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Rapid Prototyping Applied to Maxillofacial Surgery

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1. Introduction

What is rapid prototyping (RP)?

The word prototyping was first used in engineering to describe the act of producing a prototype, a unique product, the first product, or a reference model.

In the past, prototypes were handmade by sculpting or casting, and their fabrication demanded a long time. Any and every prototype should undergo evaluation, correction of defects and approval before the beginning of its mass or large scale production. Prototypes may also be used for specific or restricted purposes, in which case they are usually called a pre-series model.

With the development of information technology, three-dimensional models can be devised and built based on virtual prototypes. Computers can now be used to create accurately detailed projects that can be assessed from different perspectives in a process known as computer-aided design (CAD). To materialize virtual objects using CAD, a computer-aided manufactory (CAM) process has been developed. To transform a virtual file into a real object, CAM operates using a machine connected to a computer, similar to a printer or peripheral device.[13]

In 1987, Brix and Lambrecht used, for the first time, a prototype in health care. It was a three-dimensional model manufactured using a computer numerical control (CNC) device, a type of machine that was the predecessor of rapid prototyping.[6]

Some rapid prototyping machines had already been in experimental use in the 1970s, and computed tomography (CT) was invented in the 1960s by Godfrey N Hounsfield, an electronic engineer, in collaboration with Allan McLeod Cormack, a physicist. However, it was only in the 1990s that an actual three-dimensional model was built to reproduce the anatomy of a patient based on CT images obtained during that patient's examination[4], thanks to advances in CT scanner quality and the development of specific software for this purpose. In 1991, human anatomy models produced with a technology called stereolithography were first used in a maxillofacial surgery clinic in Viena.[16]

Prototyping was developed to respond to the need to test functionality, ergonomics, shape, adaptation and design in production engineering, an area in which the term prototyping is

widely known.[13] This term has been adopted by health care, although models manufactured according to CT images are not exactly prototypes, but rather replicas, because they are not created by a designer or planner, but replicated according to images scanned by, in this case, a CT unit. The model for use in health care is the materialization of a three-dimensional image provided by the CT scanner.

Fig. 1. Virtual file and corresponding prototype built using rapid prototyping.

The graph below lists some economic sectors that use rapid prototyping.
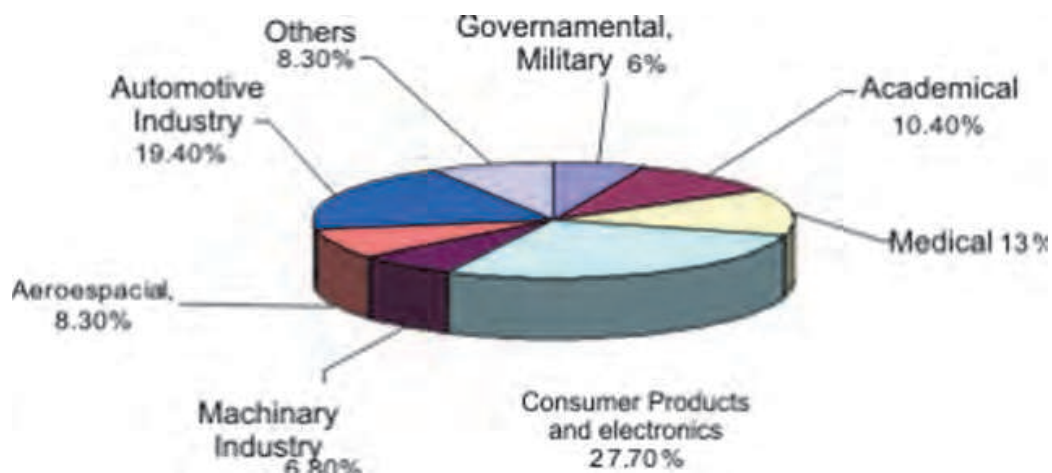
2. Prototype quality in health care

The quality of prototypes in the areas of dental and medical care has been the focus of some discussions. The accuracy assigned to prototypes is variable, and, according to the literature, prototype distortion reaches 0.6% when compared with CT scans.[19]

To understand the several factors that affect the quality of a prototype used in healthcare, it is important to understand how the anatomic model to be reproduced is created.

Quality and final precision of a prototype to be used in health care depend on four factors, summarized in the four steps below:

- Patient preparation
- CT scanning
- Image manipulation
- Prototyping technology

2.1 Patient preparation

To obtain good quality images, the patient should be evaluated, receive the necessary information and be prepared before undergoing CT scanning. These procedures should

minimize the harmful effects of artifacts on CT images and ensure accurate image reproduction when the prototype is manufactured. The critical area of facial CT scanning is tooth occlusion, or the area of contact between mandibular and maxillary teeth when the mouth closes. Therefore, the crowns, restorations and metal cores should be removed before scanning. The mouth should be kept open during scanning to avoid that artifacts produce fusion between maxillary and mandibular teeth; if there is fusion, the jaws will not separate after the model is complete.

In cases CT scanning is planned to occur after orthodontic appliance placement, the orthodontist should choose brackets without nickel or ceramic brackets, because they produce fewer artifacts.

Ct scanning can produce very relevant additional information when radiopaque markers are used, but they should be carefully manufactured and fixed to be faithfully reproduced. Figure 2 shows a prosthesis with duplicate teeth and a radiopaque marker (barium sulfate). The model was built to establish the tooth-bone relation; however, the prosthesis, which should be over the alveolar ridge, was displaced from the desired position. Image reconstruction revealed that the undesired displacement resulted form the improper use of a luer syringe plunger to keep the mouth open. This example stresses the importance of the information that should be given to the patient. CT scanning had to be repeated and the patient was exposed to another radiation dose.
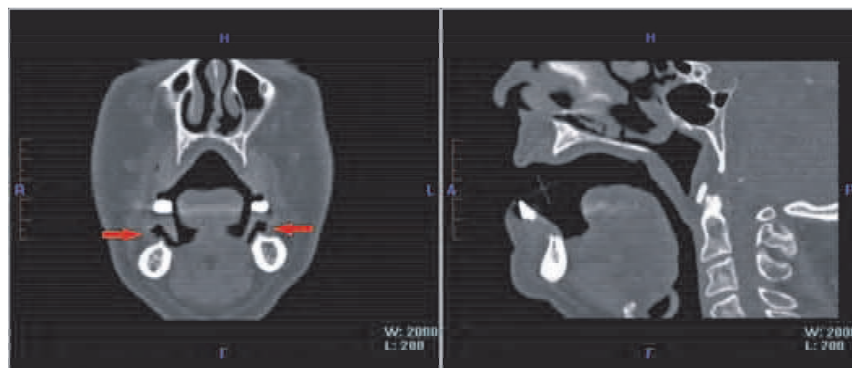

Fig. 2. Arrows indicate prosthesis displacement on both sides due to improper advice to bite on a syringe plunger to keep mouth open during CT scanning of mandible.
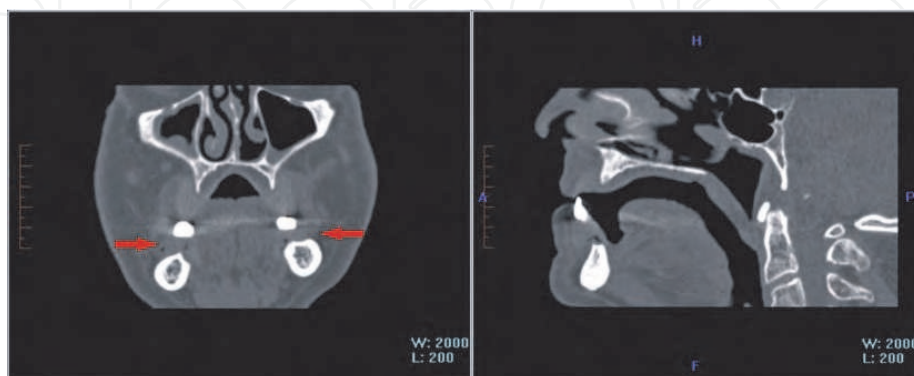

Fig. 3. Arrows point to correction of position of prosthesis in Figure 2 in patient's second CT scanning. Models produced from these images reproduced a perfect bone-teeth relation and ensured correct implant placement.

While radiographic contrast media are often used to examine the vascular and digestive systems in Medicine, in Dentistry radiopaque markers are frequently used to reproduce missing teeth and guide the surgeon during planning procedures that involve bones. To reproduce missing teeth on CT images, several radiopaque markers can be used, such as metal balls, gutta-percha points, metal rings, stored teeth, or a mixture of autopolymerizing acrylic resin and barium sulfate.

Fig. 4. Image of a maxillary total prosthesis with teeth duplicated in radiopaque material to determine tooth-bone relation and define most adequate points to insert implants.

2.2 Computed tomography (CT)

Of the advances in CT equipment, two deserve special attention due to their importance in the production of models to be used in health care: the reduction in CT slice capture time, which results in faster and more accurate evaluations and avoids distortions in three-dimensional image reconstruction; and image manipulation, which significantly improves its high-definition quality.

The principle of CT image production, similarly to conventional radiology, is the partial absorption of X-rays by the human body. While fat and air, for example, are easily passed through, bone and metal are not.

Basically, a CT scan indicates the amount of radiation attenuated at each portion of the section under analysis and translates variations into a grey scale that produces an image.

As a tissue's capacity to absorb X-rays is closely associated with its density, zones with different densities will have different colors, which will enable their differentiation.

Each image pixel corresponds to the mean attenuation of tissues in a certain zone, and attenuation is expressed in Hounsfield units in honor of the creator of the first CT machine.

- Hounsfield scale (HU)
- water: zero HU
- air: -1000 HU
- bone: 300 to 350 HU
- fat: -120 to -80 HU
- muscle: 50 to 55 HU

For CT scanning, the patient is placed on a table that moves into an aperture of about 70 cm in diameter. Around this aperture there is an X-ray tube in a circular gantry. At 180 degrees,

that is, opposite the X-ray tube, there is an X-ray detector that captures radiation and sends information to the computer to which it is connected.

2.2.1 Terms
Images are stored in Digital **I**maging and **C**ommunications in Medicine (DICOM) files.
Threshold – selection of density according to anatomic structure of interest;
Matrix size – number of lines and columns that form CT images, usually 512 x 512;
FOV – field of view, or area captured during scanning;
Shades of gray:
- 8-bit scanner - 2^8 = 256 shades of gray
- 12-bit scanner - 2^{12} = 4,096 shades of gray
- 16-bit scanner - 2^{16} = 65,536 shades of gray
- Human eye – detects about 10 to 60 shades of gray.

2.2.2 Types of CT scanners
Conventional: during examination using conventional machines, the gantry moves a full rotation around the patient, and the X-ray tube emits radiation that, after passing through the patient's body, is captured in the opposite side by the X-ray detector. Data are then processed in a computer, which analyzes the attenuation variations along the section under examination; these data are used to reconstruct an image as a shape. The table moves a little further then, and the process is repeated for a new image a few centimeters from the first site.

Helical, Multislice, Ultrafast: more recent machines, called helical CT scanners, move as a helix around the body of the patient instead of in full circles. Therefore, if the slice is to be 10 cm thick, the gantry will advance 10 cm during each gantry rotation. Intermediate slices at, for example, each 2 cm may be obtained simply by digital reconstruction because the area under examination was scanned during one helical movement. Therefore, the patient receives lower radiation doses during scanning. Multislice units scan multiple simultaneous slices during each gantry rotation because they have several radiation emission and reception units. Ultrafast machines are used in CT scanning of the heart because they can produce slices at 50 to 100 millisecond intervals.
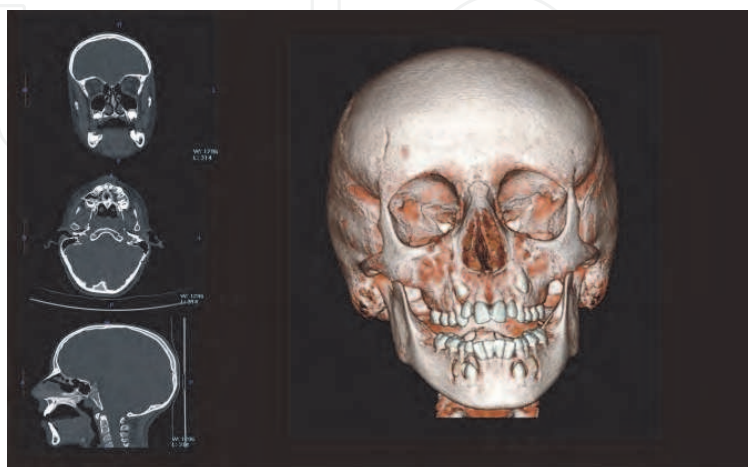

Fig. 5. Three-dimensional image formatted according to scan obtained using a multislice unit.

Cone-Beam CT: Cone-beam CT scanners do not build images slice by slice. Instead, they capture all the area to be examined with a few exposures, and image formatting and slicing is performed by software developed for this specific purpose. This type of CT unit has the advantage of exposing the patient to a lower radiation dose than the other scanners. However, due to the lower number of exposures, the most peripheral areas of the image are much sharper, whereas the most central fields, which receive a lower radiation dose, lose part of their sharpness. Because of that, the radiologist should receive information about the region of interest, so that the center point or fulcrum of acquisition does not overlap with structures of interest in this region. Currently, three brands of cone-beam CT scanners for dentistry are available in the market: *NewTom*, *Accuitomo* and *I-Cat*.
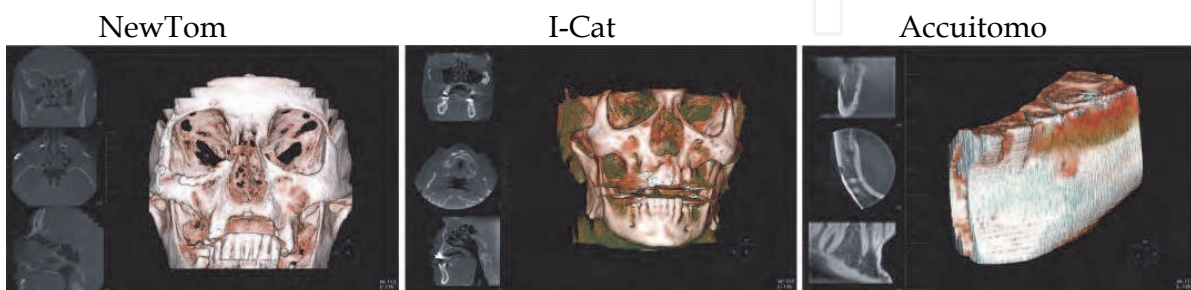
NewTom   I-Cat   Accuitomo

Fig. 6. Images captured with the three types of cone-beam CT scanners available in the market.

2.3 Image manipulation

Images captured in the DICOM format are processed using specific three-dimensional reconstruction software. Good-quality software provides several auxiliary tools to process images and convert them to STL format, which is the standard file format used by prototyping machines. A 3D STL file consists of a mesh of triangles, and the greater the number of triangles used in producing the image, the better the definition, precision and fidelity in the reproduction of anatomic details of the area of interest.[24]
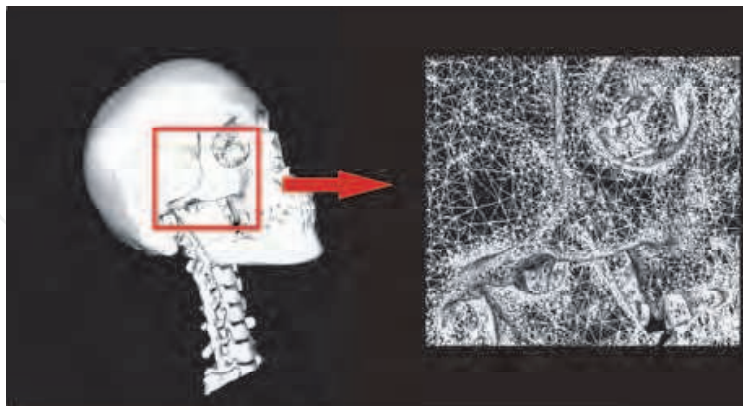

Fig. 7. On the left, 3D reconstruction. On the right, example of triangle mesh in a STL file.

The quality of a STL file depends on the software used for the conversion of CT images into a three-dimensional format. After the STL file is prepared, the prototyping technology that will be used to convert it into a model should be chosen. Images will then be sliced at thicknesses compatible with the technology chosen and sent to the prototyping unit to build

the model. Therefore, the same STL file may generate prototypes with great differences in quality and accuracy because these features depend on the technology chosen.

Images should be manipulated by specialized personnel to avoid distortions that may affect the accurate reproduction of anatomy. The threshold should also be carefully chosen, because differences may result in more or less bone being detected and may compromise the quality of the prototype.

The region of interest for the surgeon should be made very clear so that it is fully scanned during CT to produce images that will later be used to fabricate the prototype. The CT scan shown on the right in Figure 8 was captured using a large FOV that included the whole face. The region of interest, however, was only the maxilla, and only part of the image would be used. The correct procedure in this case would be the restriction of FOV to the maxilla because the whole scanned image would then be used, and the resulting quality would be substantially better.
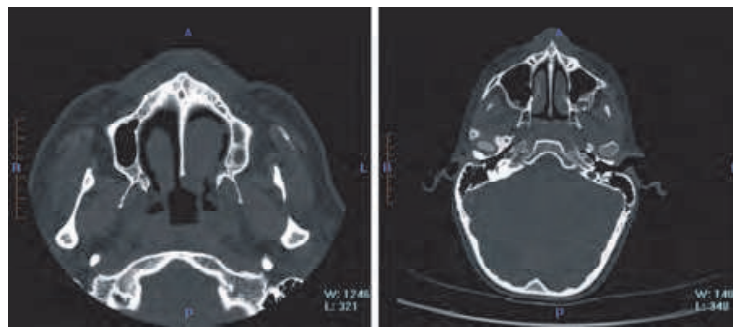

Fig. 8. On the left, CT scan in which FOV was restricted to the maxilla, which produced a more detailed image. On the right, FOV included a large area and reduced details of the maxillary area, the area of interest in this case.

Spatial Relation Retainers (SRR), which may be ordered from the prototyping laboratory, are very useful aids in establishing the tooth-alveolar bone relation. They preserve the position of the teeth used as radiopaque markers in relation to bone structures by means of retainers created virtually and reproduced together with the prototype. The patient's prosthesis is placed over this model to reproduce the thickness of the mucosa. SRR may also be used to retain the spatial relation of bone fragments in complex fractures.
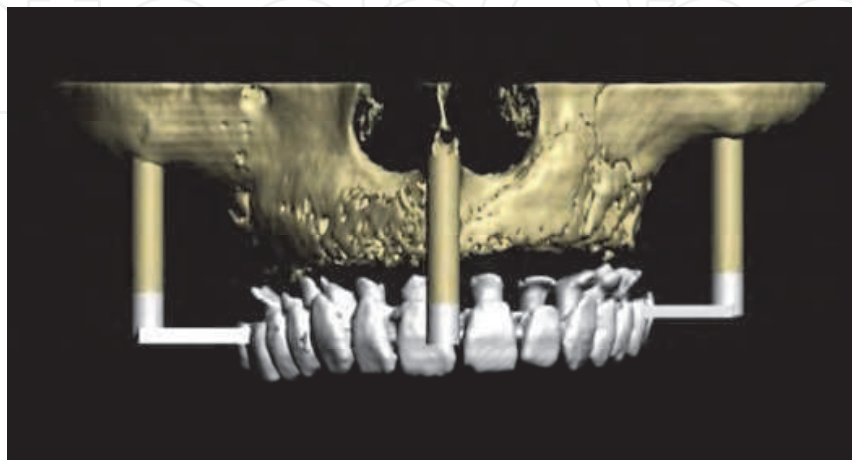

Fig. 9. Spatial relation retainers (SRR)

The first software developed to establish the interaction between CT and RP was Mimics, produced by the Belgian company Materialise. Several other packages have been developed since then, each one with advantages as well as limitations. Currently, some software packages allow surgeons to interact and perform virtual planning, which can then be saved directly in a STL file.

2.4 Rapid prototyping technology

Todd Grim seems to have found the best definition of rapid prototyping. According to him, rapid prototyping may be understood as "a collection of technologies that are driven by CAD data to produce physical models and parts through an additive process".[4,13] Based on this concept, all rapid prototype technologies create their three-dimensional models by means of addition of layers of a material that will fuse to give shape to the object previously planned. The main technologies currently available in the market are:

2.4.1 Stereolithography (STL)

Stereolithography (STL) is the oldest and most important rapid prototyping technology and the one best known all over the world. The term STL is sometimes mistakenly used interchangeably with "rapid prototyping". STL uses a wide range of different materials and may be used for several types of production.

In its process, a liquid resin (acrylic, epoxy or vinyl) is photosensitized using an ultraviolet (UV) laser beam. The STL unit has a vat that is filled with resin and a platform inside it that moves downwards. The computer sends information to the platform about each layer of the virtual model to be polymerized. Machine number control positions the platform on the surface of the layer of resin, and the laser beam literally draws the first layer. After the completion of each layer, the platform moves downward and dips the previously solidified layer into the liquid resin so that a new layer can be polymerized and stacked on the top of the previous layer, and successively so until all the model is complete. At the end of the process, the model will be immersed in resin and should, therefore, be rinsed in an isopropyl alcohol bath to remove all the non-polymerized material.[13]

The thickness of the layers that generate prototypes using STL is 0.025 mm, which results in a surface of good quality.

2.4.2 Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) is based on the superposition, on a platform, of successive layers formed by the deposition of filaments of a plastic material for the production of the model. At the same time, two types of material are deposited: a plastic material used in building the body of the object, and a brittle material that fills ups empty spaces and gives support to the object. Later, this brittle material is removed to obtain a clean prototype.

The material used for the model is ABS, and the material used for the support structures is a mixture of ABS and lime. The FDM machine has a platform that moves vertically along the Z axis and a head with two extrusion tips that extrude heated filaments of build material: one to feed the model layers and the other to deposit the layers of support structures. For each layer, coordinates, or "roads" are generated along which the extrusion tip deposits the molten filament material. At the end of each layer, the platform moves down and the head begins the deposition of more material for the other layer, repeating the operation until the model is complete.[13]

The thickness of the layers that generate FDM prototypes is 0.178 mm, which generates a rough surface of poor quality. As the model is made of a plastic material, it cannot be cut because melted plastic will stick to the tool.

2.4.3 3D printing

Three-dimensional (3D) printing is a technology that is similar to inkjet printing in computers. However, instead of ink, the heads spread a binder composed of an aqueous solution and a glue. The machine has a reservoir for one type of powder, which may contain mixtures of material, such as plaster and starch, a platform that moves horizontally and down while the powder solidifies, a roller to distribute and evenly spread the powder to the fused, and a print head that is filled with the binder.

The building process is described below: the roller moves over the build tray and evenly spreads a uniform layer of powder that resembles a rug; the print head moves in the X and Y axes and releases a jet of binder onto the powder; and the binder fuses the powder; the platform then moves down and another layer of powder is deposited and receives a binder jet. This second layer binds and adheres to the previous layer, and the process is repeated.

When completed, the remaining loose powder is aspirated from the surface of the model. This process does not confer great resistance to the model. Therefore, after completion, the models have to receive infiltrating materials to improve their resistance. This finishing process may change some anatomic details in the prototype surface.[13]

The thickness of the layers generated by powder binding is 0.1 mm, which gives the prototype a slightly irregular surface, low resistance and low accuracy due to the nature of the material used in its fabrication.

2.4.4 Inkjet – PolyJet

Launched by the Objet company in 1999 and introduced in Brazil in 2004 by the ARTIS Prototyping Company, the major characteristic of this technology is the construction of highly-accurate prototypes using liquid acrylic resin.

The production begins with the deposition of successive layers of acrylic resin that are stacked up to create the prototypes.

During production, two types of material are used: acrylic resin, which will form the body of the object, and a gelatinous material to fill empty spaces during production and serve as a support structure for the prototype. The gelatinous material is easily removed later using a jet of water.

The thickness of build layers in this technology is 0.016 mm, which ensures excellent surface finish and the reproduction of small details.

In health care, a translucent amber resin is used to provide visualization of canals, ducts and sinuses. The model can be cut and fixed with screws because its resistance is similar to that of bone.

2.4.5 Selective laser sintering

Selective laser sintering (SLS) is a versatile technology that can be used to build prototypes with several materials, such as nylon, metal, elastomers and plastic.

This technology uses a laser beam that fuses powder particles of the material to be used. After a layer is laser-sintered, a new powder layer is added to continue the production of the prototype.

The thickness of the layers in this technology is 0.1 mm, and the objects have a slightly irregular, highly porous surface.[13] Because of the large variety of materials used, it is well known in engineering, although its cost is high.[13]

2.4.6 Comparison of layer thickness using rapid prototyping technology

Figure 10 shows a comparison between the number of layers to build a section measuring 1 mm high and 1 mm thick using the different rapid prototyping technologies. Each technology has a minimum material deposition thickness to form a build layer. The thinner this layer, the better the surface finishing and the smoother the prototype surface.

Technology 1mm	FDM	3D Print	SLS	SLA	PolyJet
Number of slices to complete 1 mm	6 slices of 0,178 mm	10 slices of 0,1 mm	10 slices of 0,1 mm	40 slices of 0,025 mm	62 slices of 0,016 mm

2.4.7 Adequate prototyping technology

The choice of an adequate prototyping technology is fundamental for the final quality of a prototype because, as seen before, each technology uses different types of material and has different characteristics.

In some cases, prototype translucency may be important for the evaluation of drill direction and depth. In other situations, it might be more important to have an opaque material to evaluate asymmetries, for example. Still in other cases, the specialist may choose a technology that uses more resistant material, such as nylon, to reproduce fine, delicate structures, although it is difficult to work with drills in this material because friction and heat may melt it and block the advancement of the drill. There are also wax models, cast models, or even models made directly using metal.

The choice, therefore, depends on the purpose of the prototype. The characteristics of the several technologies, described in Table 1, should, therefore, be well known to make the right choice.

	FDM	3D Printing	SLS	STL	PolyJet
Translucency	No	No	No	Yes	**Yes**
Resistance	High	Low	High	High	**High**
Precision	Low	Low	High	High	**High**
Material	**Plastic**	**Plaster**	**Nylon**	**Resin**	**Resin**

Table 1. Characteristics of the prototypes built using the major rapid prototyping technologies

These characteristics should be analyzed also according to prototype application so that the results of their use are satisfactory.

	Graft planning	Implant planning	Surgery simulation	Guide fabrication	Visual assessment
Translucency	No	Yes	Yes	Yes	**No**
Resistance	Low	High	High	High	**Low**
Precision	Low	High	High	High	**Low**
Material	**Resin, plaster, plastic, nylon**	**Resin**	**Resin**	**Resin**	**Resin, plaster, plastic, nylon**

Table 2. Necessary characteristics of prototypes according to their clinical use

Previous studies about CT quality indicated that a good CT examination currently provides axial images with a thickness of about 1 mm and distance between slices never greater than 1 mm. Therefore, RP technologies have greater precision than current CT scanners. In the case of PolyJet, each build layer is about 62 times thinner than the thickness of a good quality CT slice.

3. Rapid prototyping protocol in health care

The quality of a prototype depends, first, on the quality of the images, as in the case of a digital camera.
The good quality of a 3D reconstruction depends on the use of all the axial sequential slices, because reconstruction is produced by stacking up the different axial slices. For example: a scan with 200 1-mm thick slices will produce a 3D image of 200 mm, or 20 cm.
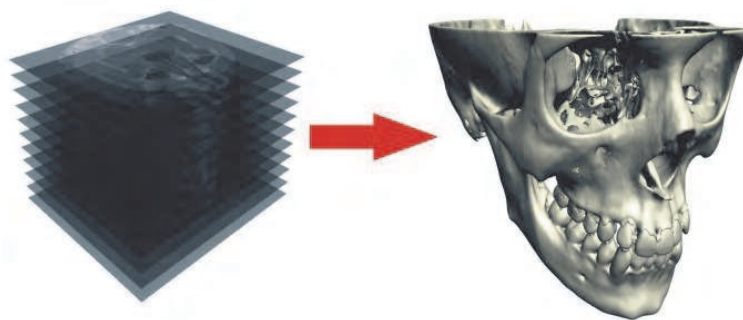

Fig. 11. Principle of superposition of axial CT slices to create a three-dimensional model.
The region of interest and its boundaries should be clearly stated in writing in the exam request, together with the observation that the protocol should be followed.
The protocol to guide radiologist to acquire good-resolution CT scans is:[29]
- CT scanning should acquire axial slices 1 mm thick or thinner;
- CT scanning should keep a distance of 1 mm or less between slices;
- Gantry should not be tilted (gantry tilt = 0);
- Only the sequence of 2D axial images in DICOM format should be recorded in the CD;
- FOV should be limited, but all the region of interest described in the request should be included;
- When the region of interest is the face, the patient's mouth should be kept open during CT scanning to ensure the separation between mandible and maxilla;

- Voxel ratio should be 1:1 (pitch = 1:1);
- The window should be standard, in the original format of the CT scanner.
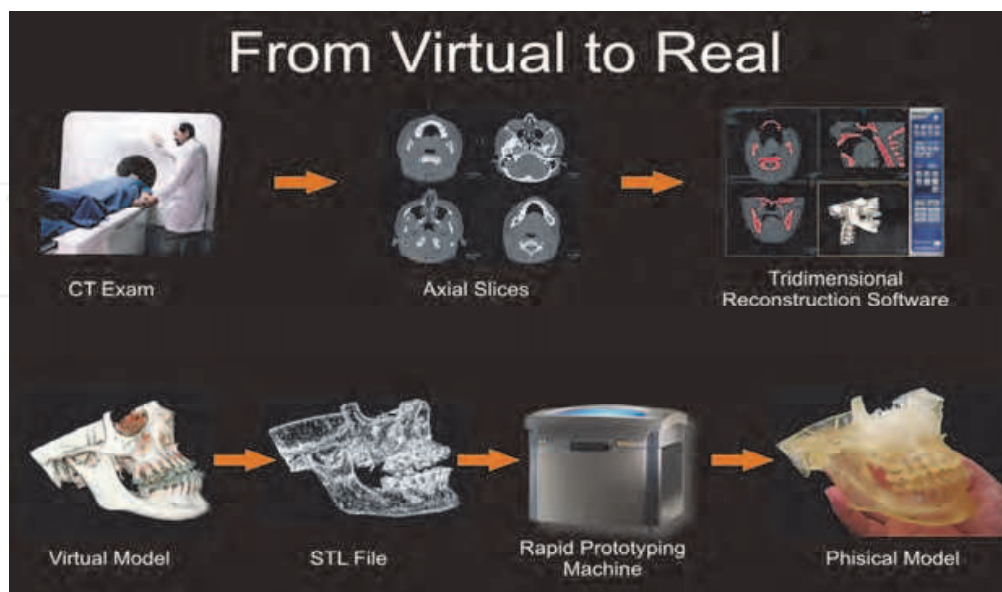

Fig. 12. Step by step sequence to fabricate a prototype of a human anatomic structure
* Attention: to fabricate the prototype, images should be stored in DICOM format and recorded in a CD-ROM or sent via the Internet to the prototyping bureau; the CT scan films are not necessary.

4. Uses of prototypes in health care

In December 1998, the Phidias Project was established in the European Community to explore and evaluate the applications of rapid prototyping in medical and dental care. The project brought together over 40 health care organizations in 11 EU countries and lasted four years. It included 253 surgeries that used prototypes in several specialties.[31]

This Project findings showed that most prototypes were used in implant surgery planning (29%), tumor evaluation (22%), trauma treatment (17%), and treatment of congenital anomalies, in 13% of the cases.[31]

Some results of the Phidias Project are analyzed in the tables below:

Indications for medical model

Diagnosis	n	Percentage (%)
Tumor	56	22
Trauma:	43	17
Congenital anomalies	32	13
Orthognathic surgery	18	7
Skull/implant	15	6
Tooth implant	74	29
Orthopedic surgery	11	4
Other diagnoses	4	2
TOTAL	253	100

Table 3. Phidias Project data about indication of prototypes in health care

Reasons to use model in planning

Increase diagnostic quality	109
Produce preoperative guide implant	108
Plan surgery	183
Prepare resection guide	31
Obtain patient approval	99
Use as guide during intervention	123
Simulate intervention preoperatively	105
Other reasons	36

Table 4. Phidias Project data about reasons to use prototype during surgery planning.

How preoperative planning affected the intervention

Planning skin incision	34
Whether to operate or not	66
The general surgical concept	131
Details of surgical concept	167
Composition of surgical team	77
Positioning patient on surgical table	22
Selection of material for osteosynthesis	94
Selection of instruments and resources	115
Site of osteosynthesis material implant	108
Sequence of intervention	121

Table 5. Phidias Project data according to effect of rapid prototyping on planning

How model planning
affected the result of surgery in comparison with other imaging modalities

	Little	Somewhat	Very much
Precision and quality of bone transplant	1	4	35
Precision and quality of osteotomy	3	2	94
Communication with other health workers	8	11	134
Communication with patient	17	6	164
"Confidence" during intervention	17	19	156

Table 6. Phidias Project data according to comparisons between rapid prototyping and other diagnostic imaging modalities.

There are several applications for 3D models, and new purposes constantly arise in different areas of health care. The use of prototypes in immediate trauma is not common, but it is rather frequent in trauma sequelae. Prototypes are very useful in planning surgeries[8] for facial reconstruction and are essential to reestablish symmetry for the patient.[6]

Models can be used for rehearsal and more accurate planning and bring reductions in surgical time.[6,8,23] When surgery is performed in a hospital, time reduction implies lower costs with anesthesia and hospitalization because the patient is usually discharged earlier than expected.[14]

Prototypes can and should be used in several situations, such as:
-    Evaluation of asymmetrical features

- Reconstruction of symmetrical structures using mirroring
- Fracture assessment
- Modeling rigid internal fixation plates and screw selection
- Modeling osteogenic distractors
- Calculation and adaptation of bone grafts
- Tumor assessment
- Fabrication of surgical guides

4.1 Evaluation of asymmetries

The use of prototypes provides the exact degree of asymmetry and defines the skeletal contribution to deformities. Models provide accurate measures that facilitate planning and performance of corrective surgeries.[6,8,23] A complete face model provides access to all the patient's anatomic structures bilaterally and defines what symmetry relations have to be restored. During surgery it is practically impossible to accurately establish the asymmetrical relations because only one side is exposed.

4.2 Reconstruction of symmetry using mirroring

When trauma or asymmetry is limited to one of the sides of the face and does not go beyond the middle line, what is necessary to reestablish symmetry with the unaffected side can be evaluated.

Three-dimensional software resources may be used to mirror the unaffected hemifacial structure and the superposition of this structure over the affected side. This procedure provides information to perform a Boolean process, the subtraction of the affected structure, leaving only what would be necessary to reconstruct it. In cases of bone loss, the volume and outline of the missing area can be reproduced accurately using data from the opposite side. The same process may be used in reverse to define how much should be removed in cases of unilateral bone excess.

This virtual mathematical process opens several possibilities: the prototype may be produced only for the area that needs reconstruction (result of the Boolean process) and then this specimen can be duplicated in biocompatible material and implanted in the patient. Also, the prototype of the reconstruction site, together with the affected anatomic structure, may be used to determine the best site for plates and fixation screws, or they may suggest not to use any of these, but, rather, to use a negative structure (impression) virtually created over the structure for reconstruction, thus producing a prototype that would be a cast for the reconstruction site.[6]

This process is not limited to bone, and may be used even for the reconstruction of soft tissues, such as in the cases an ear is lost, in which the ear in the opposite side would be mirrored to reproduce the missing ear.

When loss affects the middle region, a CT database of other patients may be used to search for a similar bone fragment to reconstruct the missing anatomic structure virtually or to use CAD software and literally redesign the region.

4.3 Fracture assessment

To interpret fractures using radiographs has always been a problem in maxillofacial surgery. No matter how skilled the surgeon, the radiologist, or both, difficulties arise due to the superposition of images of different anatomic structures. CT has reduced this

problem, but has not eliminated it. Anatomic image slicing has provided a more complete evaluation and reduced interferences, but the real dimension of the injury still depends on the imagination and experience of the surgeon despite the latest resources. Virtual 3D reconstructions on the computer screen, for example, are not palpable, and, no matter how real they seem to the observer's eyes, they are always, after all, flat images displayed on a screen or printed on paper.[19]
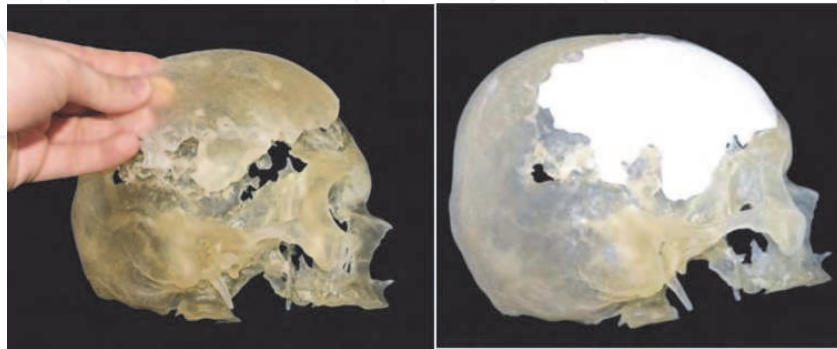

Fig. 13. Reconstruction of skull anatomy using mirroring. The prototype of the area to be reconstructed was built in duplicate in surgical acrylic to be implanted in the patient.

This problem has been finally solved with the advent of prototypes, which enlarge the capacity of the surgeon to understand the real extension of injuries, as if handling the fragments in an open surgical field.[16]
Surgical planning became simple because these new technologies determine the most appropriate point for access, plate casting and screw size.[16] Moreover, prototypes can be used for a more detailed case documentation and to facilitate communication with the patient, who can visualize and better understand the extension of the problem.
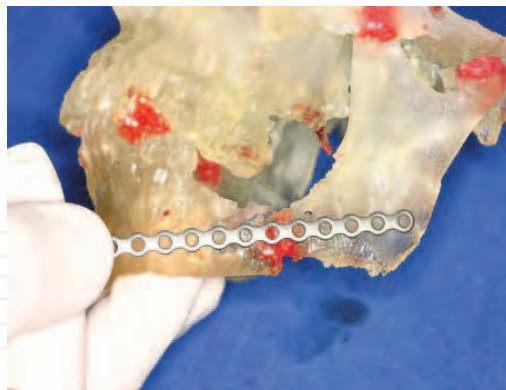
Fig. 14. Preoperative reconstruction plate preparation according to prototype

4.4 Modeling rigid internal fixation plates and screw selection
Reconstruction plate preparation for operations reduces surgical time dramatically. As seen before, the plate can be modeled previously, be used as a surgical guide, and ensure an accurate and efficient adaptation.[17] Patients that undergo partial resection of the mandible have major displacements of the bone stumps due to the traction of the masticatory muscles. In such cases, prototypes can be used to reposition the displaced fragments and move the condyles and the middle line back to their previous positions.

The previous selection of mini-plates and screws has several advantages in orthognathic surgeries. Surgical simulations using plate models and the calculation of screw size, as well as the choice of the best place for their fixation, greatly reduce surgical time.[16,17] However, the most important factor is accurate planning, and modeled plates will serve as guides to reposition bone segments.
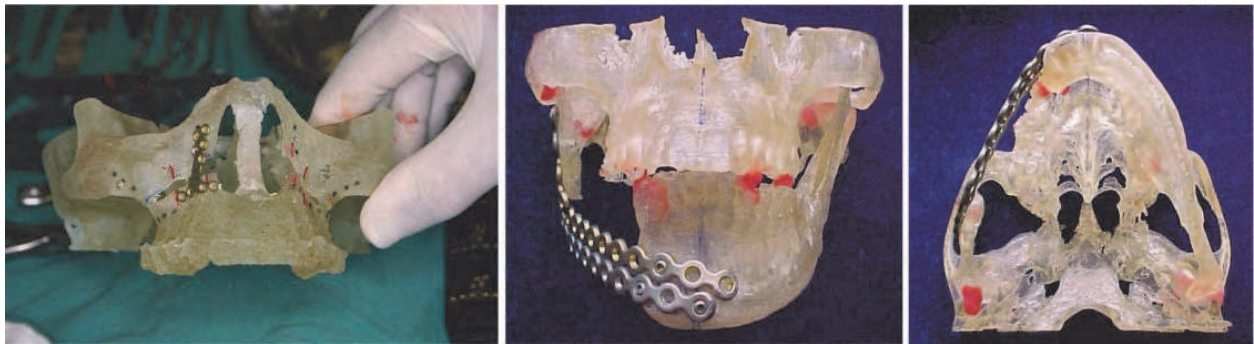

Fig. 15. Modeling rigid internal fixation plates for orthognathic surgery (left) and fabrication of double personalized mandible reconstruction plate by soldering (center and right).

4.5 Modeling osteogenic distractors

Modeling osteogenic distractors directly on the bone at the time of surgery poses a great problem due to the difficulty in evaluating distractor vector, because the distal fragment cannot be moved far enough to evaluate its direction. Prototypes not only predict distraction direction, but also evaluate all the process. All patient movements can be assessed until the final fragment position is reached.[12] Planning the path that the fragment will follow may indicate possible complications, such as limitations in distractor excursion in convergent osteotomies.

Fig. 16. Modeling and evaluation of distraction vector in a case of osteogenic distraction.

4.6 Calculation and adaptation of bone grafts

Prototypes are equally important in planning bone graft reposition, either to repair loss or correct a defect. Graft size and shape are calculated by sculpting the graft, adapting it to the previously sterilized model, and taking it to the surgical field.[11] This calculation is easily made when any modeling material is used, such as wax and acrylic resin. The volume guides the surgeon to decide about the amount of bone that should be removed from the donor site or selected from bone segments obtained from bone banks.
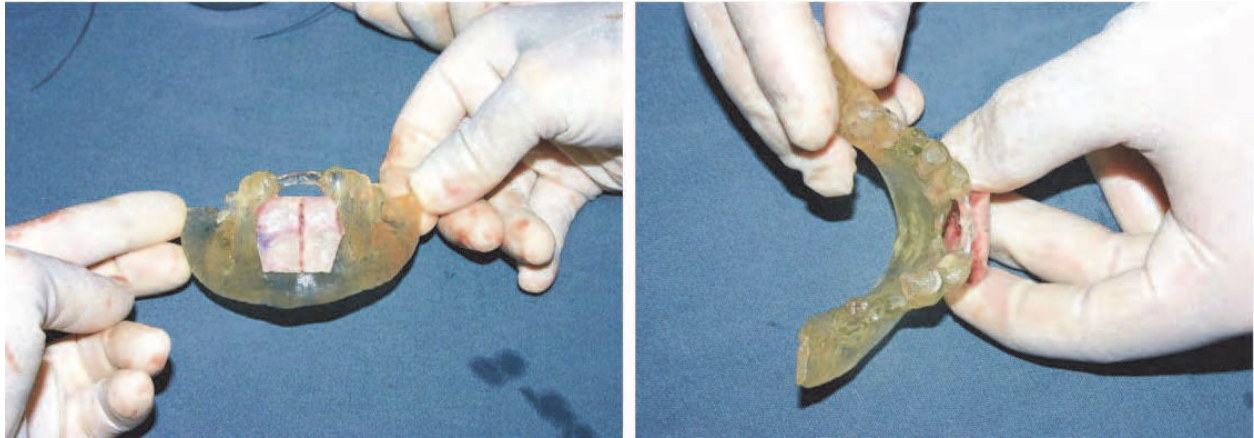
Fig. 17. Adaptation of bone graft on the prototype.

4.7 Tumor assessment

The assessment of tumors by using radiographs may not answer questions about the real extension of the lesion. In addition to providing a more careful evaluation of extension, prototyping also facilitates the conversation with the patient about the real situation and severity of the case, and serves, therefore, not only as a diagnostic instrument, but also as a valuable tool for the communication between the specialist and the patient.[9,14,17,23]

Prototypes also enable previous planning and rehearsing, which ensures the detailed analysis of each case.[8,17]

Figure 18 shows a mandibular keratocyst extending from the ascending ramus to the apex of the first premolar. The prototype played an extremely important role in explaining the need for a surgery to the patient, and was also used to calculate the amount of PRP necessary to fill the bone defect completely.

Fig. 18. Prototype of a mandible segment demonstrates odontogenic keratocyst.

The large ameloblastoma seen in the figure 19 had compromised all right mandibular body, the ascending ramus and coronoide process. Only the rapid prototyping is able to reproduce the reality with such accuracy.
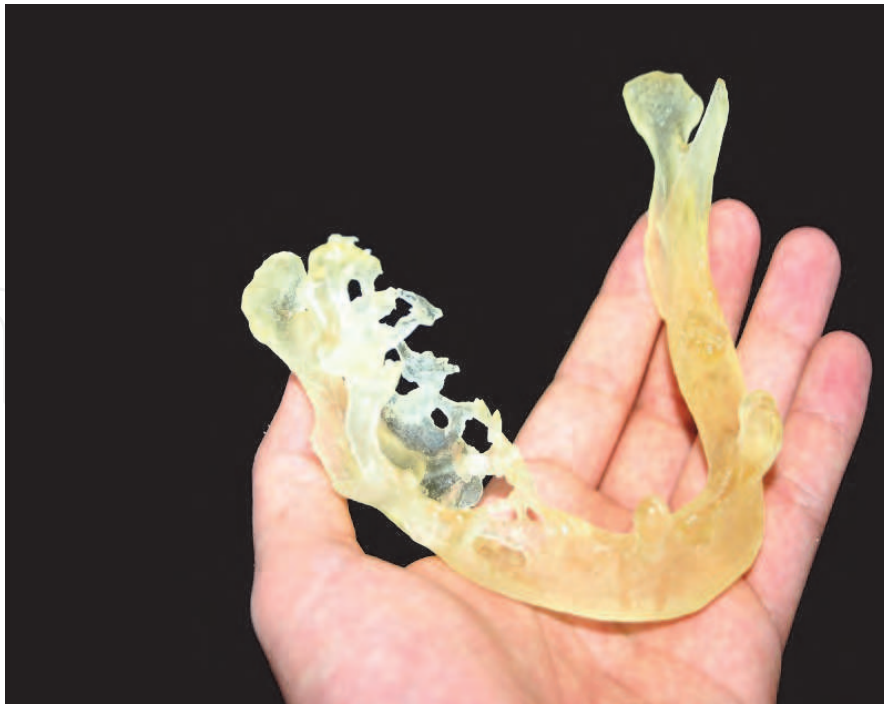
Fig. 19. Evaluation of a multilocular ameloblastoma of mandible.

4.8 The creation of surgical guides

The prototype offers a unique opportunity to work and the cost-benefit becomes positive only when using this feature for something beyond mere illustration[19].

The production of surgical guides, which are common in implants can also be of great valuable in Maxillofacial Surgery.

The possibility of the producing a guide that can be taken to the surgical field and adapted on the patient's bone to guide various types of procedures, can significantly expedite a surgery and it can increase its probability of success[23].

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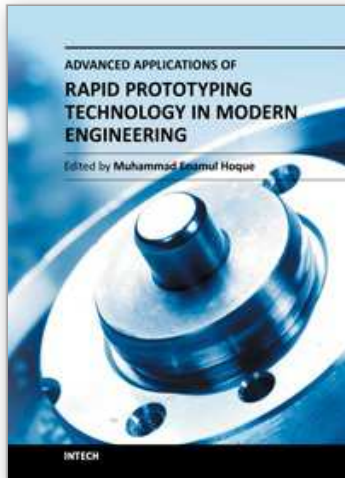
Advanced Applications of Rapid Prototyping Technology in Modern Engineering

Edited by Dr. M. Hoque

Rapid prototyping (RP) technology has been widely known and appreciated due to its flexible and customized manufacturing capabilities. The widely studied RP techniques include stereolithography apparatus (SLA), selective laser sintering (SLS), three-dimensional printing (3DP), fused deposition modeling (FDM), 3D plotting, solid ground curing (SGC), multiphase jet solidification (MJS), laminated object manufacturing (LOM). Different techniques are associated with different materials and/or processing principles and thus are devoted to specific applications. RP technology has no longer been only for prototype building rather has been extended for real industrial manufacturing solutions. Today, the RP technology has contributed to almost all engineering areas that include mechanical, materials, industrial, aerospace, electrical and most recently biomedical engineering. This book aims to present the advanced development of RP technologies in various engineering areas as the solutions to the real world engineering problems.

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