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REVIEW ARTICLE

Rapid prototyping-assisted maxillofacial reconstruction

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Rapid prototyping (RP) technologies have found many uses in dentistry, and especially oral and maxillofacial surgery, due to its ability to promote product development while at the same time reducing cost and depositing a part of any degree of complexity theoretically. This paper provides an overview of RP technologies for maxillofacial reconstruction covering both fundamentals and applications of the technologies. Key fundamentals of RP technologies involving the history, characteristics, and principles are reviewed. A number of RP applications to the main fields of oral and maxillofacial surgery, including restoration of maxillofacial deformities and defects, reduction of functional bone tissues, correction of dento-maxillofacial deformities, and fabrication of maxillofacial prostheses, are discussed. The most remarkable challenges for development of RP-assisted maxillofacial surgery and promising solutions are also elaborated.

Key words: Biomaterials, computer-aided design (CAD), imaging, maxillofacial reconstruction, rapid prototyping (RP)

Key messages

- Rapid prototyping (RP) technologies have found many uses in oral and maxillofacial surgery, including restoration of maxillofacial deformities and defects, reduction of functional bone tissues, correction of dento-maxillofacial deformities, and fabrication of maxillofacial prostheses.
- Further development of RP-assisted maxillofacial reconstruction requires measures to tackle the challenges of conflicts between precision and speed, variety of materials, varied cost, and multidisciplinary development.

Introduction

The market competition nowadays has become increasingly fierce. Rapid product development and global market conditions require entrepreneurs to produce high-quality products in an environmentally friendly way, in the shortest time, with minimal expenditure. To satisfy these strict needs for product development, rapid prototyping (RP) technologies have been developed and have received much attention rapidly and globally. This century has witnessed significant increases in applications of RP technologies for manufacturing parts or models rapidly. These technologies adopt accurate stacking-up methods for generating an entity, namely from a point to a surface, and then from the surface to a 3D object by accumulation under the control and management of a computer using existing dimension data of computer-aided design (CAD). Compared to traditional manufacturing methods, RP technologies promote product development while simultaneously reducing cost and depositing a part of any degree of complexity theoretically without mold during the shaping process. Due to these characteristics, they have been extensively used in a number of industries, such as aerospace, automotive, coin-making, tableware, saddletrees, jewelry, and medicine (1). Notable among these are medical uses which account for approximately 15% of the total applications of RP technologies (2).

In dentistry, RP technologies are mainly used for assisting orthopedics (3), prosthetics (4,5), implantology (6,7), and maxillofacial surgery (8–13). The applications to oral and maxillofacial surgery include fabricating personalized implants/intermediate splints/prostheses for maxillofacial reconstruction (14–16) and supporting the whole operation process, which consists of preoperative diagnosis, planning and simulation, intraoperative navigation, and postoperative evaluation (17–22). RP technologies are also used to produce precise physical models with which 3D-virtual models are combined to help and enrich the teaching–learning process for medical students and inexperienced doctors, and to promote communication between surgeons and patients (23,24). The widespread uses of RP technologies in oral and maxillofacial surgery benefit from the development and availability of imaging techniques, such as 3D computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound scanning (25–27), with which precise and functional models can be generated rapidly for the surgery. The variety of materials and devices of RP technologies also contributes to the technical progress in these applications.

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In recent years, use of RP technologies in oral and maxillofacial surgery has been highlighted in a large number of publications. However, a timely and detailed review which embodies rapid development of RP technologies in maxillofacial reconstruction is still lacking. This paper aims to deliver an overview of RP-assisted maxillofacial reconstruction covering both fundamentals and recent applications of RP technologies. It begins with an introduction to RP technologies including their development history, characteristics, and principles. This is followed by a detailed discussion on applications of RP technologies to maxillofacial reconstruction. The concluding remarks touch on the challenges of RP-assisted maxillofacial reconstruction and promising measures/solutions to tackle these challenges. The paper is expected to offer a useful guide for the development of RP technologies for maxillofacial reconstruction and for the entire field of dentistry.

Historical development

The history of rapid prototyping (28–31) can be traced to the late 1960s when Herbert Voelcker proposed an idea to do 'interesting things' with automatic and computer-controlled machine tools. He developed the earliest mathematical theory and algorithms for solid modeling of 3D objects in 1970s, which were then used for designing almost everything mechanical, ranging from toy cars to skyscrapers (24). In 1984, Charles Hull invented the first RP technology, stereolithography (SLA), for fabricating solid objects by successively 'printing' thin layers of the ultraviolet curable material one on top of the other. This technology uses a UV laser as heating source and relies heavily on the materials used. In 1987, Carl Deckard proposed to build up models layer by layer which turned into the second RP technology called the selective laser sintering (SLS). It was based on a 3D digital model using CAD or other 3D data sources. A laser beam was first used to fuse powdered materials into a layer, and then the next layer of powder was placed on the previous one until the entire model was obtained. In the same year, Brix and Lambrecht first used a 3D model, manufactured by a RP predecessor called a computer numerical control (CNC) device, in health care. In 1988, Scott Crump invented the third RP technology, fused deposition modeling (FDM), which can print objects using a variety of materials including acrylonitrile butadiene styrene (ABS), polycarbonate (PC), ABS-PC-blend, and polyphenylene sulfone resins (PPSU) in an open space without support of unused materials. In 1991, RP machines were commercialized by three companies: Stratasys, Cubital, and Helisys. In particular, Helisys released and sold the first system of laminated object manufacturing (LOM) which became the fourth RP technology. In the manufacturing process, layers of adhesive-coated plastic, paper, or metal laminates are fused together and cut into shape with the aid of a knife or a laser cutter. Compared to other RP technologies, it produces relatively large solid parts with a size of up to $550 \times 800 \times 500$ mm. In the same year, a maxillofacial surgery clinic in Vienna first used human anatomy models created by SLA for surgery. In 1993, Massachusetts Institute of Technology (MIT) invented the fifth RP technology, known as the 3D printing. In 1996, the term '3D printer' was used to refer RP machines. Like an ordinary ink-jet desktop printer, a 3D printer manufactures successive layers of material that create a 3D object. It was found to be more affordable, simpler, and speedier than other RP technologies. Based on the 3D printing technology, a number of machines, such as ThermoJet and Spectrum Z510, were developed for manufacturing various products including the Urbee car, bikinis, chocolate, aircraft, AIRBALL, and a moonhouse. In the new century, more applications of RP technologies to medicine have been reported. These technologies were used to fabricate customized mandibular implants, splints, custom-made prostheses, blood vessels, artificial organs, biological ointment, etc. Table I presents the historical development of RP technologies and relevant medical uses (24,28–31).

Table I. Historical development of rapid prototyping and relevant medical uses (24,28–31).

Year	Inventors	Developments
1967	Herbert Voelcker	proposed an idea to do 'interesting things' with the automatic and computer-controlled machine tools (RP was born)
1970s	Herbert Voelcker	introduced mathematical theory and algorithms for solid modeling
1984	Charles Hull	invented 3D models
1986	Charles Hull	invented stereolithography (SLA)
1987	Carl Deckard	invented selective laser sintering (SLS)
	Brix and Lambrecht	used a 3D model in health care
1988	Scott Crump	invented fused deposition modeling (FDM)
1991	Helisys Inc.	sold the first system of laminated object manufacturing (LOM)
1991	A maxillofacial surgery clinic in Vienna	first used RP models of human anatomy in maxillofacial surgery
1992	Stratasys Company	sold the first FDM-based machine
	DTM Corporation	sold the first selective laser sintering (SLS) system
1993	Massachusetts Institute of Technology (MIT)	patented '3-dimensional printing techniques'
1995	Z Corporation Company	developed actual 3D printers
1998	3D Systems Company	introduced a 3D printer called ThermoJet
2005	Z Corporation	invented a 3D printer called Spectrum Z510
2010	3D Systems Company	manufactured Urbee car
	Anthony Atala	printed trachea
2011	Shapeways and Continuum Fashion	printed bikini
	University of Southampton	manufactured aircraft
2012	Scottish scientists	printed artificial heart
	Children's National Medical Center in Washington	printed artificial liver tissue
	LayerWise	printed transplant jaw
	Anthony Atala	printed blood vessels
2013	A 3D printing company in Texas, USA	printed metal pistol
	Scott Hollister	printed trachea splint
	Organovo Company	printed micro liver
2014	Philipp Günther Inc.	printed AIRBALL
	Mikael Genberg	printed moonhouse
	Jonathan Cook	printed 3D smart watch
	Darryl D'Lima	printed biological ointment

Characteristics of RP technologies

The wide applications of RP technologies are attributed to their technical characteristics, especially the advantages over traditional manufacturing approaches. They include high-precision manufacturing, short manufacturing cycle, simple production process and low production cost, personalized manufacturing, complex manufacturing, and early visualization of product design (32).

High-precision manufacturing

The precision of RP technologies depends on the materials, techniques, and machines used. In general, it can be controlled below 0.05 mm, which is sufficient for most uses (33). For example, SLS and 3DP techniques were used to reproduce 3D models of craniomaxillary anatomy (34). By taking measurements with an electronic caliper, dimensional errors of only 2.10% and 2.67% for SLS and 3DP models were observed, respectively. The models satisfactorily reproduced anatomic details, except for thin bones, small foramina, and acute bone projections.

Short manufacturing cycle, simple production process, and low production cost

RP technologies eliminate the steps of mold design and fabrication in traditional processes, creating solid models from 3D data of CAD software directly. Hence, they have a short manufacturing cycle, simple production process, and low production cost. For instance (35), implants could be manufactured directly by RP technologies based on a virtual model established by CAD without the need for a physical model for repairing a post-traumatic zygomatic deformity, saving time and surgery costs. The advantages can also be found in other biomedical surgeries where the image data acquired preoperatively are available for the interactive use of the surgeons at all times. The technologies not only guide the intraoperative orientation, but also reduce the operational time, risk, postoperative morbidity rate, and cost.

Personalized manufacturing

RP technologies realize the design by computer modeling which makes revisions of models (e.g. size, shape, and scale) easy and real-time, offering a great convenience for production of personalized products. Some complex curves, which are not available using traditional methods, can be obtained by computer modeling. This advantage enables the appearance of prototypes to be more personal. Over the past decades, RP technologies have been applied successfully in the cranial and maxillofacial surgery for fabrication of various facial prostheses (36,37), auricular prostheses (38–40), and nasal prostheses (41).

Diversity of manufacturing materials

RP technologies can use different materials, such as metal, stone, and plastic, to meet the needs of different areas. Titanium, calcium phosphate cements, ceramics, and polymers are commonly used manufacturing materials for maxillofacial reconstruction. For example, anatomical 3D pre-bent titanium implants fabricated by RP technologies have been used for repairing orbital floor fractures and achieved satisfactory outcomes (42). Synthetic onlay bone-grafting materials, consisting of acidic calcium phosphates, brushite and monetite, have been used as an attractive alternative to autologous onlay bone grafting in maxillofacial surgery (43). Besides, methylmethacrylate was used for fabricating cranial prostheses for craniofacial reconstruction (44).

Complex manufacturing

The whole production process of RP technologies is digital and associates with the CAD model directly. One can modify the data at any time before manufacturing, so the product manufacturing process has little to do with the complexity of the products, making up for the deficiency of traditional processing technologies. In medicine, a number of complex medical devices and artificial organs have been manufactured by RP technologies, such as audiphone, miniature liver, artificial blood vessel, heart, and skeleton (29). RP technologies have made gratifying achievements in medicine attributed to the characteristic of complex manufacturing.

Early visualization of product design

RP technologies give users and producers an idea of how a product will look even in the very early stage of designing. Before RP technologies came into being, producers were not able to determine the exact physical appearance of the product until the final product was manufactured. With RP technologies, manufacturers can monitor the actual product at various stages during development. The users can also get hands-on experience with the part and make sure it will be what they expect. In practice, early visualization provides great benefits to medicine. It was reported that RP technologies could improve surgical planning, mainly procedures carried out by the surgeons, owing to the better comprehension and visualization of the anatomy in complex pathologies of bone or vascular structures (45). A study on craniofacial, maxillofacial, and skull base cervical spinal pathology of 45 patients also revealed that the biomodels produced by RP technologies presented almost every anatomical and pathological structure with a high resolution and quality (46). The applications of RP technologies significantly improved results of operative planning.

Principle

Process

The properties of products by RP technologies depend on the manufacturing process (47). Common RP technologies involve five main steps, as shown in Figure 1 (48).

1. *Building the solid model*. This step acquires data by imaging techniques (e.g. CT/laser scanning) and uses standard software (Auto CAD, Solid Works, Pro/Engineer, Catia, etc.) to build a 3D solid model.
2. *Dispersing the solid model*. Because a solid model often has some surface of irregular form, the model should be pretreated before processing. For example, curve is not fully realized in practice and should be simulated using tiny straight line segments for further data processing. Since the STL (STereoLithography) file is simple and practical, it has become the most commonly used RP file format used for docking with related equipment.
3. *Slicing the model*. Based on the characteristics of the solid model, a suitable processing direction is selected to slice the dispersed solid model using a series of the cutting plane with a fixed interval in the prototyping direction. It is aimed at extracting contour information of the section obtained by model slicing.
4. *Forming and processing*. According to contour information of the section, forming heads (e.g. laser head/jet head) scan and stack up materials layer by layer on the workbench under the control of a computer. These layers are then bonded until the final prototype product is obtained.

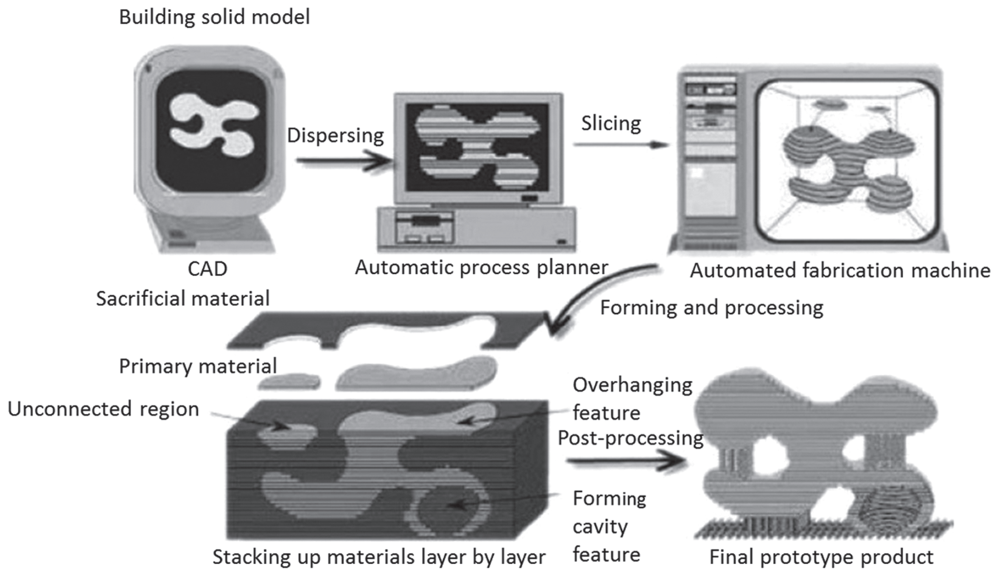

Figure 1. RP process chain showing main process steps. Adapted from reference (48) with permission of Rapid Prototyping Journal, Emerald, Copyright 2009.

5. *Post-processing*. After the model is created, sacrificial materials (residues of material) are removed. If necessary, the model is ground, polished, varnished, or sintered in a high-temperature furnace to increase its strength and performance.

Classification

Based on the initial state of material and forming methods, RP technologies can be classified into more than 10 types. The most commonly used RP technologies in medicine are stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), laminated object modeling (LOM), and 3D printing (3DP) (49). Other less used technologies include selective mask sintering (SMS), solid foil polymerization (SFP), and laser jet chemical vapor deposition (LCVD) (50–53). Figure 2 gives an overview of these main technologies (50).

Stereolithography (SLA)

Stereolithography (SLA) is the oldest and most widely used RP technology developed by 3D Systems in the United States. As shown in Figure 3 (54), SLA is based on the polymerization reaction of photosensitive resin. Under control of a computer, a UV laser scans the liquid resin along with each layered section contour of the part point by point, making the resin layer scanned undergo a polymerization reaction, forming line

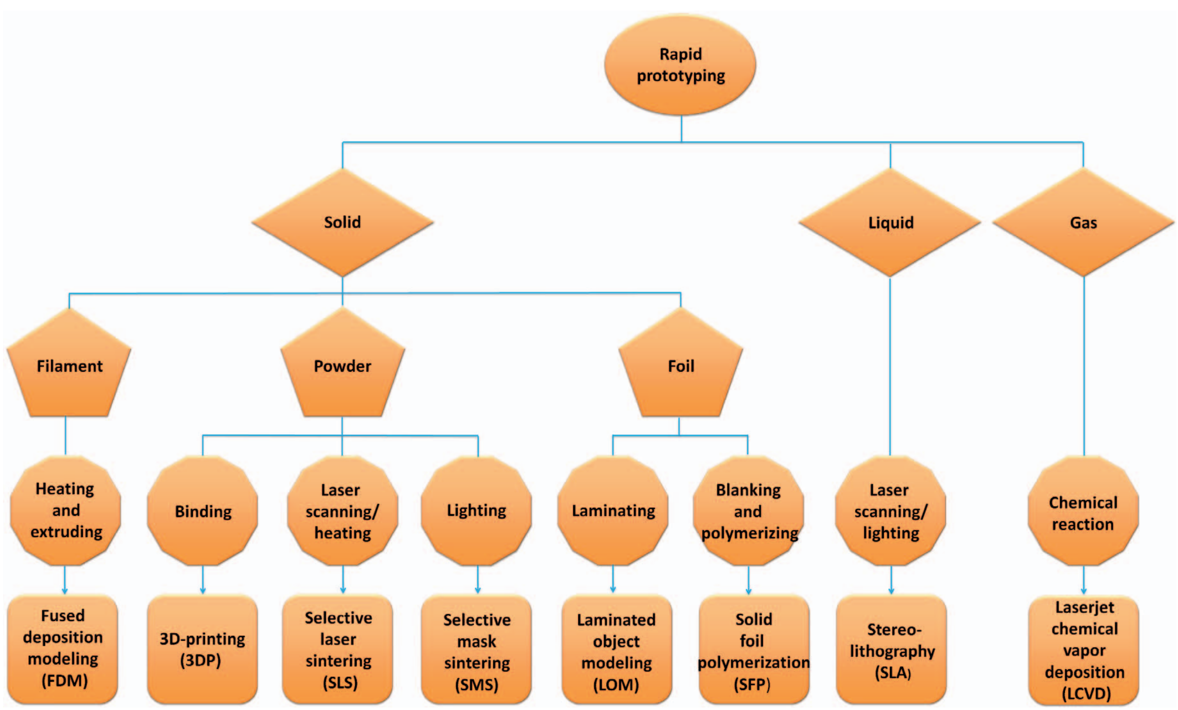

Figure 2. Overview of RP technologies. Adapted from reference (50) with permission of Macromolecular Materials and Engineering, John Wiley and Sons, Copyright 2008.

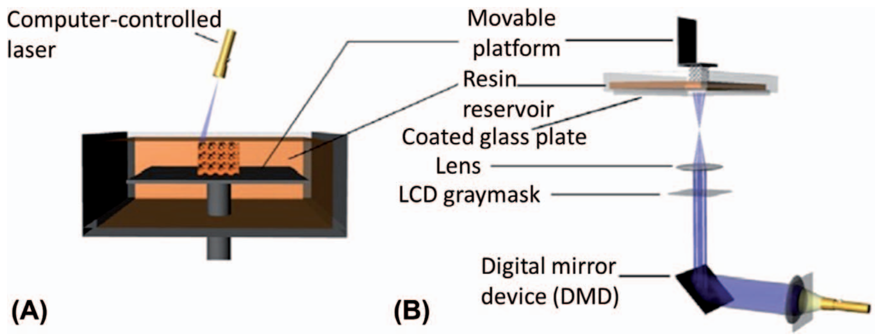

Figure 3. Schematic of two types of SLA setups. (A) A bottom-up system with a scanning laser. (B) A top-down setup with digital light projection (DLP). DLP is a method to illuminate the resin. A 2D pixel pattern is projected onto the coated glass plate with a digital mirror device (DMD), and then a complete resin is cured immediately. Adapted from reference (54) with permission of UTpublications, University of Twente, Copyright 2010.

gradually. A thin solidified layer of the part, made up of the lines, is then formed. Once one layer becomes solid, the platform moves down a distance of a lamellar thickness, and then the solidification of the next layer starts. The new solidified layer is bonded securely to the previous layer, and this operation is repeated until the prototype part is manufactured completely (55). This technology has been widely used to educate students, patients, and trainees and to rehearse surgical planning before surgery (56–59). It was used to produce impressions in maxillofacial reconstructive surgery and in sub-periosteal dental implant surgery (60–64). Another use of SLA models in dentistry is to fabricate surgical drilling templates during dental implant insertion (65–67).

Selective laser sintering (SLS)

The selective laser sintering uses laser as the energy source for manufacturing, as shown in Figure 4 (48). After powdered materials are scanned by laser beam at a certain speed and energy density based on the 2D data of each layer, the materials are sintered into the object with a certain thickness in a forming cylinder. There is a piston in the cylinder which moves down a layer thickness to accommodate the next layer of powder. The powdered materials are paved by a powder spreading roller again before scanning of a new layer. This step is repeated until all layers are scanned. Post-processing treatments, such as grinding and drying, may be necessary for manufacturing perfect parts after removing the excess powder (55). In practice, the SLS technology is especially useful for fabricating removable partial denture (RPD) frameworks (68,69).

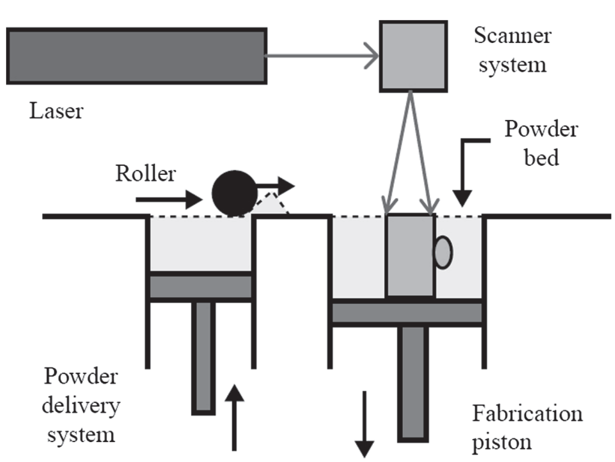

Figure 4. Schematic of the SLS technology. Adapted from reference (48) with permission of Rapid Prototyping Journal, Emerald, Copyright 2009.

Fused deposition modeling (FDM)

The first equipment based on fused deposition modeling was developed by American Stratasys in 1993. This technology is based on a CAD model, which is divided into several thin layers, generating 2D (x–y plane) geometric information which controls the moving track of the FDM nozzle. As shown in Figure 5 (70), the hot melt material (PCL filament, ABS resin, nylon, wax, etc.) is heated to a semiliquid state using a FDM heating head. Under computer control, the nozzle extrudes semiliquid state material at a lower temperature (approximately 0.5°C above its melting temperature) to form the solidified layer on the platform along with the moving trajectory of 2D geometric information. The material is solidified layer by layer with a vertical lift system, eventually forming a 3D part or scaffold from the bottom to the top (55). A FDM system can make the wax modeling process completely automatic, producing wax molds at more than 150 units per hour (71).

Laminated object manufacturing (LOM)

The laminated object manufacturing process involves heating and bonding of a foil material (paper/sheet, ceramic foil, metal foil, etc.) which is pre-coated with thermosol. As shown in Figure 6

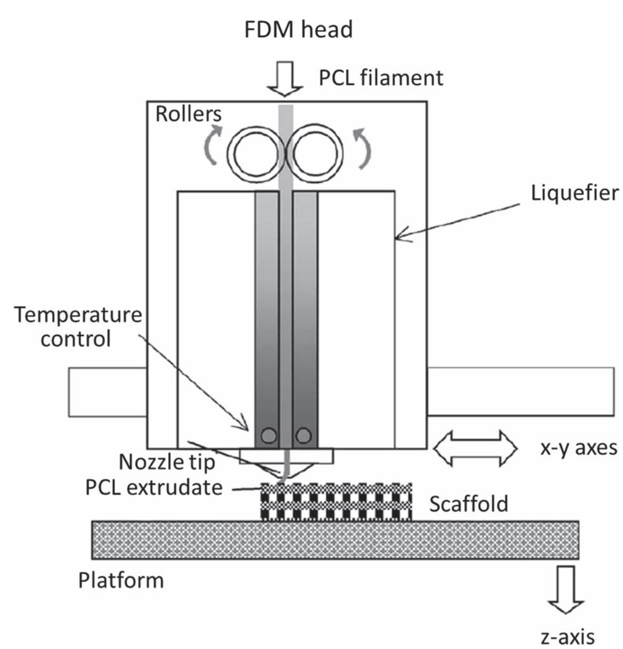

Figure 5. Schematic of the FDM technology. Adapted from reference (70) with permission of Biomaterials, Elsevier, Copyright 2002.

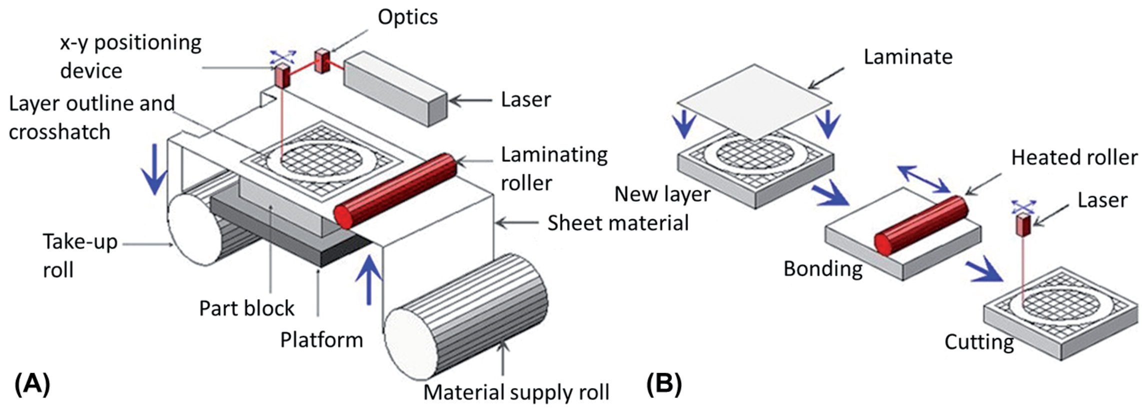

Figure 6. Schematic of the LOM technology. (A) Heating. (B) Bonding. Adapted from reference (72) with permission of Manufacturing Practices, Indian Institute of Technology Delhi, Copyright 2012.

(72), it can produce viscous materials in a heated state and in a single side with a hot roller. A laser located at the top of the platform acquires data according to a CAD layered model. The sheet material provided by the material supply roll is cut into internal and external outlines of parts using a laser beam, and then a new layer of sheet is superimposed on the top. With a laminating roller and laser beam, individual layers of the sheet material are bonded until the whole prototype is finished in the take-up roll.

3D printing (3DP)

The principle of 3D printing is shown in Figure 7 (48). When the forming cylinder falls a distance equal to the layer thickness, the powder supply cylinder is raised to a height and excess powder is extruded and pushed to the forming cylinder after paving and compacting using a powder spreading roller. Under computer control, an ink jet head injects adhesive selectively based on 2D geometry information of the next layer, constituting a surface. The principle is similar to that of a conventional printer. Delivering powder, paving powder, and injecting adhesive proceed successively. This process is repeated until a 3D model is completed (55) and excess powder is collected by a powder collecting device. This technology is especially useful for surgical planning and simulation (3,73).

Table II compares the technical characteristics of SLA, SLS, FDM, LOM, and 3DP in terms of materials, system type, forming technique, accessible part size, layer thickness, cooling-off/curing time, precision, advantages, disadvantages, applications, cost, and commercial time (48–52,74–77).

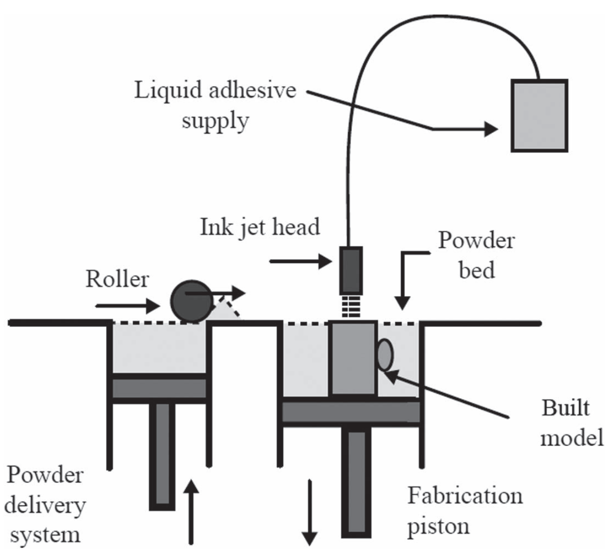

Figure 7. Schematic of the 3DP technology. Adapted from reference (48) with permission of Rapid Prototyping Journal, Emerald, Copyright 2009.

Use of RP in maxillofacial reconstruction

Background

In maxillofacial reconstruction, the major technical challenges are accurate positioning of the osteotomized bone fragments, identification of fissure marks, restriction of the surgical incision, and treatment of facial asymmetry. Traditional technologies cannot successfully tackle these issues because of difficulty in identifying the morphology of patients' internal organs and tissues, in fabricating sufficiently complex models, and in processing certain details of the templates. To facilitate maxillofacial reconstruction, CAD/CAM has been applied since the late 1980s (78). It allows preoperative virtual manipulation of CT data sets and makes generation of a precise 3D virtual representation of the skull possible, with which osteotomies and reduction on the 3D model can be performed. It can also be combined into a surgical system for navigation of the maxillofacial surgery (79–83). However, the application of CAD/CAM to maxillofacial reconstruction is still limited due to its low production speed and high cost. To overcome the limitations, RP technologies, which are based on CAD/CAM, numerical control technique, laser technique, and materials science, were introduced to oral and maxillofacial surgery in the 1990s (28). They are characterized by rapid speed, relatively low production cost, and accurate fabrication of solids of complex shapes using a wide range of materials. These technologies also easily reproduce the morphology of anatomical structures with physical prototypes, making RP technologies promising for application in medical fields. Due to these advantages, RP technologies have been successfully used for treating various maxillofacial defects, congenital or acquired malformations, and facial asymmetry and deviation (14–16).

Materials for RP-assisted maxillofacial reconstruction

Successful application of RP technologies to maxillofacial reconstruction depends, to a large extent, on the materials selected for fabrication of personalized implants and prostheses. The materials can be classified into three categories: autologous bone grafts, non-autologous bone grafts (84), and alloplastic bone replacement materials such as titanium (85,86), ceramics (87), and polymers [e.g. acrylic bone cement, polyetheretherketones (88,89) and silicone (42)].

Table II. Comparison of selected RP technologies (48–52,74–77).

	SLA	SLS	FDM	LOM	3DP
Materials	Photopolymers (acrylic and epoxy resins)	Metals, sand, thermoplastics (PA12, PC, PS)	Thermoplastics (ABS, PC, ABS-PC-blend, PPSU)	Foils (paper, polymers, metals, ceramics)	Thermoplastics, cement, cast sand
System type	Liquid-based	Powder-based	Solid-based	Solid-based	Powder-based
Forming technique	Laser/light-based	Laser/heat based	Heat and extrusion/ nozzle-based	Lamination	Adhesives/molding
Part size/(mm)	$600 \times 600 \times 500$	$700 \times 380 \times 550$	$600 \times 500 \times 600$	$550 \times 800 \times 500$	$508 \times 610 \times 406$
Layer thickness	0.03–0.25 mm	0.1–0.15 mm	0.127–0.254 mm	0.015–0.12 mm	0.178–0.356 mm
Cooling-off/curing time	No cooling-off or curing time up to 30 min	Depending on geometry and bulk	No cooling-off or curing time	Depending on geometry	No cooling-off or curing time
Precision	< 0.05 mm	0.05–0.1 mm	0.1 mm	0.15 mm	$0.1/600 \times 540$ dpi
Advantages	Good surface finish, can be made transparent, high mechanical strength	Good mechanical strength, broad range of materials	Good mechanical strength, fast fabrication time, low toxicity	Produces relatively large parts	Fast fabrication time, low toxicity, capability of being colored, relative material variety
Disadvantages	Limitations to material selection (epoxy and acrylic resin), post-cure required	Elevated temperatures, local high energy input, uncontrolled porosity, toxic gases	Elevated temperatures, small range of bulk materials, rough surface finish, support structure must be removed	Model with thin walls; hollow objects cannot be made by this method	Large tolerance, lower strength models, rough surface finish, material must be in powder form, weak bonding between powder particles, might require post-processing
Applications	Creation of conceptual, geometric, and functional prototypes	Creation of visual and functional prototypes, tools for injection pressing, hard tools and electrical discharge machining (EDM) electrodes	Production of functional prototypes and for precision casting technology	Conceptual design	Mechanical engineering, aeronautics and shipbuilding, architecture, precise design of implants, selection of instruments
Cost ($/kg)	From 160	From 190	From 60	From 190	From 30
Relative sample cost[a]	Medium	Medium-high	Low-medium	Medium-high	Low
Commercially available since	1987	1991	1991	1990	1998

[a]Cost depends on the number, size, and complexity of samples.

Autologous bone grafts

Autologous bone grafts are considered to be the gold standard for reconstruction of bony defects attributed to their biocompatibility, high mechanical strength, easy incorporation into the defect and replacement by normal bone, low risk for infection, and radiopacity. For example, free fibula flap is the most commonly used autologous bone grafts for surgical or virtual planning in reconstruction of mandibular defects (90–93). Particles of autologous cancellous iliac bone are also used to reconstruct defects in the mandibular body (94). Besides, autogenous bone grafts are used for vertical ridge augmentation and for correction of vertically deficient edentulous ridges (95–101). The principal disadvantages of autologous bone grafts are their limited availability, donor site morbidity, and the risk of unpredictable resorption.

Non-autologous bone grafts

Non-autologous bone grafts have abundant sources, including the bone tissue of amputation, rib of resection in thoracic operations, and fresh cadaveric bone. The shape and size of non-autologous bone grafts are unlimited. They also have biological activity when compared to alloplastic materials. However, non-autologous bone grafts have infectious and immunological risks and thereby are rarely used in clinical applications. With the development of bone preservation technology, infection prevention measures are enhanced. The continuously in-depth studies of immunogenicity and osteoinduction of non-autologous bone grafts (102,103) are expected to help expand their applications.

Alloplastic bone replacement materials

There are various alloplastic bone replacement materials, including titanium, bioceramics (mainly calcium phosphate ceramics or cements), and polymers (e.g. acrylic bone cement, polyetheretherketones, polyethylene, and silicone). Alloplastic materials have several reconstructive advantages over autogenous bone grafts, such as no donor site morbidity, easier fixation to the defect site, and no change in the defect contour after operation. They are usually used in non- or low-load-bearing graft sites as cranial and maxillofacial skeletal substitutes (104–116).

Titanium. Titanium is a material of choice due to its wide availability, biocompatibility, good mechanical properties, easy intraoperative contouring, and rigid fixation (117). A porous titanium implant will have high yield strength and elastic modulus which are reduced in a fully dense implant. A flexible titanium plate can avoid the stress-shielding effect which causes considerable resorption of bone (118). Because of the lightweight and good elasticity of titanium, titanium is created as titanium micro-mesh systems for orbital fracture repair and other cranial and maxillofacial surgery. Titanium trays, titanium plates, and titanium implants are also fabricated for reconstructing cranial and maxillofacial defects. Nevertheless, titanium has several disadvantages in clinical uses. It is thermally conductive and susceptible to infection, annoying the patient very much (119). Its rough or irregular edges may catch on adjacent soft tissues. Large titanium implants are also massive (120) and they do not have the macroporous architecture that would allow them to be truly osteoconductive. Moreover, the radiological artifacts of titanium (121,122) may influence postoperative monitoring.

Bioceramics. Calcium phosphate ceramics or cements (CPC) are the most frequently used bioceramics materials for clinical applications because they can overcome limitations of autologous grafts. Among CPC materials, monetite (dicalcium phosphate anhydrous) is very important because it is resorbable and osteoinductive (123,124). Monetite onlays, which can be produced in customized designs using 3D printing, are suitable for vertical bone augmentation (125,126). However, they cannot fully satisfy the aesthetic requirements because appropriate modification of the shape of monetite implants is difficult.

Nowadays, compatible calcium phosphate implants or scaffolds, which are fabricated by 3D powder printing, are used for computer-aided surgery, cranioplasty, and maxillofacial surgery. Hydroxyapatite (HA) is probably one of the most investigated CPC materials in 3D printing since it closely resembles the mineral phase of natural bone (127–31). It also has high biocompatibility, bioactivity, and osteoconductivity (112–115). A large amount of work was carried out using conventional ceramic processing for hydroxyapatite synthesis. Recently, RP technologies have been used to fabricate complex shaped hydroxyapatite implants and scaffolds (125–131). The main problems of hydroxyapatite (HA) and other similar phosphates [e.g. b-tricalcium phosphate (b-TCP)] result from their limited *in vivo* resorption and remodeling capacity. They are inappropriate as onlay bone graft substitutes for vertical bone augmentation (132,133).

Polymers. The most commonly used polymer for maxillofacial reconstruction is methylmethacrylate (acrylic) (134). It is cheap, stable, strong, radiolucent, thermal-resistant, and well tolerated by host tissues and does not affect postoperative radiologic imaging. Compared with autogenous grafts, biocompatible methylmethacrylate implants are more durable and predictable. In clinical applications, methylmethacrylate and other polymers are used to fabricate custom-made implants or prostheses for cranial and maxillofacial reconstruction (135–137). They are also used as an ideal material to create biomodels. The major shortcomings of the polymers are associated with their non-osteoconductive properties, resulting in possible rejection of the implant and inflammatory reaction (138,139), and high rate of infectious complications (140,141). Methylmethacrylate implants have a non-porous structure, and thereby they do not allow tissue in-growth inside the implant.

Applications of RP to maxillofacial reconstruction

The main applications of RP technologies to maxillofacial reconstruction include restoration of acquired maxillofacial deformities and defects, reduction of functional bone tissues, correction of dento-maxillofacial deformities, and fabrication of maxillofacial prostheses to improve the facial aesthetics.

Restoration of acquired maxillofacial deformities and defects

Application of RP technologies can improve restoration of the maxillofacial acquired deformities and defects. Imaging tools such as CT, MRI, and scanner are used to acquire data, with which the biological or anatomical model is manufactured by RP technologies. The biomodel (17–20,142,143) established then assists preoperative diagnosis, planning, simulation, and surgical training. It also simplifies the operation procedures and supports subsequent surgery or pharmaceutical treatment. On the other hand, RP technologies can be used for fabrication of customized implants. The individual implant provides an adequate accuracy of fit to the defect. The direct prefabrication of RP technologies avoids disadvantages of traditional strategies such as indirect manual modeling on life-size models or intraoperative modeling. Also, no complications such as infection, extrusion, and seroma occur in the follow-up period.

Manuel Oliveira et al. (144) reported a patient who was the victim of a facial gunshot wound and suffered from partial destruction of mandible and other bone structures. In the study, an innovative 3D biomodel was fabricated by the SLA technology to calculate the length, angulations, exact contours, and general

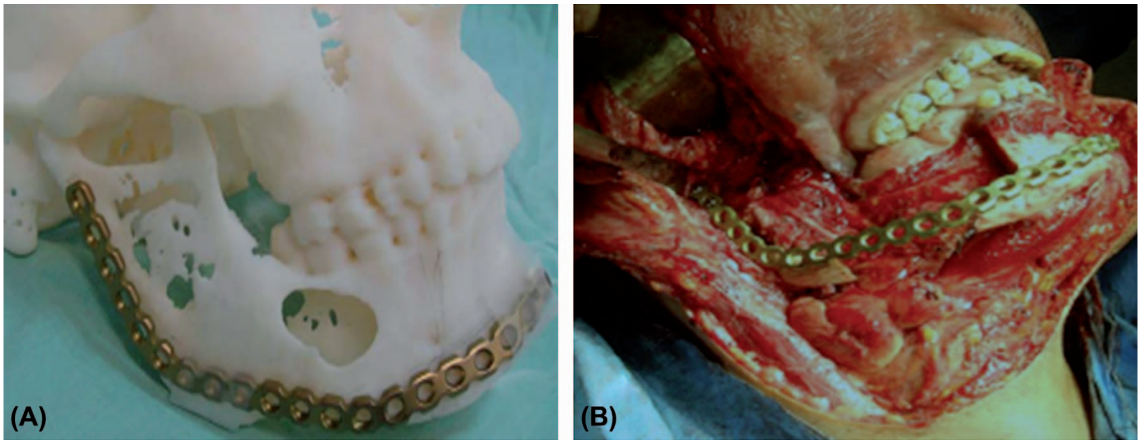

Figure 8. (A) Precontoured mandibular reconstruction plate placing over the right mandible with ameloblastoma, (B) Reconstruction plate bridging the gap following tumor resection. Adapted from reference (15) with permission of Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology, Elsevier, Copyright 2009.

morphology of iliac crest and fibula flaps for maxillofacial reconstruction. The models (145) supported surgical planning and preoperative rehearsal and could be used to reproduce templates for the individual prosthetic and implants, improving the accuracy of implant and fit of defects fixation. Meanwhile, the surgery time was reduced by biomodeling which also promoted team cooperation and teaching demonstrations with hands-on integrative use of patient data. The biomodels did not need specialized equipment or knowledge for interpretation and might easily be transported. With the SLA technology, facial symmetry and functionality were greatly improved after the surgery.

Adir Cohen et al. (15) reported three patients who suffered from defects of different degrees in their mandibles following mandibulectomy. Several 3D models were fabricated by RP technologies (SLA and 3D printing) for accurate contouring of plates and planning of bone graft harvest geometry before surgery. According to the 3D models, reconstruction was performed with a 2.4-mm locking plate, obtaining accurate adaptation of the plate and excellent symmetry in short operation time. The precontoured mandibular reconstruction plate was placed over the right mandible, and the reconstruction plate bridged the gap following tumor resection, as shown in Figure 8. The application of RP technologies led to shorter exposure time to general anesthesia, reduced wound exposure period, and less blood loss (146–148). Compared with SLA, the 3DP technology was more accurate (accuracy of 0.1 mm to 0.016 mm), more efficient, faster, easier, and cheaper (cost ratio was 1 to 3) for mandibular reconstruction. It was suitable for printing smaller and more complex structures.

Joël Brie et al. (149) developed a calcium phosphate implant to reconstruct large and complex cranial and maxillofacial bone defects (>25 cm^2) using the SLA technology. The implant with thin edges was able to overlap the surrounding living bone, preventing the migration of the implant to the inside of the skull. Nevertheless, it exhibited insufficient mechanical strength and a greater risk of infection for patients due to its total macroporous structure (150–152). To tackle these problems, the same research group manufactured another implant with a predominantly dense structure and macroporous areas only at the edges using the same RP technology. It was indicated that the implant had good mechanical strength and biointegration, satisfying the requirements for reconstruction of large (>25 cm^2) or complex (fronto-orbital area) cranial and maxillofacial defects.

Xiao-Jing Liu et al. (153) used a resin template involving a fibula flap as a messenger to reconstruct maxillofacial defects caused by mandible tumor ablation. The surgeons shaped the fibula flap by applying a RP-made resin template as a guide. It transferred virtual information into real surgery, and the bone grafts were implanted to the defect areas. Compared to traditional imaging techniques, such as spiral CT, 3D imaging, and stereomodels, for improving preoperative planning for cranial and maxillofacial surgeries (154), the template as a 3D fibula flap model produced by the RP technology was more flexible, more convenient, easier to handle, and carried sufficient information to guide the surgery. It could also be easily revised or rebuilt to meet the alternative boundary during operation. To evaluate the reliability of the resin template (155,156), a novel technique, which was based on registration and comparison of 3D images from postoperative and virtual planning models, was developed as an alternative to detailed measurements on two- or three-dimensional images. The results showed that the RP-made resin template was a reliable messenger for maxillofacial reconstruction.

Uwe Klammert et al. (157) used 3D powder printed calcium phosphate implants for reconstruction of cranial and maxillofacial defects on a human cadaver skull with bony defects. The 3DP technology was applied to fabricate two types of implants (brushite and monetite), which were then inserted into the cranial defects and fixed with miniplates, as shown in Figure 9. The

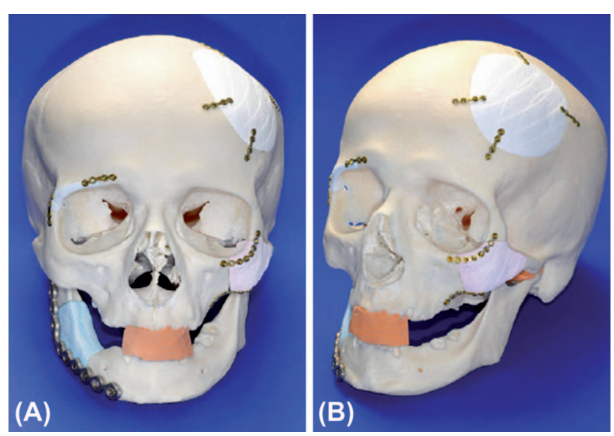

Figure 9. (A) General view of the implant-bearing skull. Implants are fixed with miniplates for mandibular defect. (B) The drill holes for screw insertion were made after positioning of the implants using a common bone drill. Adapted from reference (157) with permission of Journal of Cranio-Maxillofacial Surgery, Elsevier, Copyright 2010.

processing chain from data acquisition to printing of the implants proved to be practical and simple. It was also easy to revise the implants during the operation by burring. The calcium phosphate material offered appropriate biocompatibility and adjustable resorption behavior, making modification of implants with temperature-sensitive drugs (e.g. loading with bioactive proteins or antibiotics at room temperature) possible. The customized implants showed a high degree of accuracy of fit (dimensional accuracy of $\pm$ 200 μm).

In general, prototyped individual bone-grafting trays were used for restoring discontinuous mandibular defects (158,159). However, animal and clinical trials (158,159) have shown that considerable resorption of bone was caused by the trays which shielded the graft from stress. To tackle this issue, Libin Zhou et al. (94) designed and manufactured a flexible tray using a RP technology. The prototype flexible tray was used to carry particles of autologous cancellous iliac bone to reconstruct a 40-mm defect in the mandibular body. Sequential radionuclide bone imaging was used to monitor the bone metabolism. Compared to conventional trays, bone metabolism was more active in the flexible tray in the early stages. A finite element analysis was used to compare the distribution of strain on the bone grafts that were placed in flexible and conventional trays. It was found that most of the strains on the graft resulted in a beneficial mechanical environment in the flexible tray, while more than half of the graft was in the lowest class of strains (disuse $\leq$ 50 μstrains) in the conventional tray. The flexible tray could efficiently eliminate the shielding from stress, allowing more occlusive force to be conducted onto the bone graft.

Gursel Turgut et al. (160) reported that a total of 11 patients, who had various-sized cranial and maxillofacial defects, underwent reconstruction using polymethylmethacrylate. In the polymerization process there was an exothermic reaction of polymethylmethacrylate, which damaged cranial and maxillofacial tissues. The SLA technology was used to fabricate preoperative implants and prostheses made of polymethylmethacrylate that exactly fitted the defects without local tissue damage. The accuracy of treatment was improved without infection, seroma, extrusion, and/or contour irregularity. It was revealed that the SLA technology was suitable for reconstructing moderate and complex cranial and maxillofacial defects that have enough soft tissue coverage without any contact with a third space.

Leonardo Ciocca et al. (161) developed an innovative protocol using the FDM technology to produce individual HA scaffolds for bone marrow stem cells to reconstruct bony defects of a functional stress-loaded area (i.e. the temporomandibular joint). With this protocol, a resected condyle model fabricated by the FDM technology was applied to evaluate the fit of the bone substitute scaffold. Apart from the model, two templates as surgical guides were manufactured to reproduce virtual sectioning of the mandible in the surgical environment, allowing surgeons to section the condyle in the same line as the virtually planned section. At last, under the surgical condition, the condyle of the right mandibular bone was removed and replaced with the rapid prototyped plastic scaffold. However, it should be emphasized that only the HA scaffold external complex surface was tested in the protocol. The inner part of the scaffold, which should reproduce the trabecular part of the bone, was not examined.

Junhui Cui et al. (162) used titanium plates/mesh to treat three patients with bilateral craniomaxillofacial post-traumatic deformities. The titanium plates fabricated by the SLS technology were preshaped on 3D resin skull models manufactured by a RP device (Union Technology, Shanghai, China) (Figure 10A and B). With the 3D models and surgical planning, the location, shift distance of the osteotomy, reduction and fixation direction, and facial contours were determined. The titanium plates could then be implanted into the locations appropriately. After 1 month, the patients' facial contour/symmetry (Figure 10C and D), mouth opening (Figure 10E and F), and occlusion (Figure 10G and H) were well recovered. This method, which combines surgical planning, 3D model surgery, and preshaped implants, not only shortens the duration of operation time but also enables surgeons to plan a more feasible surgical procedure for better therapeutic effects.

Reduction of functional bone tissues

RP technologies have been widely used for reduction of functional bone tissues. The RP-reproduced 3D model of skeleton structure

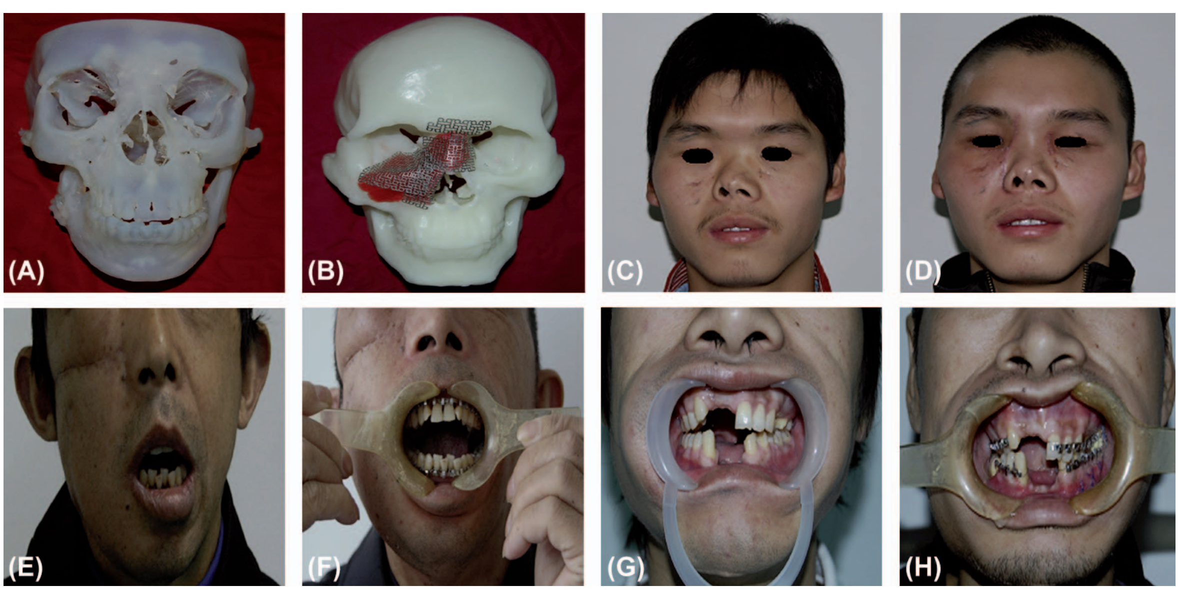

Figure 10. Preoperative planning for patients with craniomaxillofacial post-traumatic deformity. (A) Resinous craniofacial model manufactured using a rapid prototyping device. (B) Preshaping of titanium mesh or plates on rapid prototyping models. (C) Preoperative view of the patient. (D) Postoperative view of the patient. (E) Preoperative mouth opening of the patient. (F) Postoperative mouth opening of the patient. (G) Preoperative occlusion. (H) Postoperative occlusion. Adapted from reference (162) with permission of Journal of Oral and Maxillofacial Surgery, Elsevier, Copyright 2014.

has proved helpful in diagnosing fracture form, evaluating fracture characteristics, and formulating surgery design (163). Surgeons could observe bony structures more clearly before the operation and shape the implant in advance with this model. Moreover, by performing simulation surgery on the 3D model, accurate and smooth surgery could be achieved. On the other hand, supplementary computer-assisted surgical (CAS) techniques (164–167) including the mirror-imaging technique (168–172) have been found useful for restoring maxillofacial fractures, improving facial symmetry, and increasing the accuracy of the surgical procedure. Integrating RP technologies with supplementary CAS techniques will have great practical value of repairing maxillofacial fractures, although long-term functional follow-up for verification of its effectiveness are necessary and worthwhile.

Marcin Kozakiewicz et al. (173) reported fixing orbital floor fractures of six patients using the 3DP technology (Figure 11A). Several 3D virtual models were first created based on CT images (Figure 11B), and then 3D physical titanium mesh models were fabricated using the RP technology. These models were used as templates to form a 0.4-mm thick titanium mesh implant (Figure 11C), which was then inserted into the orbital floor defect areas. The 3D models assisted in identifying anatomical landmarks and in positioning implants during surgery. Use of the 3DP technology eliminated the difficulties in fitting and adjusting implants within the orbit due to its complex anatomy structure.

The traditional method used for reduction and fixation of zygomatico-orbito-maxillary complex (ZOMC) fractures depends on the surgeon's experience, which results in low precision and efficiency (174). To address this issue, Peng Li et al. (175) introduced a method to treat ZOMC fracture and deformity occlusion using the FDM technology with the help of software Mimics 10.01. After the spiral CT data was imported into the software Mimics 10.01, a virtual 3D model was generated, and virtual surgical planning was carried out under computer control. To realize the virtual repair planning, three reposition templates and one skull model were manufactured using the FDM technology. A 3D virtual template, attaining precision of 0.4 mm every layer, was transferred into a physical object. Although it had a less precision when compared to SLA and LOM technologies (with precision of 0.05–0.1 mm) (176), the accuracy, speed, and cost of the template were suitable for clinical use. In this case, the crucial part was the design of reposition templates with appropriate size and boundary. With the physical template, patients got satisfactory reconstruction for maxillofacial complex fracture and an ideal occlusion. The treatment outcome was exactly consistent with preoperative planning.

Wei Zhong Li et al. (78) reported repair of ZOMC fracture using an AFS laser RP machine with software, Mimics 10.0, for design of surgical procedure, virtual surgery, and final evaluation. This protocol provided an opportunity to obtain a precise 3D anatomical model by acquiring the spiral CT scanner data and to perform osteotomies on the model preoperatively. Furthermore, a 3D virtual reconstruction model built by the software was used to navigate the reduction (78–84). Hence, with the help of this protocol, surgeons could fully recognize the fracture shift and accurately locate the osteotomy during the operation and predict operation outcomes. The protocol is useful for reconstruction of the maxillofacial skeleton, especially in the repair of ZOMC fracture.

Xiang-Zhen Liu et al. (177) introduced 3D virtual surgical planning and SLA templates for ZOMC fractures associated with orbital volume change and evaluated the surgical outcomes quantitatively. The sequence of the treatment and assessment involved five steps: data acquisition, surgical planning, SLA template fabrication, operation, and evaluation. The results showed that the mean orbital volume of the injured side was 29,301.26 ± 3,833.61 mm^3, which was considerably different from the uninjured orbit (26,790.88 ± 3,948.03 mm^3; $P < 0.05$). Postoperatively, the mean orbital volume of the repaired side was 27,063.59 ± 3,875.38 mm^3, which was close to the uninjured side ($P > 0.05$). The quantitative assessment demonstrated that SLA templates for ZOMC fractures are helpful for restoring facial symmetry and concordance of bilateral orbit volumes.

Segmental mandibular resection poses a challenge to maxillofacial surgeons considering accurate contouring of reconstruction plates, restoration of mandibular symmetry, and accurate positioning of condyles in the glenoid fossae. Adel Abou-ElFetouh et al. (178) proposed to use a RP machine (VisiJet SR 200, 3D Systems, Rock Hill, SC, USA) for fabricating patient-specific templates to pre-bend reconstruction plates symmetrically, guide osteotomies, and reposition the condylar process in the proximal edentulous segment in its preoperative position. Compared to other computer-guided templates for segmental mandibular osteotomies which were widely used (179–183), this method had the following advantages. First, only a rapid prototyped plastic template was used, which simplified the design with shorter fabrication time (total intraoperative time was reduced by 30–45 min) and less materials. Moreover, this technology cut down the costs by about 80% in comparison with other work where the whole mandibles were rapidly prototyped as templates. It was also less time-consuming and more accurate when compared to the studies that inserted the reconstruction plates into defects without use of any form of intermaxillary fixation, or fabricating the silicone stamps manually based on models.

Maxillofacial surgeons usually face the challenges of repositioning osteotomy caused by the scarring and distortion of the

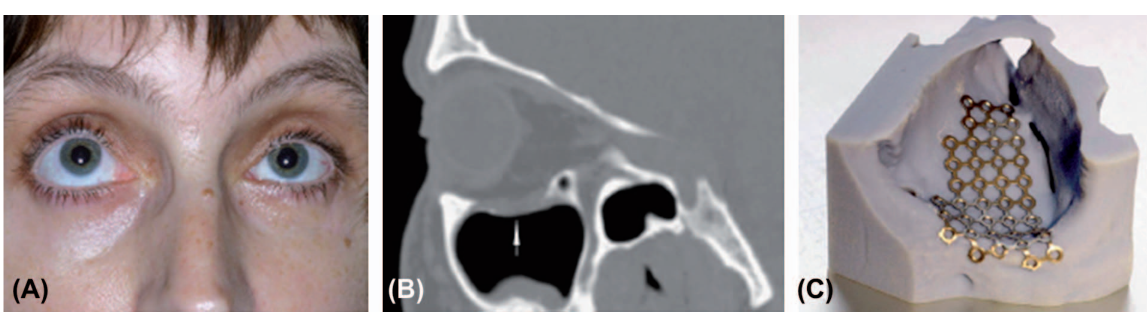

Figure 11. (A) Appearance of face before treatment of left side blowout orbital fracture where lowered left eyeball, restricted upward movement, and narrowed palpebral fissure are observed. (B) Computer tomography image of the left orbit with sagittal plane reconstruction with arrow indicating the damaged orbital floor. (C) Physical (solid) model of left orbital floor with formed titanium mesh. Adapted from reference (173) with permission of Journal of Cranio-Maxillofacial Surgery, Elsevier, Copyright 2009.

surrounding and overlying tissues. There are not enough reference points on the lateral midface in the repositioning surgery, causing difficulties in locating the osteotomized segments and thus in obtaining satisfactory aesthetic or functional outcomes (184–187). To solve these problems, Christian Herlin et al. (35) combined a surgical simulation with the SLS technology to fabricate an implant for repair of a post-traumatic zygomatic deformity. To simulate the contralateral zygoma and the repositioning of the soft tissues, a high resolution multi-slice 3D CT scanner (helix with 0.6-mm slice thickness, 0.4-mm distance between slices, Phillips Brillance) was used to obtain data. A virtual model was then created based on the 3D data and then used for performing virtual simulation. With this virtual model, design and accurate location of the implant became possible. Moreover, based on the virtual model, the implant was manufactured with the SLS technology directly, which reduced time and surgery cost.

RP technologies were proposed to integrate with other methods for repair of maxillofacial bone fractures. Fan Feng et al. (188) presented an approach combining mirror-imaging and SLA technologies to treat four patients who had unilateral malar and zygomatic arch fractures. At first, two 3D skull models were created by using a RP machine. After obtaining data from CT scanning, the first model was created to perform surgery simulation; the other model which was obtained by mirroring the unaffected side was used to shape the titanium plates in advance, and then the plates were fixed into the fractured side. With the mirror-imaging technique, the design of titanium plates or other prostheses could be simplified by mirroring the healthy side to obtain an anatomically symmetric counterpart. This technique made the operation process easy with good esthetic outcomes. With the SLA technology, simulated surgery on RP models based on 3D CT scanning was a feasible solution to guide the reduction of malar and zygomatic arch fractures. The surgeons could see bony structures more clearly and objectively and evaluated pre- and postoperative fracture displacement. The integration of mirror-imaging and SLA technologies led to simple and accurate cure of unilateral facial fractures.

Correction of dento-maxillofacial deformities

In orthognathic surgery, a number of methods are used to correct dento-maxillofacial deformities, such as distraction osteogenesis (189–191), use of customized implant (170) or template (192), free tissue transfer (193) or lipofilling (194), and application of intermediate splints. RP can be integrated with other techniques to produce intermediate splints (195–202). However, such splints may not have sufficient accuracy. To handle this problem, different materials, instruments, and methods (203–209) were introduced at the stage of the RP-reproduced model to improve the accuracy of maxillary positioning during the surgery. By combining RP technologies, optical dental scanning, cone beam computed tomography (CBCT), and manufacturing technique of traditional plaster dental casts, the fabrication of intermediate splints can achieve adequate accuracy for clinical uses.

Distraction osteogenesis is a new technology for correcting dento-maxillofacial deformities (210–212). However, desirable occlusion is difficult to achieve with distraction osteogenesis, and the mandibular movement including both linear and rotational changes is complex. To overcome these limitations, Jun-Young Paeng et al. (213) proposed a systematic analysis-planning protocol using a 3D surgery simulation software and a RP model for effective planning distraction osteogenesis in hemifacial microsomia. Firstly, a 3D model created by the surgery simulation software was used to measure the mandibular deficiency. The angulation of the distraction device to the mandibular border could thus be determined. This was followed by a surgery simulation on the RP model. By assuming that only one movement path of the distal segment was possible during the osteogenesis, the process was simplified and the location and direction of the device were confirmed during the surgery simulation process. Still, the planning protocol provided information about the direction, the sequence, and the desired distance of vertical and horizontal distraction, ensuring desired clinical results. The 3D surgery simulation software and RP model were proved effective for correcting hemifacial microsomia with unidirectional distraction devices.

Libin Zhou et al. (169) used a customized implant to treat a 23-year-old man with an 8-year history of unilateral hemifacial microsomia (Figure 12A). At first, a resin model fabricated by a SLA device was used for preoperative planning to help them understand the 3D deformity of the patient. By projecting a mirror image of the healthy mandible according to analysis of the deformity, a customized implant model was produced (Figure 12B). Based on the implant model, a polymeric implant was fabricated and implanted into the affected side of the mandible to restore facial symmetry. Mirror imaging permitted the exact symmetrical bony reconstruction. The hemifacial microsomia was corrected, and a symmetrical facial contour was obtained, as shown in Figure 12C.

The 3D models play an indispensable role in planning orthognathic surgery. However, use of 3D models for correcting dento-maxillofacial deformities has a strict limitation (214,215). The

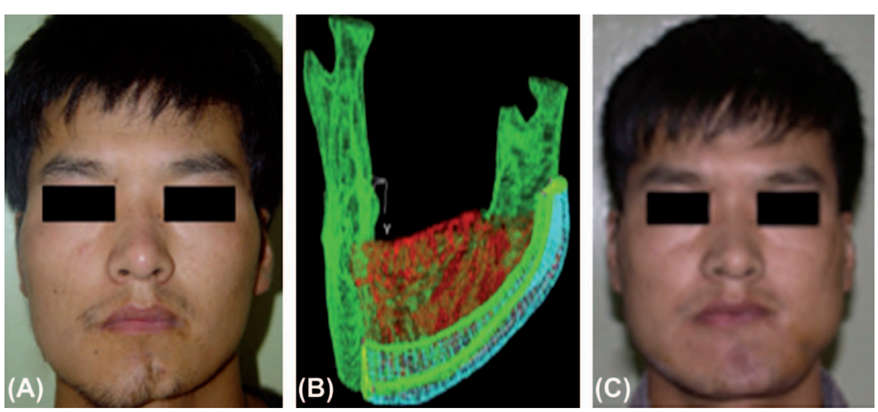

Figure 12. (A) Preoperative view. (B) Computer-aided design. The unaffected right mandible was mirrored to the left (red). The discrepancy between the mirrored right mandible and the native left mandible (green) was extracted (blue). For additional compensation of the atrophied soft tissue, the outer surface was expanded by 1.5 mm. (C) Postoperative view with the facial symmetry reconstructed. Adapted from reference (169) with permission of British Journal of Oral and Maxillofacial Surgery, Elsevier, Copyright 2009.

teeth themselves do not replicate accurately due to their complex anatomical structure and resultant beam hardening. To resolve this problem, Ashraf F. Ayoub et al. (216) developed a simple technique integrating plaster dental casts into a RP-reproduced 3D composite physical model of the mandibular to treat complex cranial and maxillofacial deformities with satisfactory accuracy. The 3D printed model guided the large bone removal and predicted the mediolateral rotation of the proximal mandibular segments. It measured mandibular rotations and the impact of mandibular advancement or set-back on the condylar segment more accurately. These features of the model made its use for producing occlusal wafers to correct dentofacial deformities successful and satisfactory. The 3D printed model of mandible and its associated dentition were sufficiently accurate for supporting surgical diagnosis, planning and simulation, selecting surgical procedures, and producing guiding occlusal wafer.

In orthognathic surgery, the intermediate splint determines the esthetic results. It is important to improve the accuracy of intermediate splint production. In general, the intermediate splints were fabricated manually, and the dimensional errors might come from each step of the whole fabrication (217–222), such as bite registration, facebow registration, and transfer from facebow to articulator. To obtain an accurate intermediate splint, Yi Sun et al. (223) presented a new method that applied three different modalities (CBCT, optical dental scanning, and 3DP) for bimaxillary surgery. Compared with the traditional workflow, this method had much lower differences between the planned and the actual surgical change of the maxillary positioning, found to be 0.50 ± 0.22 mm, 0.57 ± 0.35 mm, and 0.38 ± 0.35 mm in the sagittal, vertical, horizontal direction, respectively (224–228). The method also eliminated errors in facebow registration and in the step of transfer from the facebow to the articulator. The paired-point facebow registration used in this method facilitated the locating of the maxilla.

Another similar study on manufacturing orthognathic splints was reported by Marc Christian Metzger et al. (201). They developed a new approach that combined the conventional splint technique, modern virtual 3D planning, and the 3DP technology to manufacture orthognathic splints for ideal occlusion for correction of dento-maxillofacial deformities. The important details of occlusal anatomy, wear facets, and interdigitation were precisely transformed into the virtual situation, which ensured the efficiency and accuracy of the manufacturing process. The fabrication of the splints was found to be easy, cheap, and fast.

In traditional methods (229,230), intermediate wafer was one of the most frequently used surgical-assisted devices for orthognathic surgery. However, manufacturing the wafer is time-consuming, and positioning the maxilla with the wafer during the operation is difficult. To overcome these challenges, a pair of surface templates fabricated by the SLA technology was developed as an alternative to the use of intermediate surgical wafer for treating a patient with transverse maxillary cant and maxillary midline deviation (Figure 13A–C) (192). The surgeons performed virtual osteotomies and moved the bony segments to the desired position in surgical simulation, which minimized errors in manufacturing surgical wafers. During the surgery, the surgeons used preosteotomy surface templates which were fabricated using the SLA technology to fix the screw holes predrilled on the bone. Hence, the movement and position of the maxilla were maintained by the surface templates instead of the wafer. The patient's maxillary transverse cant and midline deviation were corrected, as shown in Figure 13D and E. Most laboratory and intraoperative steps were saved, and high surgery accuracy was achieved.

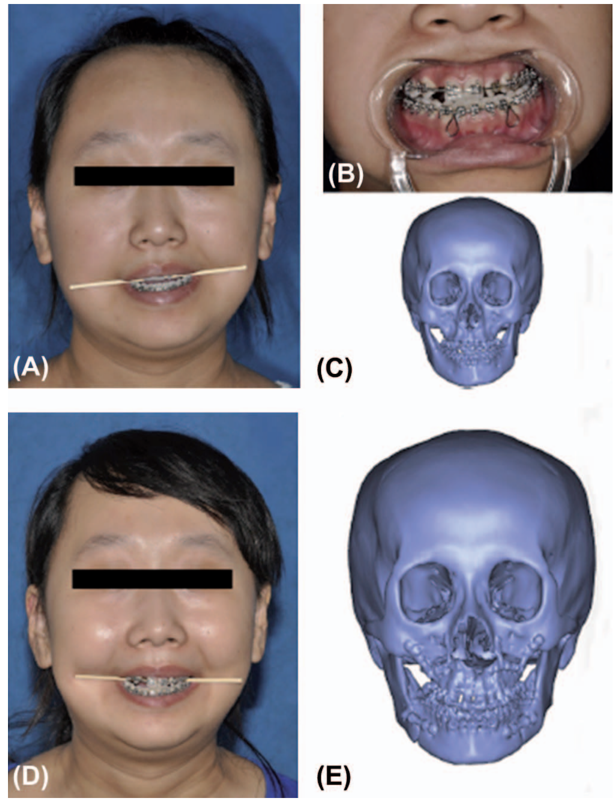

Figure 13. (A) Patient's preoperative frontal view. (B) Frontal view of centric occlusion with transverse maxillary cant and maxilla midline deviation. (C) Preoperative 3D model reconstructed based on CT scanning. (D) Postoperative frontal view: the patient's maxillary transverse cant and midline deviation were corrected as the preoperative surgical design. (E) Postoperative 3D model reconstructed based on CT scanning. Adapted from reference (192) with permission of Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology, Elsevier, Copyright 2010.

Due to geometric complexity of the bony and other facial structures, correcting severe facial asymmetry is still a challenging task. The traditional manual model surgery is time-consuming and fallible for treatment of facial asymmetry. To solve these problems, Laszlo Seres et al. (231) reported a case that used virtual computer-aided surgical planning and an intermediate surgical wafer fabricated by a 3D printer to treat a 26-year-old male patient who had a severe right-sided hemimandibular elongation (Figure 14A–C). Compared to traditional methods using the single-jaw technique, a two-jaw procedure based on virtual planning was performed in this case (232). The mandible was rotated into the correct position following virtual bilateral sagittal split osteotomy, and the treatment planning and model surgery (a virtual splint that can be materialized by RP) were performed simultaneously. The intermediate wafer was fabricated with the highest printing accuracy, indicating its good reliability as a tool for transferring virtual surgery into the operating room. It can be seen that the facial symmetry of the patient was improved significantly (Figure 14D and E) and stable occlusion (Figure 14F) was achieved. The advantages of computer-aided surgical planning and 3D printing for correction of facial asymmetries were clearly demonstrated.

Fabrication of maxillofacial prostheses

Tumor ablation and maxillofacial trauma usually lead to a large area of defects in the maxillofacial region which needs a facial prosthesis (233–237). Various methods which integrate RP technologies (238,239) with advanced imaging techniques, such as 3D

Figure 14. (A) Initial facial view. (B) Initial facial smiling. (C) Pretreatment intraoral photograph. (D) Final facial view. (E) Final facial smiling. (F) Final intraoral photograph. Adapted from reference (231) with permission of Head and Face Medicine, BioMed Central, Copyright 2014.

optical imaging (238) or laser scanning (239), were proposed to fabricate a facial, a nasal, or an auricular prosthesis for aesthetic improvement of an impaired maxillofacial appearance. The combined methods have less discomfort for the patient and no distortion from conventional impression materials or patient position in spite of relatively expensive devices and possible mismatched colors between model and natural skin tones.

In traditional methods, moulage impression is commonly used to restore extraoral maxillofacial defects. However, it is time-consuming and sometimes causes discomfort for the patient, distortion of the site because of the weight of the impression material, and deformation of the soft tissue due to the pressure of the impression material and changes in tissue location with modifications of the patient's position. To solve these problems, Jennifer V. Sabol et al. (238) proposed a protocol, for the first time, using a 3D image capture device (3dMDface^{TM}) (240–243) and the SLA technology to fabricate a facial prosthesis for an 80-year-old female patient who had a adenoid cystic carcinoma to her ethmoid and left maxillary sinus (Figure 15A). By transferring the data into a ZPrint CAD file and a SLA file, the virtual designs from the 3dMDface^{TM} System were converted into a physical model for prosthesis fabrication by the SLA technology (Figure 15B). Based on this model, a stone mold was created using clay and a previously fabricated ocular prosthesis (Figure 15C). After the clay was removed, the cleansed mold was pigmented and packed with a composite material before the final prosthesis was fabricated (Figure 15D). Compared to conventional methods, this new protocol caused less discomfort for the patient without restrictions for materials. Furthermore, the colored mold could provide contours, shading, and an open-eye position. Further research is ongoing toward improvement of model color match of the prosthesis in absence of the patient, enhancement of fit of the prosthesis, and reduction of fabrication time.

As discussed before, most techniques for fabrication of facial prostheses have some drawbacks (244–250), such as deforming soft tissues and causing discomfort for patients. To avoid these disadvantages, Zhihong Feng et al. (239) reported a novel approach using 3D optical imaging and the SLA technology to design and fabricate a realistic facial prosthesis for a patient who had right facial malformation after resection of a tumor (Figure 16A). The software, Geomagic Studio 10.0, was first used to cut a lateral margin area (2 mm wide and 0.5 mm thick) on the 3D preliminary facial prosthesis (Figure 16B and C). A wax prosthesis was then manufactured by using WAX-100 composite wax powder with

Figure 15. (A) Picture of patient taken with 3dMDfaceTM. (B) Color model made with the ZPrinter® 450 (Z Corporation, Burlington, MA) and a high performance composite material. (C) Clay sculpture on model. (D) Patient with final prosthesis and glasses. Adapted from reference (238) with permission of Journal of Prosthodontics, John Wiley and Sons, Copyright 2011.

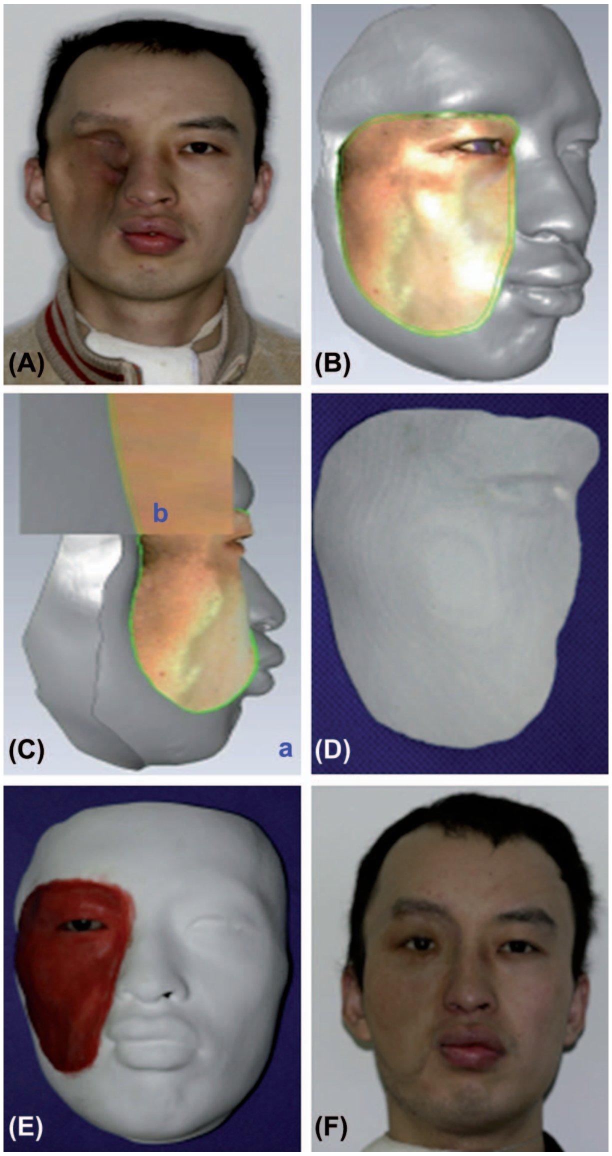

Figure 16. (A) Patient with facial malformation. (B) A margin 2 mm wide was measured and cut. (C) A layer of the virtual preliminary prostheses 0.5 mm thick was subtracted (a) and the subtracted layer of 0.5 mm magnified (b). (D) Rapid prototype wax prosthesis. (E) Finished wax prosthesis with surface texture, follicular orifices, and adaptable margin. (F) Patient with final silicone prosthesis. Adapted from reference (239) with permission of British Journal of Oral and Maxillofacial Surgery, Elsevier, Copyright 2010.

an AFS-360 laser RP machine. After post-processing, the prosthesis was used to reconstruct the large defects on the patient's face, while other characteristics of the face such as surface texture and follicular orifices that did not appear in the wax prosthesis were created by a technician. After the lateral margin area that had been removed from the virtual preliminary prosthesis was restored (Figure 16D and E), the wax prosthesis was modified and refined on the patient's face, and processed into a silicone prosthesis using traditional procedures (Figure 16F). This method proved to be particularly useful for designing the shape and position of the prostheses. Still, it has less risk of error and less reliance on artistic skill to generate a highly realistic prosthesis.

Medical adhesives, mechanical support (e.g. eyeglasses), and osseointegrated craniofacial implants are extensively used for retaining nasal prostheses (251–256). However, some imperfections of these traditional materials exist. The fabrication of nasal prosthesis is time-consuming, and thin margins of the prosthesis and soft tissues are easily damaged when they are removed for maintenance and cleaning. Also, an eyeglasses-supported nasal prosthesis system may lead to displacement with an opening at the margins of the prosthesis. Hence, an immediate solution is needed. Leonardo Ciocca et al. (41) fabricated an immediate provisional eyeglasses-supported nasal prosthesis with laser scanning and the FDM technology for a 58-year-old patient who lost his entire nose after being shot (Figure 17A). This multidisciplinary protocol cut the time for provisional prosthesis manufacturing from 27 hours (traditional methods) to 3.66 hours. It also reduced costs from $1,020 (conventional manual procedures) to $520. The quality of the patient's life was improved by using a digital eyeglasses model and nasal prosthesis (Figure 17B).

Another example of fabricating a nasal prosthesis using the RP technology (SLS) was reported by Guofeng Wu et al. (13). A customized facial prosthesis was fabricated as an alternative to wax or clay sculpted patterns used in the traditional production of facial prosthesis. The time for sculpting was significantly decreased because the nasal waxing was fabricated by the SLS machine automatically. Besides, satisfactory reproduction of the facial contours was achieved due to the high accuracy of the computed model (the precision was within 10 μm). Compared to the cost of SLA photopolymer resins, the cost of SLS wax was decreased by 40%. The market price of a SLS machine was only about 75% of the price of a SLA machine. Hence, the SLS technology is more advantageous for both patient and the maxillofacial prosthetist.

The design and manufacture of an auricular prosthesis for maxillofacial defects were investigated intensively (257–264). However, the unresolved problem is that the base of the external ear must fit perfectly onto the defective side. To achieve this goal, Leonardo Ciocca et al. (172) introduced the 3DP technology to make an implant-retained maxillofacial prosthesis. It allowed scanning and positioning of the lost ear directly onto the computer screen, which eliminated the diagnostic waxing, making an impression of the healthy and defective side unnecessary. With rapid prototyping, the preparation of the stone mold is also unnecessary.

Discussion

RP is a fast-growing manufacturing technology that has been extensively used in medicine, especially dentistry including orthopedics, prosthetics, implantology (6,7), and oral and maxillofacial surgery (8–13). Its applications to maxillofacial reconstruction include restoration of acquired maxillofacial deformities and defects, reduction of functional bone tissues, correction of dento-maxillofacial deformities, and fabrication of maxillofacial prostheses. With RP technologies, complex 3D models, personalized implants, intermediate splints, and prostheses are fabricated

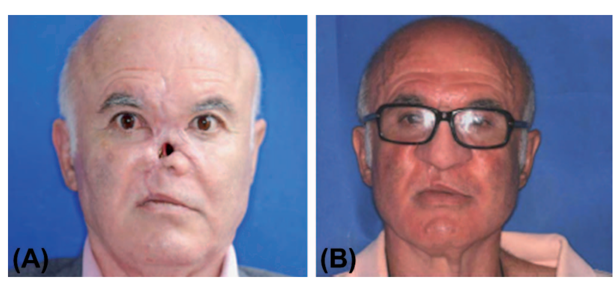

Figure 17. (A) Initial appearance of patient's face with injury from accidental gunshot. (B) Final prosthesis on patient. Adapted from reference (41) with permission of Journal of Rehabilitation Research and Development, U.S. Department of Veterans Affairs, Copyright 2010.

for the reconstruction. To improve RP-assisted maxillofacial reconstruction, however, four technical challenges resulting from the inherent characteristics of RP technologies need to be tackled, as shown in Figure 18.

Conflicts between precision and speed: There are conflicts between precision and speed of the production associated with the principle of RP techniques. In some cases (265–273) the precision of the finished product by RP technologies is not high enough to reach a strict standard, and thereby a slower production speed would be necessary. This is particularly true for fabrication of parts with thin walls or fine patterns which are difficult for RP technologies. On the other hand, RP systems usually create prototype parts in hours. With increasing product volume, the production time needs to be prolonged. The precision and speed are conditional upon each other, and the manufacturing efficiency may not meet the requirement of mass production.

To resolve this conflict and improve precision and speed for maxillofacial reconstruction, several factors require attention. First, the whole production process should be taken into consideration. Any improvement in design, revision, and creation processes may result in a more accurate model for maxillofacial reconstruction, which will end up making fewer flaws to the final prototypes in a shorter period. Second, the precision and speed of RP technologies for maxillofacial reconstruction depend on the materials used. It is important to select or control the phase, morphology, and microstructure of materials for prototyping (274). The effect of modifying morphology and structure of materials on the RP process can be confirmed by pre-sintering material particles using the SLS technology which decreases each layer thickness, leading to improved surface characteristics for manufacturing models with high precision and speed (275,276) for maxillofacial reconstruction. Third, the manufacturing process is dynamical. Both the non-equilibrium nature of materials and the stability of the laser beam or light influence the RP precision and speed. Further studies on understanding of beam–material interaction are crucial. Fourth, intensive effort must be made on predicting and controlling the formation of intermediate products and microstructures during manufacturing for improved precision and speed. To achieve this purpose, theoretical modeling and simulation for the whole manufacturing process are necessary. From this perspective, establishing appropriate heat and mass transfer models for simulation is critical. Fifth, the improvement in precision and speed requires a RP process database, which will optimize the material design and preparation, and help select the optimal RP techniques for fast and precise maxillofacial reconstruction without repetition of unnecessary and unfavorable manufacturing processes. For example, in oral and maxillofacial surgery, a number of techniques were developed to measure the precision of medical models (238,239), but currently there is no gold standard. It is necessary to select the most reliable measurement techniques to determine the precision of the models based on a relevant database. Sixth, the forming heads of the RP machine may significantly affect the speed and precision. Although multiple types of the heads (laser-based, light-based, heat-based, or laminated) have been developed, further work must be devoted to improving forming heads for high precision and speed in rapid prototyping. Finally, as an additional step, post-processing is a good approach for increasing RP precision with little sacrifice of speed.

Variety of materials: Nowadays, a number of materials, such as metals, stone, and plastics, have been used to manufacture products, but the selection for maxillofacial reconstruction is still limited. There exist some limitations on many of common materials used for RP-assisted maxillofacial reconstruction. For

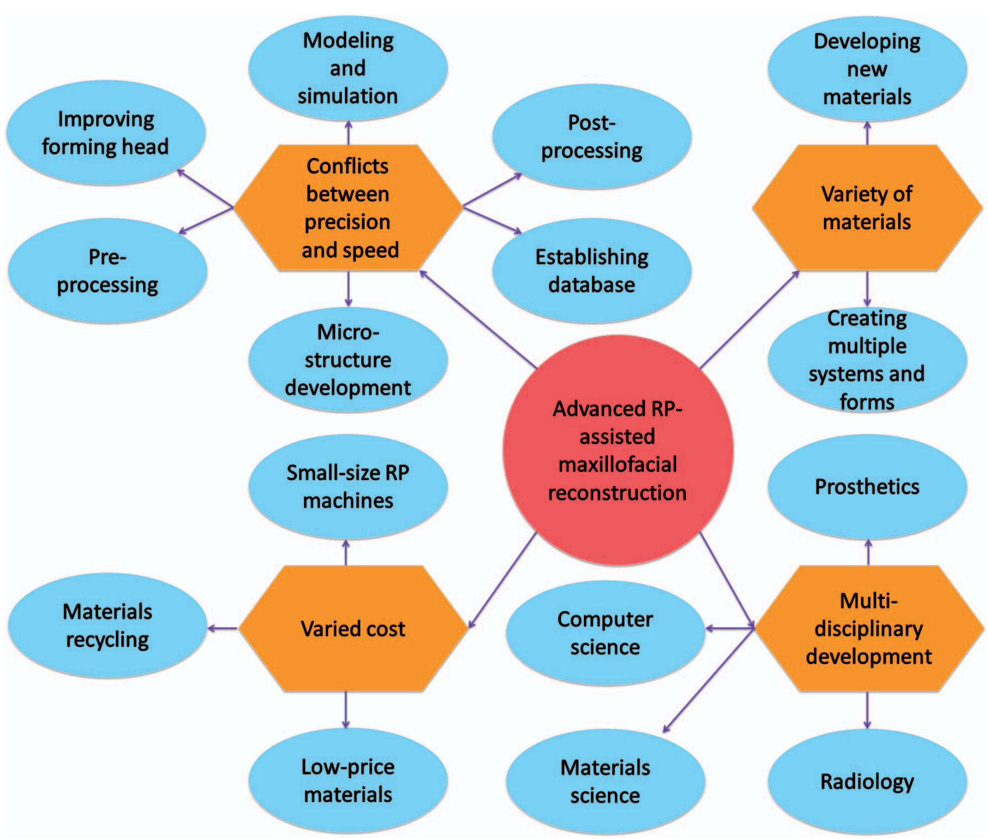

Figure 18. Solutions for technical challenges faced by advanced RP-assisted maxillofacial reconstruction.

example, titanium cannot replace ingrowing bone or function as a carrier system for bioactive substances (277) satisfying the aesthetic requirements. Various alloplastic bone replacement materials are only suitable for non- or low-load-bearing graft sites. Therefore, new materials should be developed for RP technologies. In this regard, promising candidates include nano-materials, composite materials, smart materials, heterogeneous materials, and functional gradient materials, especially easy-shaping metallic materials. Further effort to create multiple systems and forms of materials, including pre-alloyed/blended/composite metallic (e.g. Fe, Ni, Ti, Al, Cu, and Mg) based powders (278) is also crucial. For function purposes, new materials loading with bioactive substances such as proteins or antibiotics with RP technologies are necessary for fabricating implants for restoration of maxillofacial defects. Novel polymers that will be easier to cure and that are temperature-resistant may also be introduced for maxillofacial reconstruction because more stable materials will make prototypes more adaptive to actual service conditions. Additionally, the variety of materials can be further enhanced by modifying the form of materials. As noted before, powdered materials are very common because many RP technologies involve powder spreading (e.g. SLS) or powder feeding (e.g. 3DP). Since they have relatively low flowability during manufacturing, measures to improve their chemical and physical properties by optimizing preparation techniques are important and necessary for selecting machinable, moldable, or castable materials for a successful RP application in maxillofacial reconstruction.

Varied cost: The cost of a prototype/model produced by RP technologies for maxillofacial reconstruction may vary significantly, depending on the size of the item, the price of manufacturing materials and RP machines, and the number of revisions needed to reach the final product-ready version. Hence, the cost associated with prototyping can be an attribute or a detriment, hinging on the actual product being developed. RP technologies may be inappropriate for mass production in medicine owing to the high unit-of-production cost. This is partly because some printed materials for maxillofacial reconstruction are expensive. For instance, the price of some basic materials such as photosensitive resin, ceramic powder, and metal is between \$200 and \$500/kg. Another reason is the higher cost of RP machines compared with conventional manufacturing devices. For example, a small, portable, desktop 3D printing machine, Objet24, was developed recently by Objet Geometries. Although it was cheaper than Objet's other machines, it still cost almost \$20,000 (279).

To reduce cost for RP-assisted maxillofacial reconstruction, new and low-priced materials should be developed. Small, portable and desktop RP machines should also be created for distributed production for the reconstruction and needs of family daily life. A promising method for lowering facility cost is to develop office-based systems (280), which are controlled by a clinician using CAD for the manipulation of images. These systems were believed to be less expensive based on a simpler technology. Another approach to lower facility cost is building RP machines using waste materials and open sources. It has been demonstrated that the cost of RP machines, such as 3DP printers, could be decreased by over 80% using open-source hardware (281).

Multi-disciplinary development: Without doubt, RP technologies will have wider applications in oral and maxillofacial surgery, such as correction of temporomandibular joint ankylosis (282), restoration of congenital cleft lip, cleft palate, and facial cleft (283), and minimally invasive surgery. For further development of RP technologies in maxillofacial construction, promoting multidisciplinary research is highly recommended because the co-operation between the RP technology, oral and maxillofacial surgery, prosthetics, radiology, materials science, and computer science is essential for successful applications. For example, advanced imaging techniques such as spiral CT or CBCT, laser or optical scanning, and mirror-imaging techniques should be integrated with RP techniques for satisfactory maxillofacial surgery, especially for repairing maxillofacial fractures and for improving facial symmetry. This integration is also important for realizing remote on-line manufacturing under network control. In a word, the collaboration across the disciplines is able to improve efficiency and quality of RP-assisted oral and maxillofacial surgery, promoting the development of dentistry.

Conclusion

Rapid prototyping is a fast-growing manufacturing technology that has been widely used in medicine, including oral and maxillofacial surgery, due to its ability to promote product development while at the same time reducing cost and depositing a part of any degree of complexity theoretically. The paper reviews the fundamentals and applications of RP technologies to maxillofacial reconstruction. The historical development, characteristics, and the principles of RP technologies are discussed. The applications of RP to the main subfields of maxillofacial reconstruction, namely restoration of maxillofacial deformities and defects, repair of functional bone tissues, correction of dento-maxillofacial deformities, and fabrication of maxillofacial prostheses are elaborated. Current challenges for further development of RP-assisted maxillofacial reconstruction from perspectives of precision and speed, materials, cost, and integration of methods are discussed, and corresponding potential measures/solutions are proposed. This review is expected to provide an insight into the current status and future development of RP technologies in oral and maxillofacial surgery and in dentistry.

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