able to determine the anomaly and propose an orthodontic treatment plan, and design and fabricate the

appurtenant orthodontic appliances (see Chapter 8).

Also the oral and maxillofacial surgeon will 'lose' competencies with time as it is very likely that with the advent of new technologies as augmented reality the projection of anatomy and operation planning (simple) operations can be done by robots. Moreover, when imaging technologies and robotics further develop, a surgical robot will become able to take over move complicated operations that may be hindered by the human factor.

Conclusion and future directions

Currently, 3D technology is already commonly applied in decision making, fabricating surgical guides, and dental restorations etc. Complete 3D workflows are yet scarce and the added costs of such workflows are still rather high. But it will just be a matter of time before complementing technology will take over many diagnostic and manual skill of the dental profession. As a result, the dental profession will change with time making the dentist to a monitor and supervisor of the dental health as part of the general health while the dental technician will evolve into a planner and engineer for the actual dental treatment.

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Summary

Even though the first digital workflow for a dental application was described in the early 1970's and was materialized in the early 1980's, it did not inundate general dental practice at that time. Those days, burdened by lavish prices, challenging procedures, arduous handling and restricted applications, digital technology was only embraced by early adopters and 3D aficionados. Due to the exponential gain in processing power, the decrease in costs of hardware and the development of user-friendly software, nowadays a shift is presumed to take place. Yet, technology and end-users seem to have reached a level that facilitates the rapid flourishing of new appliances and services that deliver (parts of) a 3D digital workflow. Currently, many technology providers seem to emphasize on an increased remuneration as an inspiring impetus to convince less procedurally inclined practitioners to employ their technological solution. Fortunately, 3D technology seems to offer much more than just financial compensation. Technology will help care providers by making difficult procedures easier and will offer solutions allowing for a treatment and/or treatment outcome that cannot be achieved with traditional procedures. Technology will also aid in eliminating human errors and may eventually lead to humans becoming superfluous in certain procedures. Finally, technology will enable dental practitioners to deliver high quality products with a constant level of quality at a lower price, bringing a better and more affordable care within reach to a broader group of patients.
Therefore, the aim of the PhD research described in this thesis was to extrapolate available technology for optimizing 3D workflows to the dental, maxillofacial and orthodontic practice, specifically its applications in diagnostics (intra-oral dental scanners, 3D stereography), treatment planning (3D computer aided planning, digitally designed templates for placement of dental and craniofacial implants) and appliance manufacturing (single component and multicomponent appliances, complex devices for maxillofacial rehabilitation).

In chapter 2 the first steps in developing a full digital workflow for dental applications were taken: 3D scanning of a full arch with the intention to assess the accuracy of three intra-oral scanners. A master model made of stone was fitted with three high precision manufactured PEEK cylinders in the regions 36, 41, 46 and scanned with three intra-oral scanners (Lava Cos, iTero, CEREC). The digital files were imported in Geomagic software. Next, the distance between the centres of the cylinders and the angulation between the cylinders were assessed. These values were compared to the measurements made on a high accuracy 3D scan of the master model. The distance errors were the smallest and most consistent for the Lava COS. The distance errors for the CEREC were the largest and least consistent. Angulation errors were all small. The Lava COS in combination with a high

accuracy scanning protocol resulted in the smallest and most consistent errors of all three scanners tested when considering mean distance errors in full arch impressions, both in absolute values and in consistency for both measured distances. For the mean angulation errors, the Lava COS had the smallest errors between cylinders 1-2 (region 46 to 41) and the largest errors between cylinders 1-3 (region 36 to 46), although the absolute difference with the smallest mean value (iTero) was very small (0.0529°). An expected increase in distance and/or angular errors over the length of the arch due to an accumulation of registration errors of the patched 3D surfaces was observed, but the effects were statistically not significant. This study showed that for making impressions of implant cases for digital workflows, the most accurate scanner with the scanning protocol that will ensure the most accurate digital impression should be used. In our study model that was the Lava COS with the high accuracy scanning protocol.

In the study described in chapter 3, the possibilities of facial 3D scanner were assessed. Volume changes in facial morphology were assessed using the 3dMD DSP400 stereo-optical 3-dimensional scanner, which uses visible light and has a short scanning time. Twenty-four healthy volunteers with and without an artificial swelling of the cheek were scanned, twice in the morning and twice in the afternoon (in vivo measurements). A mannequin head was scanned 4 times with and without various externally applied artificial swellings (in vitro measurements). The changes in facial contour caused by the artificial swelling were measured as the change in volume of the cheek (with and without artificial swelling in place) using 3dMD Vultus® software. The in vivo and in vitro reliability expressed in intraclass correlations were 0.89 and 0.99, respectively. In vivo and in vitro repeatability coefficients were 5.9 and 1.3 ml, respectively. The 3dMD stereophotogrammetry scanner is a valid and reliable tool to measure volumetric changes in facial contour of more than 5.9 ml and for assessments of facial swelling.

In the study described in chapter 4 it was shown that current technology can help to cope with difficult treatment challenges in a predictable manner. 3D digital mapping technology was employed for predictable navigation of obliterated canal systems during root canal treatment to avoid iatrogenic damage of the root. With the aid of computer software, digital endodontic treatment planning for anterior teeth with severely obliterated root canal systems was accomplished, based on cone beam computed tomography (CBCT) scans and intra-oral scans of the dentition. On the basis of these scans, endodontic guides were fabricated for the planned treatment through digital designing and rapid prototyping.

The custom-made guides allowed for an uncomplicated and predictable canal location and management. The developed method of digital designing and rapid prototyping of endodontic guides allowed for reliable and predictable location of root canals of teeth with calcifically metamorphosed root canal systems.

In chapter 5 a systematic literature review is described of the current status of 3D technology in the prosthetic rehabilitation of maxillofacial defects (ear, nose, orbital). MEDLINE, COCHRANE and EMBASE databases were systematically searched for articles pertinent to the use of 3D technology in maxillofacial prosthodontics up to December 31, 2015. Eligible papers described the use of 3D technology in the workflow of maxillofacial prostheses. A total of 82 out of 1900 identified papers was considered eligible. Although 3D technology is increasingly used in maxillofacial prosthetics, almost all eligible papers were technical notes and case reports describing how certain steps in the traditional workflow of making maxillofacial prosthesis could be replaced by 3D technology. No clinical trials comparing different techniques are yet published neither papers assessing time efficiency or costs. Moreover, none of the included papers described a 100% 3D workflow due to lack of appropriate software and limited options for rapid prototyping, e.g., printing silicone prostheses with matching coloring and or details. It is assumed that in the near future techniques needed for 3D technology in facial prostheses will become easier to apply and cheaper with time as well as that a 100% 3D workflow for facial prostheses will become available as shown in the various chapters in this thesis. This assumption implicates that 3D technology in maxillofacial prosthodontics is evolving and will replace certain steps, if not all, in the traditional workflow of designing and fabricating facial prostheses. No full 3D workflow is yet available, however.

Applying technology to facilitate the placement of implants in challenging cases, like in the floor of the nose, is discussed in chapter 6. In dentate cases, the surgeon needs to avoid the tips of the roots of the teeth below the floor of the nose, while placing the implants in a prosthodontically preferred position in the floor of the nose. With the aid of 3ds Max software, digital planning of implants in the nasal floor based on CBCT data was performed in three patients. Surgical guides for implant placement were digitally designed and fabricated using rapid prototyping. In all three patients, implants could be placed and nasal prostheses could be manufactured as planned. All anterior teeth remained vital. Analysis of planning and post–implant placement CBCT scans revealed high accuracy of implant placement. Thus, the applied method allows for reliable implant placement in close proximity to the preoperatively planned implant position.

In chapter 7, technology to facilitate the placement of implants in challenging situations, like the mastoid region, was discussed. In this chapter a method is described that enables digital planning of extra-oral implants in the mastoid region utilizing commercially available 3ds Max software and rapid-prototyping techniques to manufacture a corresponding surgical guide. The appropriateness of the digitally designed surgical guides for placing extra-oral implants was tested on six human cadaver heads with simulated bilateral ear defects. With the aid of CAD software designed for reverse engineering and 3D animation, digital implant planning based on CBCT data was performed. On the basis of this planning, surgical guides were digitally designed and fabricated using rapid prototyping. After implant placement, a second CBCT scan was made to compare the preoperative planning with the actual postoperative implant positions. Twenty-four implants were placed in total. Comparison of the pre- and postoperative CBCT scans revealed that adequate accuracy of implant placement was achieved, both for deviation of the neck (1.56 ± 0.56 mm) and the tip (1.40 ± 0.53 mm) of the implant as well as for deviation of the angulation of the implant (0.97 ± 2.33°). The developed method for digitally planning of extra-oral implants in the mastoid area and designing surgical guides allows for placement of implants in the mastoid area in close proximity to the preoperatively planned implant position.

Apart from placement of dental implants in difficult clinical situations, other challenges exist. In chapter 8 computer-aided techniques that can be used in the reconstruction of defects in the skull are discussed. A novel technique for digital designing of an implant for cranioplasty using an easy-to-use piece of generic industrial software (Geomagic Studio) that uses a curvature-based, hole-filling algorithm was described. The advantage of this approach is that it is suitable for all kinds of defects, including those that extend across the midline of the skull. The workflow gives the user full control over the design, production and material used for the cranial implant. To show its applicability, a CBCT image was made of a patient with a cranial defect as well as of two cadaver heads. The resulting datasets were converted to a surface model. The defect was reconstructed using the curvature based reconstruction algorithm. The cranial implants were designed in software. The fit of the implants was assessed independently by two maxillofacial surgeons and by comparing the planned CAD file with CAD files of the original skull before the defect was created and the skull with the implant in place. The implants that were inserted according to the planning, showed excellent fit and adaptation to the skull. The developed digital workflow for designing custom-made cranial implants is an easy-to-use, fast method to insert well-fitting cranial implants if an autologous bone flap is not available or less appropriate.

In the study described in Chapter 9, 3D digital technology was applied to produce a multi-component dental appliance without the need of a physical model of the dentition. The dentition of a volunteer was scanned with an intraoral scanner (Lava Chairside Oral scanner C.O.S., 3M). The resulting digital impression was used to design two multicomponent orthodontic appliances. On basis of this design, biocompatible acrylic baseplates were produced with the aid of a 3D printer. The metal springs and clasps were produced by a bending robot. The fit of both appliances in the mouth of the volunteer was assessed by two experienced orthodontists. The fit of both the orthodontic appliances was rated as excellent. Thus multi-component dental appliances consisting of an acrylic baseplate and other parts, such as clasps, springs, or screws can be made with the aid of a digital workflow. When using this approach, there is no need for a physical model of the patient's dentition.

In the general discussion (chapter 10) different aspects of digital workflows are discussed and placed in a broader perspective thereby attempting to go both broader and deeper into the implications of the introduction of 3D digital technology in dentistry. Complete 3D workflows are yet scarce and added costs for these workflows are still rather high. It is predicted that, related to the exponential increase in the hardware possibilities and the equally rapid decrease in costs, a disruptive change can be prognosticated in near future. Complementing technology will than take over many diagnostic and manual skills of the dental profession. As a result, the focus of the dental profession will shift by positioning the dentist as a monitor and supervisor of dental health while the dental technician will evolve into a planner and engineer for the actual dental treatment.

Nederlandse samenvatting

De eerste digitale workflow voor toepassing binnen de tandheelkunde werd in de zeventiger jaren van de vorige eeuw beschreven en in tachtiger jaren werd gerealiseerd. Destijds ging deze technologie echter gebukt onder exorbitant hoge prijzen, ingewikkelde technische procedures en handelingen en beperkingen in de toepassingen waardoor de digitale technologie geen algemene ingang vond. Door de exponentiele toename in rekenkracht van de processoren, de dalende kosten van de hardware en de ontwikkeling van gebruikersvriendelijke software wordt verwacht dat heden ten dage de digitale technologie binnen de tandheelkunde snel algemene ingang zal vinden. Op dit ogenblik lijken immers zowel de technologie als de eindgebruikers het niveau te hebben bereikt voor een brede algemene inzet van de benodigde apparatuur en zijn diensten beschikbaar om snel, goedkoop en effectief een 3D digitale workflow te kunnen toepassen.
Veel leveranciers van producten of diensten leggen de nadruk op het behalen van hogere winsten om zodoende de tandartsen algemeen practici te overtuigen om 3D technologie in te voeren in hun praktijk. Gelukkig biedt 3D-technologie veel meer dan enkel financiële compensatie. 3D-technologie helpt zorgverleners lastige procedures eenvoudiger te maken en biedt oplossingen waarmee resultaten kunnen worden bereikt die met de toepassing van traditionele procedures moeilijker zijn te bereiken of zelfs niet mogelijk zijn. Met 3D-technologie kan de factor menselijke fout (grotendeels) worden geëlimineerd en kan er zelfs toe leiden dat de mens voor bepaalde procedures of delen van procedures niet meer nodig is. Voorts zal 3D-technologie tandartsen in staat stellen om kwalitatief hoogwaardige producten te leveren tegen een lagere prijs waardoor betere en betaalbare zorg voor een brede groep patiënten beschikbaar komt.
Gezien de bovenstaande ontwikkelingen was het doel van het in dit proefschrift beschreven promotieonderzoek om de beschikbare technologie toe te passen voor het optimaliseren van 3D-workflows voor toepassing in de tandheelkundige, maxillofaciale en orthodontische praktijk, in het bijzonder met betrekking tot de diagnostiek (intra-orale dentale scanners, 3D stereografie), de behandelplanning (3D computer ondersteunde planning, digitaal ontworpen sjablonen voor de plaatsing van tandheelkundige en craniofaciale implantaten) en het vervaardigen van hulpmiddelen (hulpmiddelen die uit één of meer onderdelen bestaan, complexe constructies voor maxillofaciale rehabilitatie).

In hoofdstuk 2 werden de eerste stappen in het kader van dit promotieonderzoek voor de ontwikkeling van een volledig digitale workflow voor toepassing binnen de tandheelkunde gezet: het 3D-scannen van een volledige tandboog met als doel het beoordelen van de nauwkeurigheid van drie intra-orale scanners (CEREC, iTero, Lava COS). Een referentie

model gemaakt van hardgips werd voorzien van drie gecalibreerde cilinders van PEEK (polyether-ether-keton). Dit model met de daarin aangebrachte cilinders werd gescand met de bovengenoemde 3D scanners. De digitale bestanden werden geïmporteerd in Geomagic software. Vervolgens werd de afstand tussen de centra van de cilinders en de hoeken tussen de cilinders (angulatie) gemeten. De gemeten waarden werden vergeleken met de waarden van het referentiemodel; deze waarden waren bepaald met een speciale hoge resolutie scanner. De afwijking in afstand tussen de cilinders t.o.v. van de waarden gemeten met de hoge resolutiescanneer (iTero) was het kleinst en meest consistent voor de Lava COS en het grootst en minst consistent voor de CEREC. De gemeten fouten in de angulatie tussen de cilinders waren voor alle scanners klein. In deze studie resulteerde de toepassing van de Lava COS met een speciaal scanprotocol tot de kleinste en meest consistente foutmarge met betrekking tot de afstanden tussen de cilinders van alle drie scanners. Met betrekking tot de gemiddelde afwijking in de gemeten hoeken van de cilinders gaf de Lava COS de kleinste fout tussen cilinders 1-2 (gebied 46-41) en de grootste fout tussen cilinders 1-3 (gebied 36-46), het absolute verschil met de kleinste gemiddelde waarde ten opzichte van de waarden gemeten met de referentiescanner was echter erg klein (0,0529°). In deze studie werd aangetoond dat voor het maken van een afdruk voor implantologie ten behoeve van een digitale workflow de meest nauwkeurige intra-orale scanner met het juiste scan protocol moet worden gebruikt. In onze studie was dat de Lava COS met het speciale scanprotocol voor hoge nauwkeurigheid.

In hoofdstuk 3 werden de mogelijkheden van een 3D-scanner voor meten van veranderingen in het gelaat onderzocht. Veranderingen in de morfologie van het gelaat werden gemeten met behulp van de 3dMD DSP400 stereo-optische 3-dimensionale scanner. Deze scanner gebruikt zichtbaar licht en heeft een zeer korte scantijd. Het gelaat van 24 gezonde vrijwilligers werd met en zonder kunstmatige zwelling van de wang gescand. De kunstmatige zwelling werd veroorzaakt door het plaatsen van een bolus van afdrukmateriaal met een bekend volume tussen de gebitsboog en de wang. Deze metingen vonden tweemaal in de ochtend en tweemaal in de namiddag (in vivo metingen) plaats. Daarnaast werd het hoofd van een etalagepop werd 4 keer gescand met en zonder extern aangebrachte zwellingen van afdrukmateriaal met een bekend volume (in vitro metingen). De veranderingen in het volume van het gelaat die werd veroorzaakt door de kunstmatige zwelling werden gemeten (meting van het gelaat met en zonder de kunstmatige zwelling) met behulp van 3dMD Vultus® software. De in vivo en in vitro betrouwbaarheid uitgedrukt in “intraclass” correlaties waren, respectievelijk, 0,89 en 0,99. De in vivo en in vitro herhaalbaarheidscoëffi-

ciënten waren, respectievelijk, 5,9 en 1,3 ml. De scanner onderschat het volume van 1,2 ml (95% CI -0,9 tot 3,4) in vivo en 0,2 ml (95% CI 0,02-0,4) in vitro. Met behulp van de 3dMD DSP400 stereo-optische 3-dimensionale scanner kunnen dus betrouwbaar veranderingen in het volume van het gelaat worden gemeten, het volume van de massa die deze zwelling veroorzaakt, kan met deze scanner echter niet betrouwbaar worden gemeten.

In hoofdstuk 4 wordt een studie beschreven waarmee wordt aangetoond dat de huidige 3D-technologie kan helpen om op een voorspelbare manier moeilijke endodontische behandelingen te verrichten. In deze studie werd 3D-technologie gebruikt om op voorspelbare wijze geobliterereerde kanaalsystemen te lokaliseren en daarmee iatrogene schade aan de wortel te voorkomen. Met behulp van software werden digitaal endodontische behandelingen van frontelementen met een geobliterereerd kanaalsysteem gepland. Cone beam computed tomography (CBCT) scans en intra-orale scans van het gebit werden gebruikt voor de planning. Gebruikmakend van deze scans werd een endodontisch richtmiddel ontworpen en vervaardigd met behulp van rapid prototyping. Met behulp van de vervaardigde richtmiddelen bleek het mogelijk te zijn om op een voorspelbare en betrouwbare wijze gebitselementen endodontisch te behandelen.
In hoofdstuk 5 wordt een systematische literatuurstudie beschreven naar de huidige stand van de 3D-technologie voor toepassing in de prothetische rehabilitatie van maxillofaciale defecten (oor, neus, orbitaal). De MEDLINE, COCHRANE en EMBASE databases werd systematisch doorgezocht naar artikelen die relevant waren voor het gebruik van 3D-technologie binnen de maxillofaciale prothetiek. Geschikte artikelen die verschenen waren voor 1 januari 2016 werden geïncludeerd. In aanmerking komende artikelen beschreven het gebruik van 3D-technologie in de workflow van het ontwerp en vervaardiging van maxillofaciale prothesen. Tweeëntachtig van 1900 gevonden artikelen voldeden aan de inclusie criteria. Hoewel 3D-technologie steeds vaker wordt gebruikt voor het ontwerp en de vervaardiging van maxillofaciale prothesen bleken de geïncludeerde artikelen hoofdzakelijk te bestaan uit “technical notes” en “case reports” waarin wordt beschreven hoe bepaalde stappen in de traditionele workflow voor het maken van een maxillofaciale prothese te vervangen door 3D-technologie. Klinische studies die verschillende technieken met elkaar vergelijken noch artikelen die de efficiëntie en kosten vergelijken werden niet gevonden. Bovendien werd in geen van de geïncludeerde artikelen een 100% 3D-workflow beschreven, veelal door beperkingen in de software en de mogelijkheden voor rapid prototyping. Het bleek bijvoorbeeld nog niet mogelijk te zijn om rapid prototypen te gebruiken voor het vervaardigen van siliconen prothesen in de correcte kleur en met de benodigde

details. Dergelijke benodigde ontwikkelingen worden in de nabije toekomst wel verwacht, waardoor een 100% 3D-workflow voor gelaatsprothesen beschikbaar zal komen.

Het toepassen van digitale technologie voor het vergemakkelijken van het plaatsen van implantaten in gecompliceerde casus, zoals het plaatsen van implantaten in de neusbodem, wordt in hoofdstuk 6 beschreven. Indien nog gebitselementen in het bovenfront aanwezig zijn, moet de chirurg beschadiging van de radices van deze gebitselementen bij het plaatsen van de implantaten. Met behulp van 3ds Max software werd de digitale planning van implantaten in de neusbodem op basis van een CBCT dataset uitgevoerd bij drie patiënten. De benodigde chirurgische guides voor het plaatsen van de implantaten werden digitaal ontworpen en vervaardigd met behulp van rapid prototyping. In alle drie patiënten konden de implantaten worden geplaatst en nasale prothesen worden vervaardigd zoals gepland. De sensibiliteit van alle voortanden bleef behouden. Dee geplande en uiteindelijke positie van de implantaten bleek goed overeen te komen.

In hoofdstuk 7 werd de technologie voor het vergemakkelijken van het plaatsen van implantaten in anatomisch moeilijke situaties, zoals de mastoïd regio, besproken. In dit hoofdstuk wordt een werkwijze beschreven voor digitale planning van extra-orale implantaten in de mastoïd regio met behulp van commercieel verkrijgbare software en rapid prototyping-technieken. Met behulp van deze tools kunnen geschikte chirurgische guides worden vervaardigd. De nauwkeurigheid van de ontworpen chirurgische guides werd getest op zes menselijke kadaverhoofden met beiderzijds een defect van het oor. Met behulp van CAD-software werd digitaal de planning voor de plaatsing van de implantaten op basis van CBCT data gemaakt. Op basis van deze planning werden de chirurgische guides digitaal ontworpen. De ontworpen guides werden vervaardigd met behulp van rapid prototyping. Na plaatsing van de implantaten, werd een tweede CBCT scan gemaakt voor het vergelijken van de preoperatieve planning met de werkelijke postoperatieve implantaat posities. In totaal werden 24 implantaten geplaatst. De vergelijking leerde dat met behulp van deze guides het implanteren met voldoende nauwkeurigheid kon worden uitgevoerd, zowel voor wat betreft afwijkingen van de hals (1,56 ± 0,56 mm) en tip (1,40 ± 0,53 mm) van het implantaat als voor de afwijking in de hoek waaronder de implantaten waren geplaatst (0,97 ± 2,33°). Met andere woorden, met de ontwikkelde methodiek is het mogelijk om op betrouwbare wijze extra-orale implantaten in het mastoïd te plaatsen.

Naast plaatsen van tandheelkundige implantaten in moeilijke klinische situaties bestaan meer klinische uitdagingen. In hoofdstuk 8 worden digitale technieken besproken die kunnen worden gebruikt voor reconstructie van defecten van de schedel. Een techniek werd geïntroduceerd voor het digitaal ontwerpen van een implantaat voor defecten van de be-

nige schedel door gebruik te maken van generieke industriële software (Geomagic Studio). Met behulp van deze software kan een algoritme worden gebruikt om een schedeldefect te reconstrueren. Hierbij wordt gebruik gemaakt van de curvatuur van het oppervlak. Het voordeel van deze benadering is dat deze geschikt is voor allerlei defecten, ongeacht of dit defect zich uitstrekt tot voorbij de middellijn van de schedel. De workflow geeft de gebruiker volledige controle over het ontwerp, de productie en het toe te passen materiaal. Om de toepasbaarheid van de ontworpen methodiek te demonstreren, werden CBCT beelden van een patiënt en twee kadaver hoofden met een schedeldefect gebruikt. De verkregen datasets werden omgezet naar een 3D-oppervlaktemodel. De defecten werden gereconstrueerd met behulp van het reconstructie-algoritme. De benodigde implantaten werden ontworpen in de software en geproduceerd met behulp van rapid prototyping. De pasvorm van de implantaten werd zowel beoordeeld door twee kaakchirurgen als door vergelijking van de het geplande CAD-bestand van het 3D model van de originele schedel met een CAD-bestand van de schedel met het implantaat op zijn plaats. De ontworpen implantaten bleken een uitstekende pasvorm aan de schedel te hebben.
In hoofdstuk 9 wordt een studie beschreven studie waarbij 3D-technologie wordt toegepast voor het vervaardigen van een orthodontisch apparaat bestaande uit een kunststofdeel en metalen draaddelen zonder dat daarbij een fysiek model van het gebit werd gebruikt. Het gebit van een vrijwilliger werd gescand met een intra-orale scanner (Lava COS, 3M). Op het verkregen digitale model werden twee orthodontische plaat-apparaten ontworpen. Op basis van dit ontwerp werden de kunststofdelen geproduceerd met behulp van een 3D printer gebruikmakend van een biocompatibele printbare kunststof. De metalen veren en ankers werden verkregen met behulp van een robot buigmachine. De pasvorm van beide apparaten werd beoordeeld door twee ervaren orthodontisten. De pasvorm van beide orthodontische apparaten werd als uitstekend beoordeeld. Bij toepassing van deze methode is een fysiek model van het gebit van de patiënt dus niet meer noodzakelijk.

In de algemene discussie (hoofdstuk 10) worden verschillende aspecten van digitale workflows besproken en in een breder perspectief geplaatst. Volledige 3D-workflows zijn nog schaars en de kosten voor deze workflows zijn nog steeds vrij hoog. In verband met de exponentiële toename van de mogelijkheden van de hardware en de even snelle daling van de kosten is de verwachting dat ingrijpende veranderingen in de algemene toepassing van 3D-technieken binnen de tandheelkunde zullen plaatsvinden in de nabije toekomst. Wanneer deze verschuiving een feit is, zal technologie veel van de diagnostische en manuele vaardigheden de tandarts hebben overgenomen. Als een gevolg hiervan zal het profiel

van de tandarts verschuiven naar die van monitor en supervisor van tandheelkundige gezondheid terwijl de tandtechnicus een planner en ingenieur voor de daadwerkelijke tandheelkundige behandeling zal worden.

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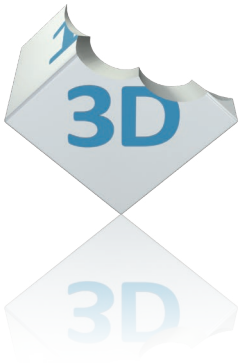

Het tot stand komen van een proefschrift is het werk van velen en ook dit proefschrift is de som van al die individuele bijdragen. Aan dit proefschrift hebben meer mensen een bijdrage geleverd dan ik op papier kan bedanken, maar een aantal mensen wil ik hieronder in het bijzonder noemen, zonder daarbij anderen tekort te willen doen.

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Mondziekten, kaak-, en aangezichtschirurgie
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ACTA:

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us to establish new goals and research projects for the future. Our discussions go beyond the boundaries of dental science and encompass broader things in life. Your keen intellect never fails to amaze me and your command of the English language both in speech and in writing make me feel like a linguistic barbarian. I'm honored that I may call you my friend.

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Disclaimer:

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The author is a key opinion leader for Dentsply Maillefer (Endodontics) and for 3M (Digital Technology).


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