Chapter 13
Maxillofacial Prostheses: Assistive Technology in Mutilated Facial Patients

Roberta T. Stramandinoli-Zanicotti, Paola F. Corso, and Maria Elizete Kunkel

13.1 Introduction

Amputation of a body part is a very difficult, delicate, and often unpredictable event. Physical loss has a major impact on life with a series of biopsychosocial changes that can interfere with the roles played by the personal, social, family, and professional fields. The emotional factor increases the resistance to accepting this loss making it more difficult for the individual to recover (Scorchio et al. 2018). The common emotions that arise after amputation are feelings of helplessness, self-strangeness, low self-esteem, loss of identity, anguish, meaninglessness, and motivation, capabilities, and limitations being experienced (Chini and Boemer 2007). The World Health Organization defines the quality of life not only as the absence of disease or illness but also as the individual's perception of their position in life, in the context of the culture and value system in which they live and concerning their goals, expectations, patterns, and concerns (Fleck et al. 2000).

The valued and monitored psychological factors for quality of life are resilience (personal mobilization to adapt to the new reality), acceptance of amputation, depression, and optimism. Psychosocial factors predisposing to quality of life include participation in social activities, working, studying, socializing with friends, associations, among others (Milioli and Vargas 2012). The amputation of any part of the body can lead to depression, performance anxiety and significantly altered relationships, body image and sexual wellbeing (Geertzen et al. 2009; Gallagher et al. 2019).

Facially mutilated individuals are those who have suffered any type of mutilation or amputation in the head and neck region, including anatomical structures such

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as ear, nose, eyes, eyelids, hard or soft palate, tongue, and other parts of the face. The etiologies can be congenital, traumatic, or due to diseases, with cancer being the main cause of amputation. Individuals with an absence of a facial structure have few options in ‘displaying’ their unusual face: covering the amputation site with bandages; carrying a prosthetic device that emulates the missing limb’s looks and baring their amputation for others to see it (Yaron et al. 2018). During their rehabilitation trajectory, these individuals commonly receive a facial prosthesis that replaces the lost part. Although this device closely resembles the absent facial area, its artificiality remains (potentially) discernible. Some studies highlight the psychosocial issues associated with facial variance, for instance, depression, social anxiety, or avoidance behavior (Koster and Bergsma 1990; Rumsey and Harcourt 2004). The psychology of appearance offers very few empirical, qualitative investigations into the way facial variance comes into play in the daily life of affected individuals, as they encounter and interact with various others. The facial mutilated individuals need to be included as persons with disabilities so that their rights can be clarified and respected.

After cancer ablation surgery or traumatic amputation, if surgical reconstruction cannot completely restore the surgical defect site, the maxillofacial prosthesis plays an important role in rehabilitation. Maxillofacial prosthesis aims the anatomical, functional and aesthetic rehabilitation, through alloplastic substitutes, of missing or defective regions of the maxilla, mandible and face, such as surgical, traumatic, evolutionary sequelae, or due to congenital malformations or developmental disorders. They can also restore lost functions, although in some cases they are limited. The purpose of the prosthesis is to restore and maintain health and comfort, correct facial defects, appearance disorders, restore and correct speech, swallowing, and chewing functions (Sharma and Beumer 2006; Beumer et al. 2011).

The final maxillofacial prostheses (MP) are fabricated with biocompatible and soft material, such as medical-grade silicone, with high tear resistance and different shore. The MP is made in a personalized way according to the needs of each patient, respecting the mutilated area to be rehabilitated (Fig. 13.1). Although they can also restore lost functions, in some cases they have limited results. The MP can be fixed to the patient’s skin with the aid of special glues or osseointegrated implants, with bar-clip systems or magnets. Although the use of implants associated with retention systems in extraoral rehabilitations has presented great advantages over the use of adhesives such as retention, support, and stability of the prosthesis, in addition to being easy to install and daily cleaning (Beumer et al. 2011), in head and neck cancer patients undergoing radiotherapy there is a risk of osteoradionecrosis. Research in animals and humans indicates that irradiated bone has a greater risk of failure and failure in osseointegration than non-irradiated bone (Stefan et al. 2009; Stramandinoli-Zanicotti et al. 2014).

Assistive Technology is based on the application of information and communication technology to meet daily needs and actively engage in everyday activities of persons with disabilities (Peraković et al. 2018). Maxillofacial prostheses are custom assistive technology devices that have benefited from industry 4.0 tools such

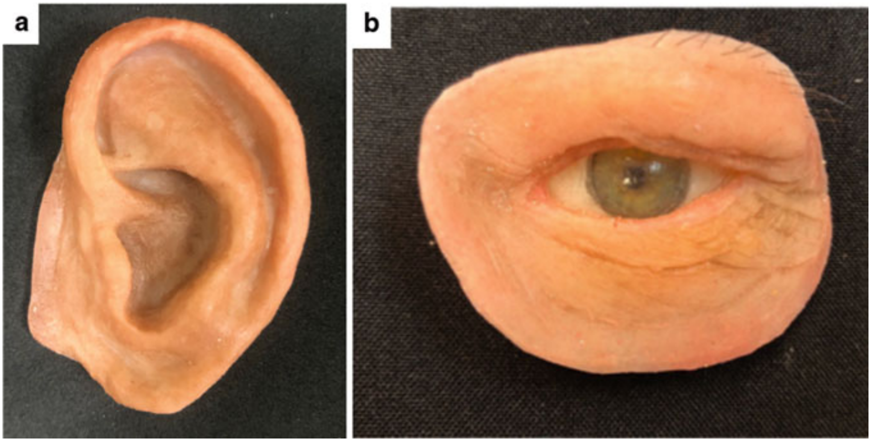


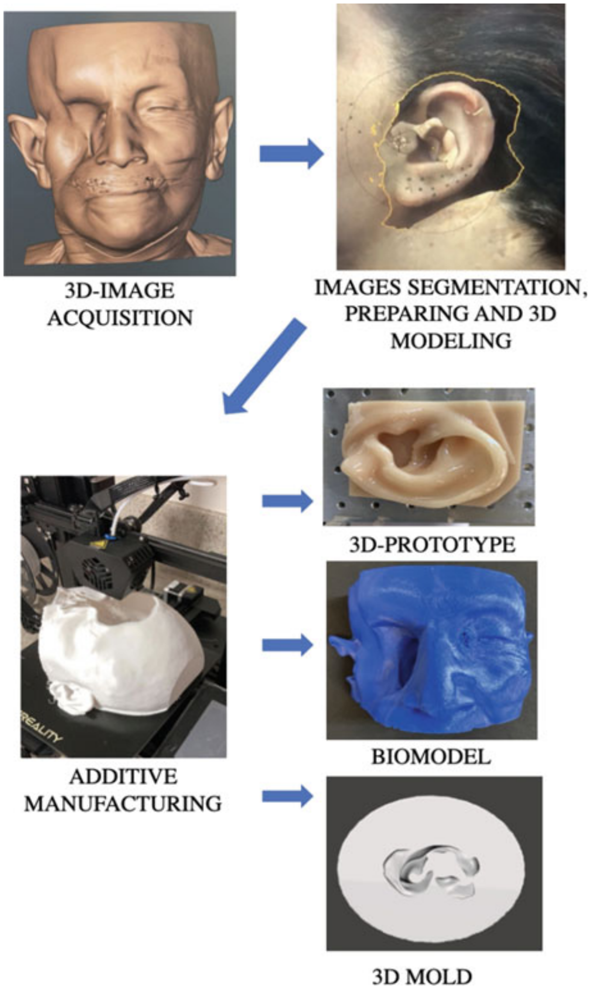
Fig. 13.1 Conventional maxillofacial prostheses: ear prosthesis (**a**) and oculus palpebral prosthesis (**b**)

as 3D scanning and additive manufacturing since the facial reconstruction treatment requires impressions of the entire face, including the defect area.

Additive manufacturing has gradually become an emerging and crucial technology in medicine. The application in healthcare provides many benefits such as better cost-effectiveness, increased productivity, and democratization of design and manufacturing. The literature highlights the use of resources and products made by 3D printing in several areas of Assistive Technology. Additive manufacturing can make objects of the most varied types and sizes, most often using low-cost material and based on a layer overlay system to create three-dimensional models. Using this technology, it is possible to reduce patient discomfort by increasing the accuracy of the directly manufactured maxillofacial prosthesis, without the need for intermediate wax and sculpting steps. The 3D technology optimizes the making of the prosthesis, enabling more favourable and predictable results. With the improvement of existing techniques and the use of additive manufacturing with new materials such as resins, silicones, biomaterials, and osseointegrated implants, the specialty has enabled the manufacture of more aesthetic, realistic, and biocompatible facial prostheses (Fig. 13.2).

In this book chapter, the role of assistive technology for facial patients will be addressed, focusing on additive manufacturing. Since the use of additive manufacturing is the final step in facial prosthesis production, it is necessary to understand all the steps that precede it. For this reason, the phases of image acquisition, segmentation, 3D modeling and printing will also be addressed in the example shown in Fig. 13.2.

Fig. 13.2 Workflow for additive manufacturing of facial prostheses



13.2 Images Acquisition

In the maxillofacial prostheses production workflow presented, first, the region of the face of the individual to be fitted needs to be scanned. All volumetric and spatial anatomical information must be provided from an image acquisition method. The structure of the scanned face is represented by a set of points arranged in the shape of a triangle, this mesh is used later to make the 3D modeling and printing of the structure. For the production of maxillofacial prostheses, the most commonly used methods are 3D reconstruction of medical images, 3D scanning and photogrammetry.

13.2.1 3D Reconstruction of Medical Images

This image acquisition method is the most used in the maxillofacial prostheses field. The data can be obtained by Magnetic Resonance Imaging (MRI), Cone Beam Computed Tomography (CBCT), or Multislice Computed Tomography (MSCT). The CBCT exam is the option with the lowest radiation dose and costs. It is the most used for dentistry because it allows a detailed view of the face in a shorter time. The exam enables us to accurately assess the quality of the bone trabeculae and isolate smaller areas of interest during the 3D reconstruction. On the other hand, the MSCT exam despite taking longer to take tomography and emitting more radiation has advantages such as better detailing of regions with thin cortical layers, such as the anterior wall of the maxillary sinus and cortical of the mandibular condyles. In addition, it also presents a better representation of the facial soft tissues involved. It is also worth remembering that the MSCT can be a tomography with a greater field of view, which is interesting in cases of extensive and/or combined maxillofacial prostheses.

The computed tomography images will provide the information of the face structure according to the Hounsfield scale, which is based on the radiodensity of the water being equal to 1 (Hounsfield 1979). Thus, the structure denser will have a higher value (bone and teeth) and the structureless dense will have a lower value (air and fat). After the exam is performed, all data is transported to the software as voxel files. It means that all the information about the volume and spatial position are precisely available. The Digital Imaging and Communications in Medicine (DICOM) format will ensure that all anatomical measurements and positions are standardized, regardless of the software being used.

The 3D reconstruction of medical images requires the segmentation process of the structures to be reconstructed using software and this process can be done manually or automatically. The computed tomography equipment has software that makes it possible to reconstruct a volume formed by all the images of the pact (Fig. 13.3). However, from a DICOM image package, it is possible to use commercial or free software to make the 3D reconstruction of the structure. Figure 13.4 shows the complete workflow of planning a maxillofacial prosthesis.

13.2.2 3D Scanning

The 3D scanner is a device able to achieve digital records from an object, regardless of its composition and density, and transmit it to the computer, making a 3D mesh. The scanner converts the reflected light into digital data using different technologies. Thousands of red laser light points can record the details of the surface of a structure from the confocal points (Van der Meer et al. 2012). It is also possible to add texture to objects, such as identifying different colours of a tooth, gums and skin characteristics.

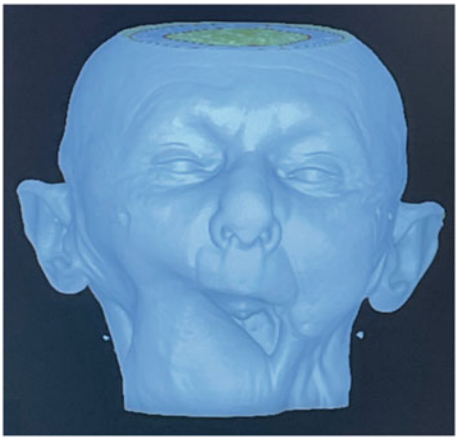


Fig. 13.3 3D face reconstruction from Multislice Computed Tomography images

In this way, when the technique is well done, the scanning will show the whole soft and hard tissues, without failures and density differences.

Previously, it was mentioned the great advantages and applications of using medical images such as MRI, CBCT, or MSCT. So why use 3D scanning? 3D scanning can make it easier to obtain anatomical structures without direct contact with the individual and without ionizing radiation. Digitization using 3D laser scanners works by emitting light, which generates a cloud of points. The point cloud created generates a vector mesh, which forms the virtual model of the scanned object. In the 3D reconstruction of computed tomography, the object appears in a variable amount of structures, depending on object density, which does not occur in scanning.

The 3D scanning technique, compared to photogrammetry, differs in terms of the number of points obtained. 3D Scanning provides a much larger number of surface points, that is, it is the most accurate technique to acquire and represent the surface of an object. Thus, 3D scanning is indicated when only the external face structure information is needed. But some disadvantages of using the scanner should be mentioned, such as the added cost and the impossibility of reaching some anatomical areas in facial mutilated patients due to the limitation of space when compared to the size of the sensor, for example. In these cases, computed tomography turns out to be the most viable option for image acquisition.

13.2.3 Photogrammetry

A third option for obtaining a 3D structure of the face is photogrammetry. There are a few different techniques for this modality. Conventional photography protocols using professional cameras or smartphones have been suggested so that a series of photos at different angles of the same scene are capable of matching 2D data (pixels) so that a 3D object (voxels) is constructed. A more precise methodology involves the use

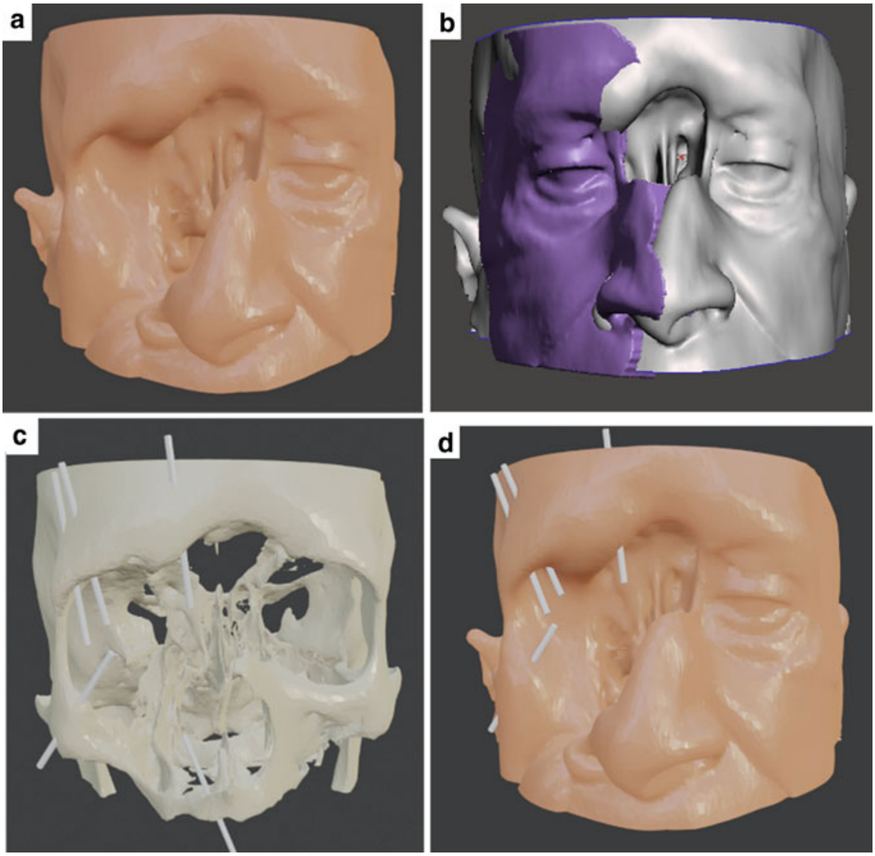


Fig. 13.4 3D face reconstruction from Multislice Computed Tomography images presenting an extensive facial defect after tumour ablation surgery (**a**). Mirroring of the contralateral side for volume and symmetry initial study of the anatomical structures (**b**). 3D evaluation of implant position in bone (**c**) and soft tissue (**d**)

of photo booths, in which numerous cameras are strategically positioned at different angles so that in a few seconds all the information obtained is quickly transformed into 3D data. In this way, there is a much smaller possibility of distortion of the structures. Other ways have also been demonstrated, such as the use of videos in high resolution through specific software, which is very reminiscent of the idea of virtual reality that can be seen in cinema. In addition to the volumetric and spatial data, photogrammetry is also able to provide texture (Ciobanu and Rotariu 2014). The main limitation of 3D scanning and photogrammetry compared to the 3D reconstruction of medical images is the fact that the individual to be scanned has to remain static throughout the process, which can take a few minutes.

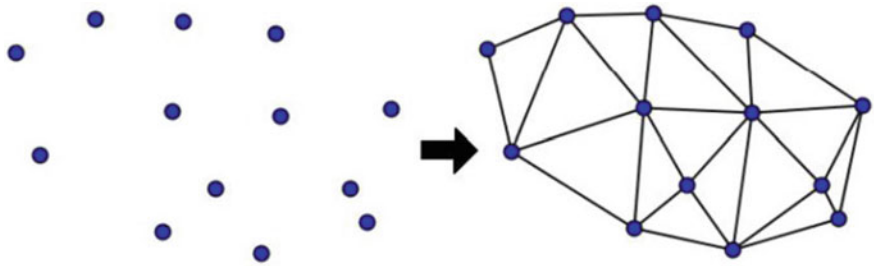


Fig. 13.5 Two-dimensional triangulation technique

13.3 3D Modeling

In this workflow step, the healthy structure of the face is digitally cropped and mirrored to fill the facial defect, this is the 3D modeling of the maxillofacial prosthesis. The modeling process, used to create devices that are attached to the patient's body, starts by scanning the anatomical region. Modeling in 3D means creating and manipulating a computer representation of an object or structure in the real world, which is virtually represented by a cloud of interconnected points, polygons or tetrahedra. When dealing with an object with dimensions, creation can be carried out virtually directly by CAD software (Fig. 13.5).

However, when the object of study has a surface with complex curves, such as the human anatomical structure, modeling becomes difficult. Thus, it is necessary to acquire the surface of this structure to represent it on a computer, as in the case of lower, upper, hip, among others, for the creation of personalized devices (Fabio 2003). Commonly, the digital model of the prosthesis to be printed is converted into a stereolithographic file (.stl file extension) which consists of important data on the surfaces of the 3D model, a 3D mesh. In the "*.stl*" model or mesh, the greater the number of triangles, the greater the resolution of the 3D printed object (Bibb et al. 2010).

13.4 Additive Manufacturing

Additive manufacturing is a production technology by successively adding material in layers through different processes. Additive manufacturing is a fast, customizable, low-cost and lightweight approach that has been used in the last years for orthotics and prosthesis fabrication (Artioli et al. 2018; Santos et al. 2018; Silva et al. 2020; Kunkel et al. 2020; Paula et al. 2021). It is a promising advancement in modern prosthetic fabrication that would alleviate several issues noted in the fabrication and use of prosthetic devices in low and middle-income countries. The long-term effects of these technologies on prosthetics need to be investigated to produce a more sustainable alternative to traditional prosthetics and enhance the field of additive manufacturing.

Table 13.1 Working principle of the main additive manufacturing processes

Process	Working principle	Advantages	Disadvantages
Stereolithography (SLA)	From light-sensitive polymers, solidification occurs after exposure to ultraviolet radiation	Excellent surface quality. Meets complex geometries. Good accuracy	Limited to light-sensitive polymers. Requires support structures. Vapors are harmful to health. Need for post-cure
Selective laser sintering (SLS)	Using a laser beam, it melts and solidifies, one layer at a time, powder-like materials such as elastomers and metals	No additional sintering and support. High range of materials. Produces metal parts without machining	High cost. Rough and porous surfaces. Lots of time and energy Castings require additional processing (leakage). Thickness distortions
Fusion deposition modeling (FDM)	By extruding polymers in a system with an extrusion nozzle that moves along the x, y and z axes	Low cost and wide range of materials. Easy operation and adjustment of the machines	Support structure. Low precision and low speed. The object supports low force in the vertical direction. Rough surface

The most innovative and simplified method in the manufacture of prostheses is the computer-aided design and manufacturing (CAD/CAM) 3D system, combined with a non-contact laser measurement system. The additive manufacturing technology can be classified by the form of the raw material used (liquid, solid and powder) or by the energy used in the processing of the layers (Volpato, 2017) (Table 13.1). The most used additive manufacturing processes in the medical field are stereolithography (SLA), selective laser sintering (SLS) and fusion deposition modeling (FDM) (Bibb et al. 2010; Kunkel and Vasques 2021) (Fig. 13.6).

Three-dimensional printing technology has gradually become an emerging and crucial adjunctive tool in the medicine area (Haleem and Javaid, 2021), including the maxillofacial prosthesis. The application of additive manufacturing in healthcare provides many benefits such as better cost-effectiveness, increased productivity, and democratization of design and manufacturing (Jin et al. 2021). There is a variety of printing materials such as polylactic acid (PLA), nylon, thermoplastic, polyvinyl alcohol (PVA) filament, acrylonitrile butadiene styrene (ABS), resin etc. These materials vary in mechanical strength, flexibility, and biocompatibility. The choice of material will also determine the amount of stress and strain that can be exerted on the prosthetics. The costs and the weight of the 3D printed prosthetics are significantly lower than in traditional prosthetics due to the type of material used and the reduction in manual labour and manufacturing costs (Ventola 2014) (Fig. 13.7).

The 3D-biomodels are indicated in cases of extensive facial mutilations, where it is not possible to perform a face impression using the traditional technique, with impression materials. Biomodels can be printed on different materials and can be

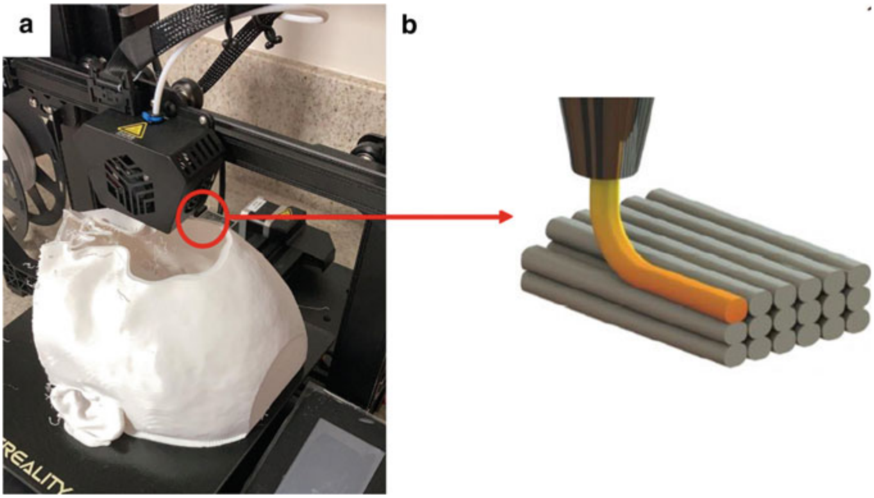


Fig. 13.6 The Fusion deposition modeling process

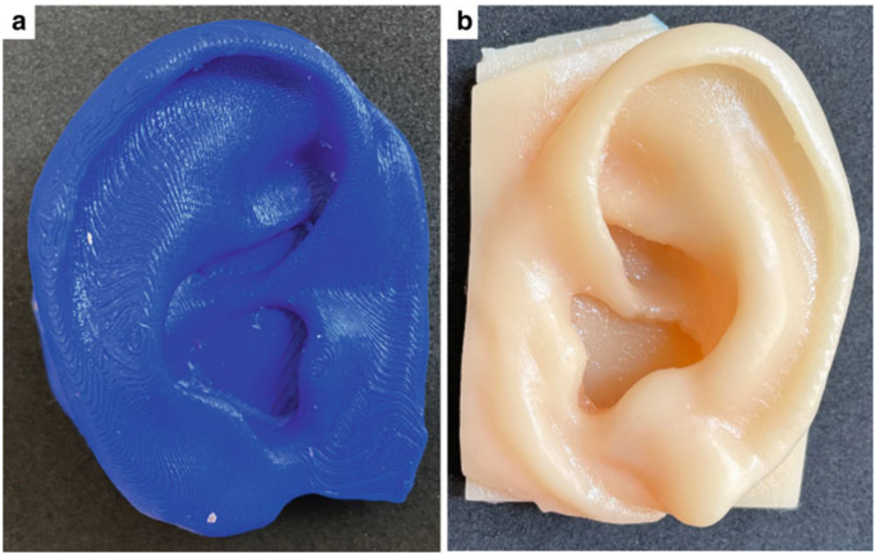


Fig. 13.7 3D printed ears manufactured by different materials and processes: **a** Polylactic acid ear manufactured by the fusion deposition modeling process and, **b** resin ear manufactured by the stereolithography process

used for studying and prosthetic planning, wax sculpting and prosthesis prototyping. A biomodel of the reconstructed digital structure of a deformed face can be obtained by Additive manufacturing, becoming a tool very useful for planning the facial prostheses and can be done in different printing materials (Figs. 13.8 and 13.9).

Additive manufacturing is an innovative technology utilized for prostheses production with the benefits of higher levels of customization and lower production costs (Ribeiro et al. 2021). However, more research and technological advancements are required to fully understand the impact of this technology on patients and how it will affect their daily life. The long-term effects of this technology should be investigated to produce a more sustainable alternative to traditional methods. Additive manufacturing is a promising advancement in modern prosthetic fabrication that alleviates several issues noted with traditional fabrication methods. The technology

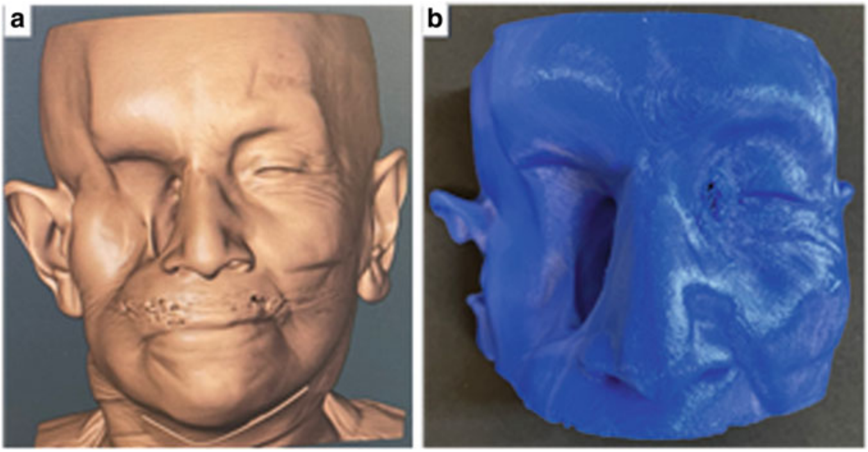
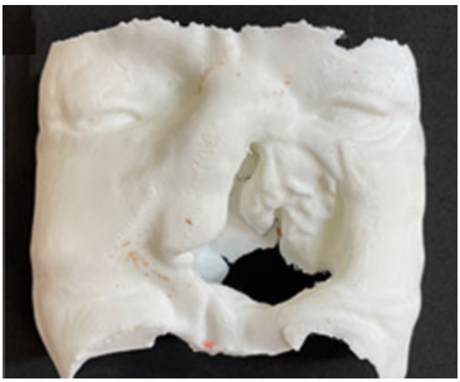


Fig. 13.8 3D face reconstruction from Multislice Computed Tomography images (**a**) and the 3D-biomodel of the face printed in polymeric mate

Fig. 13.9 3D-biomodel of the individual with an extensive face mutilation



encompasses a variety of different printing methods, using an additive manufacturing process that involves heating, excreting and fusing material layer-by-layer slowly building the object (Chimento et al. 2011).

Nowadays, there does not exist a 100% printing technology that could bring the perfect personal skin characteristics, including the many different colours, textures, wrinkles, and nuances for the maxillofacial prosthesis. In this way, the industries have been trying to bring improvements and innovations in different materials so that prostheses are more realistic. While these possibilities are not yet a financially viable option for most professionals, it is possible to have some options aimed at MP: direct printing of a part such as mirrored or virtually modeled prototyping or printing a mold.

The direct 3D printing method refers to the use of a 3D printer to print the organ model itself directly, but not always print the complete model at one time. The model can also be split into several parts for printing, and then assembled in the post-processing step. Printing a complete model at one time is the most convenient, but it has restrictions on some conditions. Indirect 3D printing method refers to the use of 3D printing to manufacture the parts for making the model, but not directly print the prosthesis model itself (Jin et al. 2021).

The indirect 3D printing methods are characterized by lower costs for 3D printers and materials, but more complex workflow and more procedures for traditional analogical methods. On the one hand, manual operation can significantly save the cost of machinery manufacturing, but on the other hand, it will increase the time cost and the error of the model, unless the operator has a high level of proficiency and skill. Generally, the indirect method is more suitable for manufacturing soft blocky structures, such as kidney and liver parenchyma. After all, making those soft materials that cannot be directly 3D printed play a role in organ models is the crucial advantage of indirect methods (Jin et al. 2021).

The directly printed prosthesis has poor mechanical properties and untested biological responses. For these reasons, the best way to fabricate facial prosthesis is to print the prosthesis mold and cure the prosthesis with silicone rubber (Bibb et al. 2010).

It is possible to fabricate soft prostheses with a low-cost desktop 3D printer. One of the methods that can be cited is the Scanning Printing Polishing Casting (SPPC), in which one, a chemical polish can be used to improve the inside of the mold and avoid the layering effect, originating from the AM process, and thus produce a prosthesis with a smoother surface. Using the SPPC method, the total cost of fabricating ear prosthesis is about $30, which is much lower than the current soft prosthesis fabrication methods, in addition to reducing working time (He et al. 2014).

13.5 Improved Construction of Facial Prosthesis by Digital Technologies

For the facial, ear, and ocular palpebral prosthesis the mirrored image is imported to the software and a virtual model of the future prosthesis is obtained for the defect side (Fig. 13.10). The superposition of anatomical structures of a donor is another possibility, mainly used in nasal prostheses. It is possible to use an image of a family member that presents the anatomical structures similar to the patient or a virtual image bank. Initially, the mirrored image is printed and then it is duplicated in wax which is fitted over the defect side. Then, it is conventionally flasked. An impression of the defect side also can be made, and the cast model is obtained in a dental flask.

The patient's skin colour can be digitized using a spectromatch skin colour system or can be checked conventionally. At room temperature, the silicone elastomer is mixed, the intrinsic pigments are added to the patient's skin colour (intrinsic colouring) and then packed into the mold. The silicone is cured conventionally. After the silicone is totally cured, the fine soft prostheses can be removed from the mold. The prosthesis is trimmed and fitted in the patient and sometimes extrinsic colouring is necessary to make the prosthesis more realistic (Figs. 13.11 and 13.12) This method eliminates the conventional laboratory steps and reduces the number of stages of the fabrication of a silicone prosthesis. The negative mold of the defect side allowed direct fabrication of the silicone prosthesis without a need for waxing or flasking procedures. Additionally, these technologies saved time and provided a

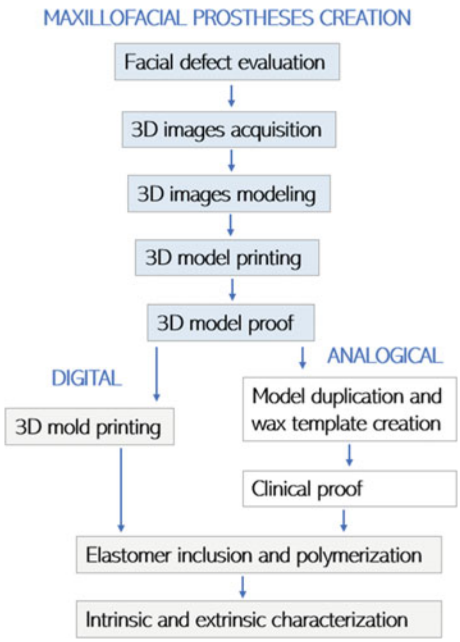


Fig. 13.10 A flowchart demonstrating the difference between the digital and traditional analogical methods

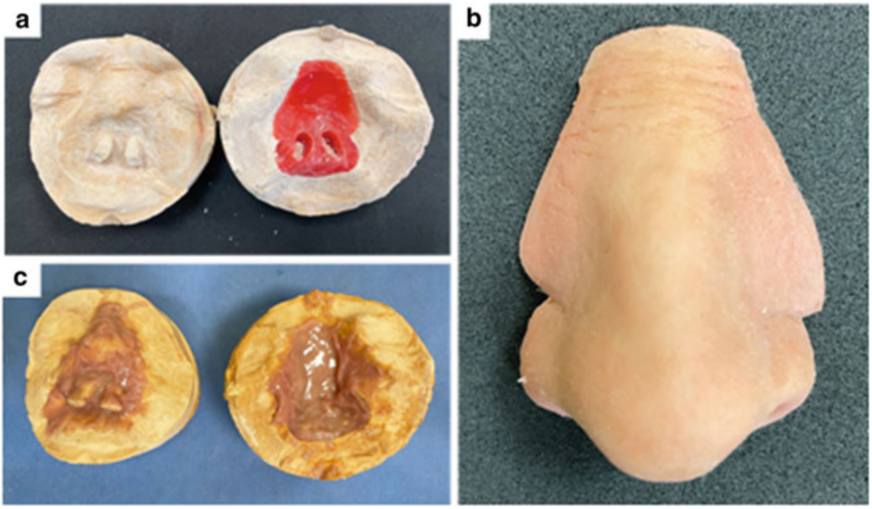


Fig. 13.11 Indirect 3D printing methods using images of a virtual bank. Mold from the final wax (**a**); elastomer with intrinsic pigmentation packed into the mold (**b**) and final prosthesis (**c**)

base for reproducible results regardless of the operator (Nuseir et al. 2015; Cevik and Kocacikli 2020).

13.6 Final Considerations

Because of the new existing technologies, it is also important to reinforce the application of AM in the construction of assistive technology, such as facial prostheses. The ease of access of this manufacturing process resulting from the cost reduction, both of equipment and inputs, associated with the dissemination of knowledge for the production of models, biomodels, prototypes, 3D molds in different materials, can allow, for example, access to low-cost, customized prostheses with a fast fabrication process.

Some studies have investigated the best form of 3D digitization of the human body for the medical field, in the development of customized prostheses (Koutny et al. 2012; Colombo et al. 2013; Ciobanu et al. 2013; Ciobanu and Rotariu 2014; Mohammed et al. 2016). Among the main disadvantages of the digital technological process in the Additive manufacturing of facial prostheses are the acquisition of equipment and supplies such as professional computers with specific configurations, different 3D printer systems, the need to acquire software that often involves costs and a learning curve. One of the biggest advantages is the possibility of visualizing the anatomical defect in different angles and planes. The level of detail of the prosthesis, quality improvement, thinning of the edges and better adaptation of the mutilated area are also considered important benefits.

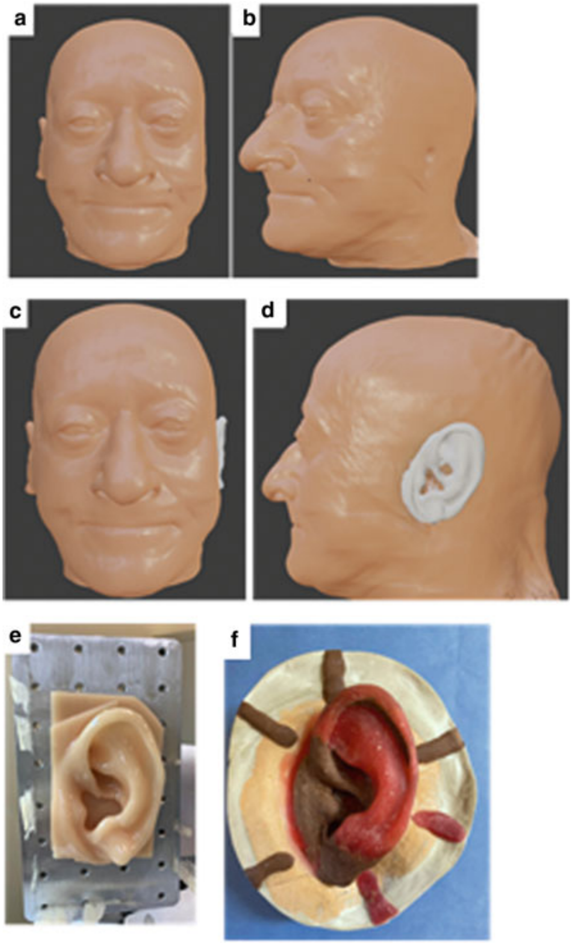


Fig. 13.12 Ear prosthesis confection through 3D mirroring. Computed tomography in a 3D reconstruction in frontal, **a** and lateral, **b** view. Ear mirroring, modeling and adaptation in frontal, **c** and lateral, **d** view. MA of the model, **e** sculpture and mold, **f** before the siliconization

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