3D workflows in orthodontics, maxillofacial surgery and prosthodontics
van der Meer, Wichert Jurjen

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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. 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. 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.

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. 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 or adding details. 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.

**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\textsuperscript{6, 9, 10}, testing of landmarks on digital models to determine where the prosthetic reconstruction should be positioned\textsuperscript{11, 12, 13}, testing different algorithms on a CT dataset\textsuperscript{14}, the use of rapid prototyping technologies to create a facial prosthesis\textsuperscript{15, 16}, the 3D accuracy of the manufactured facial prostheses\textsuperscript{17}, the immediate construction of a facial prosthesis\textsuperscript{18, 19, 20} or the construction of a digital database facilitating the production of facial prostheses.\textsuperscript{21} One paper describes a survey of maxillofacial prosthetists’ and technologists’ attitudes and opinions on the application of digital technology in facial prosthetics.\textsuperscript{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.](image-url)
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). 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. (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, orbital, nasal prostheses. (CB)CT scans have also been used as a basis for constructing nasal prostheses. Next to (CB)CT scans, MRI scans can be made. MRI scans are able to depict soft tissues in great detail. Therefore, MRI scans have been used for fabricating auricular prostheses and orbital prostheses. 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 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 and have been used successfully in digital acquisition for the production of auricular, nasal and orbital prostheses.
**Stereo-photo scanner**

Stereophotogrammetry uses multiple images of the same object taken from different viewpoints 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”.

Photogrammetry scanners have been proven to be accurate when used for measurements of distances between anatomical landmarks on the face of a subject but the resolution of the 3D model produced by most photogrammetry scanners is too low to reproduce fine skin details. 3D models produced from a photogrammetry scan were shown to be less accurate than 3D models produced with CBCT. Photogrammetry scanning has been used for nasal and orbital 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. Structured light scanners have also been proven to be accurate for measuring facial landmarks, ie distances and angles on the face of a subject. Structured light scanners have been used for auricular, nasal and orbital prostheses.

**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;

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.
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. 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.

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.

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, 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. Rapid prototyping is the way of producing the digitally designed model. There are two ways for rapid prototyping, viz., subtractive or additive manufacturing. 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 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. Such a try-on model can also be produced by a variety of additive manufacturing technologies, viz. selective laser sintering (SLS), thermopolymer printing and stereolithography (SLA).
- **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.
- **Mold for producing the facial prosthesis**: fused deposition modeling, 3D printing, SLS, laminated object manufacturing and SLA 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.

The most advocated production technology in digital workflows for facial prostheses are powderbed 3D printers. 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. 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 that are 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. 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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References


