

Review Article

Rapid Prototyping Technologies and their Applications in Prosthodontics, a Review of Literature

Kianoosh Torabi ^a, Ehsan Farjood ^a, Shahram Hamedani ^b

^aDept. of Prosthodontics, School of Dentistry, Shiraz University of Medical Sciences, Shiraz, Iran.

^b DDS, MScD. Private Practice, Shiraz, Iran

KEY WORDS

CAD-CAM;
Three-
Dimensional/methods;
Computer-aided rapid proto-
typing model;
Computer-aided design;
Dentistry

ABSTRACT

The early computer-aided design/computer-aided manufacturing (CAD/CAM) systems were relied exclusively on subtractive methods. In recent years, additive methods by employing rapid prototyping (RP) have progressed rapidly in various fields of dentistry as they have the potential to overcome known drawbacks of subtractive techniques such as fit problems. RP techniques have been exploited to build complex 3D models in medicine since the 1990s. RP has recently proposed successful applications in various dental fields, such as fabrication of implant surgical guides, frameworks for fixed and removable partial dentures, wax patterns for the dental prosthesis, zirconia prosthesis and molds for metal castings, and maxillofacial prosthesis and finally, complete dentures. This paper aimed to offer a comprehensive literature review of various RP methods, particularly in dentistry, that are expected to bring many improvements to the field. A search was made through MEDLINE database and Google scholar search engine. The keywords; 'rapid prototyping' and 'dentistry' were searched in title/abstract of publications; limited to 2003 to 2013, concerning past decade. The inclusion criterion was the technical researches that predominately included laboratory procedures. The exclusion criterion was meticulous clinical and excessive technical procedures. A total of 106 articles were retrieved, recited by authors and only 50 met the specified inclusion criteria for this review. Selected articles had used rapid prototyping techniques in various fields in dentistry through different techniques. This review depicted the different laboratory procedures employed in this method and confirmed that RP technique have been substantially feasible in dentistry. With advancement in various RP systems, it is possible to benefit from this technique in different dental practices, particularly in implementing dental prostheses for different applications.

Received November 2013;
Received in revised form March 2014;
Accepted May 2014.

Corresponding Author: Shahram Hamedani, School of Dentistry, Ghasrodasht Ave, Shiraz, Iran
P.O Box: 71345-1836 Tel and Fax: +98-071-36280458 Email: denth_dr@sums.ac.ir
shahram.hamedani@kclalumni.net

Cite this article as: Torabi K., Farjood E., Hamedani Sh. Rapid Prototyping Technologies and their Applications in Prosthodontics, a Review of Literature. *J Dent Shiraz Univ Med Sci.*, March 2015; 16(1): 1-9.

Search Strategy

This paper aimed to offer a comprehensive literature review of various rapid prototyping (RP) methods, particularly in dentistry, that are expected to bring many improvements to this field. The study was purposed to focus on the technical feasibility of the technique. A search was made through MEDLINE database and

Google scholar search engine. The keywords; 'rapid prototyping' and 'dentistry' were searched in title/abstract of publications; limited to 2003 to 2013, concerning past decade. The inclusion criterion was the technical researches that predominately included laboratory procedures. The exclusion criterion was detailed clinical and excessive technical procedures. References

of selected articles were also reviewed for possible inclusion in the study. Titles and abstracts of all selected articles were reviewed and upon identification for possible inclusion, full text of the article was reviewed thoroughly and cross-matched with the predefined inclusion criteria. A total of 106 articles were retrieved, recited by authors and only 50 met the specified inclusion criteria for this review. Selected articles had used rapid prototyping techniques in various fields in dentistry through different techniques.

Literature review

The first attempts to automate the production of dental restorations began more than 20 years ago. [1-2] Subsequently, computer-aided design/computer-aided manufacturing (CAD/CAM) technologies were introduced to the dental community in early 1980s. [1] All CAD/CAM systems have three functional components: 1) A digitalization tool/scanner that transforms geometry into digital data that can be processed by a computer. 2) Software which processes scanner data and produces a data set readable by a fabrication machine. 3) A manufacturing technology that takes the data set and transforms it into the desired product by fabricating the restoration. [1-2] To fabricate a physical prototype in industry and/or medicine, two different approaches have been utilized: subtractive and additive. [3] In a subtractive method, material is subtracted from an initial block of material to leave the desired shaped part (such as a dental restoration). [4]

Early CAD/CAM systems relied almost exclusively on cutting a restoration from a prefabricated block with the use of burs, diamonds or diamond disks. [5] This is usually accomplished by conventional numeric control (NC) machining such as milling. [6] Subtractive processes use carefully-planned tool movements to cut material. The NC machining is used typically in small model-making machines for which they are used to fabricate metallic and/or ceramic crowns in dentistry. [7] The subtractive fabrication can create a complete shape effectively, though at the expense of material being wasted. In a typical subtractive method in dentistry, approximately 90 percent of the initial block is removed to create a typical dental restoration. [1] Torabi *et al.* in their studies concluded that the CAD/CAM system could compete well with conventional systems

for clinical fit and fracture resistance and can achieve acceptable results in vitro. [8-9] Vojdani *et al.* [10] compared the marginal and internal fit of metal copings cast from wax patterns fabricated with a CAD/CAM system and the conventional method. Their findings showed that only conventional method could result in copings with clinically acceptable margins of less than 120 μ m. [10]

Alternatively, additive fabrication is a process in which the final desired part is manufactured by adding multiple layers of material on top of one another. [11] The key idea of this innovative method is that the three dimensional CAD (3D-CAD) model is sliced into many thin layers and the manufacturing equipment uses this geometric data to build each layer sequentially until the part is completed. Hence, additive fabrication is often referred as “layered manufacturing”, “direct digital manufacturing”, “three-dimensional printing”, or “solid freeform fabrication”. [12-13] Additive technology scan yield arbitrarily complex shapes with cavities and undercuts; frequently the case in human anatomy structures. [9-11]

Subtractive methods have some limitations in comparison with additive techniques: The precision fit of the inside contour of the restoration depends on the size of the smallest usable tool for each material and if the cutting tool was larger in diameter than some parts of the tooth preparation, it will result in reduction of internal fit precision or inferior marginal properties.

1. A considerable amount of raw material is wasted because the unused portions of the mono-blocks must be discarded after milling and recycling of the excess ceramic material is not feasible.
2. Milling tools are exposed to heavy abrasion and wear, therefore, withstanding only short running cycles.
3. Microscopic cracks can be introduced into ceramic surfaces due to machining of this brittle material.
4. It is neither easy nor economic for big, full undercuts and/or complex milling parts. [9, 14-16]

Rapid prototyping (RP) techniques, the so-called “generative manufacturing techniques”, exhibit the potential to overcome the described shortages. [17-20] RP simply consists of two phases: virtual phase (modeling and simulating) and physical phase (fabrication). Virtual prototyping is development of model by dynamic and

interactive simulation. The course of forming the physical model is formation of 3D physical model by CAD. Some characteristics of the process can be stated as:

Objects can be produced with different geometrical intricacy without involving the setup of the machine or final assembly. Objects can be produced by employing different types of materials such as composites. Moreover, with a controlled conduction, different materials can be used at different places in an object. The construction of complex objects can be fast, convenient and uncomplicated by additive fabrication systems. [12]

The RP techniques have been employed to build complex 3D models in medicine since the 1990s. [21-24] The chief benefit of RP techniques is the medical models that can be produced with undercuts, voids, intricate internal geometrical details and anatomical landmarks such as facial sinuses and neurovascular canals. [15, 25] The RP model is currently employed to improve medical diagnosis and to provide a precise surgical treatment plan. The technique would help shorten the surgery time and consequently reducing the patients' risk. [15, 26-27]

In current years, RP is becoming more appealing for dental purposes. The innovations in molding materials and forming procedure have improved the RP techniques so that this technology is no longer adopted only for prototyping; it is used for reproduction of real functional elements. [15, 28-29] The feasibility of this technique is increasing in different dental practice fields such as oromaxillofacial surgery and prosthesis, [30-39] production of surgical guide or physical models in dental implant therapies, [40-43] and prosthodontics. [15, 44-45]

The RP techniques can also be employed to plan, produce, and develop dental prostheses such as crowns, fixed and removable partial dentures (FPDs and RPDs) and also copings. This technique would eliminate any faults caused by human skills and intervention in traditional fabrication of dental prosthesis and comparably is time saving. [15, 46-47] Digital dental surveying and RP-produced sacrificial patterns could be accomplished to fabricate RPDs frameworks. [48] Moreover, RP has been used to reduce the extra-oral time which need to be spent in autogenous tooth transplantation. [49] In 2011, Morea *et al.* used the SLA technique for accurate insert-

ion of the orthodontic mini screws. [50]

Yu *et al.* used this technique for producing the pre-surgical nasoalveolar molds in treatment of infants suffering from unilateral cleft lip and palate. [34] The dental practice has also benefited from RP in accurate reconstruction of maxillofacial defects [51-55] and also in osteogenic distraction with satisfactory outcomes. [56-58]

Classification of RP technologies in dentistry

The frequent technologies that are adopted in dental practice are stereolithography (SLA), inkjet-based system (3DP), selective laser sintering (SLS), and fused deposition modeling (FDM). While various materials can be employed in these technologies; wax, plastics, ceramics, and metals are commonly used by several studies in dentistry. [7, 12]

Stereolithography (SLA)

This method includes a photosensitive liquid resin bath, a model-building platform, and an ultraviolet (UV) laser for curing the resin. [7] The layers are cured and bond successively to form a solid object for impression rationales, exploited in reconstructive surgeries and subperiosteal surgery in dental implant therapies (Figure 1). Fabrication of surgical drilling templates during insertion of dental implants is the current foremost purpose for using SLA models in dental practice. [7] SLA-made surgical drill guides have been proved to benefit from high precision by several well-documented researches. [59-65]

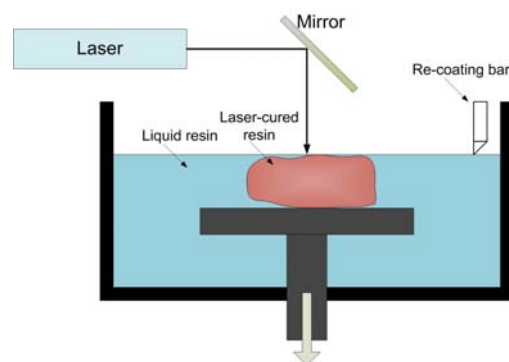


Figure 1: Schematic depiction of SLA

Inkjet-based system or 3DP

In this technique, a measured amount of the raw powder-form material is initially dispensed from a container by a moving piston (Figure 2). A roller then distributes and compresses the powder at the top of the fabrication chamber. A liquid adhesive is then deposited from the

multi-channel jetting head in a 2D pattern onto the powder, make it bond and form a layer of the object. When a layer is completed, the piston helps spread and join the next powder layer. This incremental (layer-by-layer) method is gradually continued to achieve a complete built up of prototype. [7] Unbound powder is swept up subsequent to a heating process, leaving the fabricated part sound and intact.

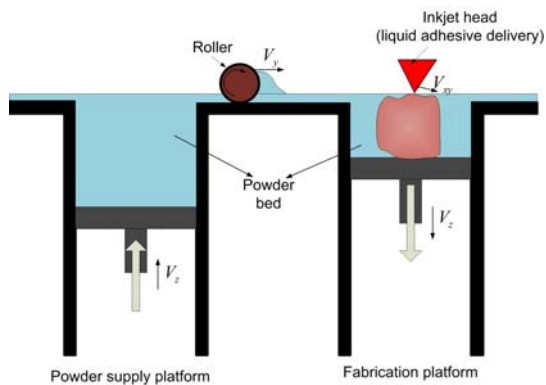


Figure 2: A schematic representation of 3DP technique

Selective Laser Sintering (SLS)

Figure 3 shows a schematic depiction of the selective laser sintering method (SLS). In SLS method, layers of particular powder material are fused into a 3D model by adopting a computer-directed laser. A roller distributes the powdered material over the surface of a build cylinder. Powder is spread layer-by-layer on top of the preceding hardened layer and sintered repeatedly. [7, 12-13] To hold the new fresh layer of powder, the supporting platform relegates one object layer thickness. The surface of this firmly compressed powder is then exposed to a beam of laser. The procedure is self-sustaining and all parts can be bond layer-by-layer. [7] SLS technique has significant advantages in dentistry,

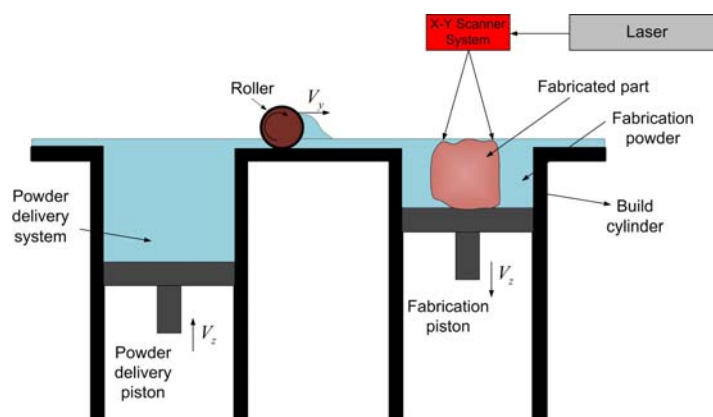


Figure 3: A Schematic image of SLS technique

particularly prosthodontics, since various thermoplastic materials such as nylon composite, investment casting wax, metallic materials, ceramics and thermoplastic composites can be used in this method. [7, 45]

Fused Deposition Modeling (FDM)

The FDM is a rapid prototyping technique in which a thermoplastic material is extruded layer by layer from a nozzle, controlled by temperature. In this technique, a filament of a thermoplastic polymer material suckles into the temperature-controlled FDM extrusion nozzle dome. It is then heated to a free-flowing semi-liquid form. The motion of the nozzle head is controlled by a processor and traces and deposits the material in extremely thin layers onto a subsidiary platform. The head leads the material into place with an ample precision. A portion of the subject is built up layer by layer and the material solidifies within 0.1s after being ejected from the nozzle and bonds to the layer below. The supporting structures are contrived for overhanging geometries and are later removed by cutting them out from the object. [7]

The applications of RP techniques in facial and dental prosthesis

RP techniques are now regarded as a promising alternative for dental prosthesis production. [15] This review particularly focuses on fabrication of wax pattern of prosthesis, all-ceramic crowns, metal prostheses (in cluding FPDs and framework for removal partial dentures) and casts for prostheses.

Dental prosthesis wax pattern fabrication

With the introduction and attractiveness of RP technology, a new style is possible for automatic wax-up const-

ruktion [66-67] illustrated in Figure 4. After the wax pattern is fabricated by RP, the traditional lost-wax process is still needed. The process is more affordable than laser melting or sintering direct manufacturing processes, which still remains financially unattainable for most dental laboratories. [15]



Figure 4: Wax-patterns fabricated by RP technology

Rapid prototyping of dental (facial) prosthesis mold (shell) Mold (shell) for metal casting

3D printing produces ceramic casting molds for metal casting using an incremental printing method. [68] With RP techniques many labor-intensive and time-consuming steps of the traditional investment casting technique is eliminated. [15] The technique also skips the process of design and manufacturing of wax and core tooling, wax and core molding, wax assembly, shell dipping and drying, and wax elimination. [15]

Mold for facial prosthesis

RP techniques have been employed effectively for fabrication of facial prosthesis over the past decade. [15, 39, 69] Pattern fabrication with the aid of RP, has been a feasible procedure, although, the conventional flasking and investing procedures were still crucial to make the actual prosthesis. Using a mold would remove the conventional flasking and investment procedures, and would shorten the process of making the prosthesis. [15, 70] Moreover, the generated resin mold can be kept since the mold is long-lasting and allows the pouring in multiple times. [71]

Mold for complete dentures

The limited available research articles reveals that advanced manufacturing technologies have not been successfully implemented in this field yet. [72] The technology briefly is comprised of the instituting a 3D graphic record of artificial teeth for parameterization positioning, yielding 3D data of edentulous models and

rims in centric relation, finding a CAD route and emergence of a software for complete dentures, fabricating physical flasks (molds) by 3DP, and finishing the complete denture using a traditional laboratory procedure. [15, 73]

Direct dental metal prosthesis fabrication

RP technology, particularly selective laser melting (SLM) and selective laser sintering (SLS) technology have been on the focus of attention of scientists for the brisk fabrication of high-precision metal parts with various resources and shapes. [53] Dental prostheses are very appropriate to be processed by employing SLS/SLM technique, regarding their complex geometry and their capability to be customized without the extensive manual pre- or post-processing steps. [15, 74]

All-ceramic restoration fabrication

A direct inkjet fabrication process has been anticipated for the fabrication of the green-zirconia all-ceramic dental restoration using a slurry micro extrusion process. [17] This innovative method is a favorable CAD/RP system with great ability to produce all-ceramic dental restorations with high precision, cost competence, and minimum material intake. This method is still in the experimental phase. [17]

In general, the advantages of CAD/CAM technique can be concluded as [1] elimination of disruptions of the impression material since the impression phase is eliminated [2] By using the surface scanner, the model can be produced without the potential possibility of tissue deformation [3] the model is formed from natural tissues, therefore, more accurate-looking prosthesis is obtained [4] less space for storage is needed since the models are stored in hard disks. When compared to all these advantages, the most highlighted disadvantage of CAD/CAM technique is its high cost. Even though most of the procedure is accomplished by the computer, proficiency of the clinician in application and coloring would impact the success of the final prosthesis. [75]

Conclusion

The literature review depicted that rapid prototyping (RP) techniques have been substantially employed in dentistry. A combination of dental sciences and manufacturing technologies is the notion behind use of RP in

fabrication of dental prosthesis. Multiple steps should be taken in fabrication of prosthesis or restoration in conventional methods which would abide manual errors and spends lot of time of dentist, laboratory technician and patient to obtain a good fitting prosthesis. With the aid of computer in RP, the numbers of steps are reduced, time is saved and dental models are reconstructed with high level of accuracy, precise form and shape with pertinent reproducibility. [76]

With advancement in various RP systems, it is possible to benefit from this technique in different dental practices, particularly in implementing dental prostheses for different applications. With research and development on a variety of RP systems and correspondingly built materials, it is possible to generate different kinds of dental prostheses for different applications.

The limited confines of the RP technology include the high cost of the tools, complicated machinery engaged and dependency on an expertise to run the machinery during production. The authors believe that RP techniques are increasingly playing an imperative role in prosthodontics and will become one of the mainstream technologies for digital fabrication of dental prostheses in near future.

Conflict of Interest

None to declare.

References

- [1] Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: current systems and future possibilities. *J Am Dent Assoc* 2006; 137: 1289-1296.
- [2] Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. *Br Dent J* 2008; 204: 505-511.
- [3] Liu Q, Leu MC, Schmitt SM. Rapid prototyping in dentistry: Technology and application. *Int J Adv Manuf Technol* 2006; 29: 317-335.
- [4] Filser F, Kocher P, Weibel F, Lüthy H, Schärer P, Gauckler LJ. Reliability and strength of all-ceramic dental restorations fabricated by direct ceramic machining (DCM). *Int J Comput Dent* 2001; 4: 89-106.
- [5] Witkowski S. (CAD-)/CAM in der Zahntechnik: Buyer's Guide 2003. *Zahntech Mag* 2002; 6: 696-709.
- [6] Petzold R, Zeilhofer HF, Kalender WA. Rapid prototyping technology in medicine--basics and applications. *Comput Med Imaging Graph* 1999; 23: 277-284.
- [7] Azari A, Nikzad S. The evolution of rapid prototyping in dentistry: a review. *Rapid Prototyping J* 2009; 15: 216-225.
- [8] Torabi Ardekani K, Ahangari AH, Farahi L. Marginal and Internal Fit of CAD/CAM and Slip-Cast Made Zirconia Copings. *J Dent Res Dent Clin Dent Prospects* 2012; 6: 42-48.
- [9] Torabi K, Ahangari AH, Salehi S, Motamedi M. A Comparison of fracture resistance of zirconia copings made with CAD/CAM technology and slip casting technique. *J Dent Shiraz Univ Med Scien* 2012; 12: 327-333.
- [10] Vojdani M, Torabi K, Farjood E, Khaledi AAR. Comparison the Marginal and Internal Fit of Metal Copings Cast from Wax Patterns Fabricated by CAD/CAM and Conventional Wax up Techniques. *J Dent Shiraz Univ Med Sci* 2013; 14: 118-129.
- [11] Cohen A. Vacuum forming applications using rapid prototyping technology. *Object Geometries: White Paper*; 2008. available at: http://www.tritech3d.co.uk/images/contentitems/63_1_1.pdf
- [12] Andonović V, Vrtanoski G. Growing rapid prototyping as a technology in dental medicine. *Mech Eng Sci J* 2010; 29: 31-39.
- [13] Weiss LE. Process overview. Rapid prototyping in Europe and Japan. Loyola College of Maryland, Baltimore, MD. Available at: http://www.wtec.org/loyola/rp/a_bios.htm#LWeiss
- [14] Witkowski S. (CAD-)/CAM in dental technology. *Quintessence Dent Technol* 2005; 28: 169-184.
- [15] Sun J, Zhang FQ. The application of rapid prototyping in prosthodontics. *J Prosthodont* 2012; 21: 641-644.
- [16] Ebert J, Ozkol E, Zeichner A, Uibel K, Weiss O, Koops U, et al. Direct inkjet printing of dental prostheses made of zirconia. *J Dent Res* 2009; 88: 673-676.
- [17] Wang JW, Shaw LL. Fabrication of functionally graded materials via inkjet color printing. *J Am Ceram Soc* 2006; 89: 3285-3289.
- [18] Tay BY, Evans JRG, Edirisinghe MJ. Solid Freeform Fabrication of Ceramics. *Int Mater Rev* 2003; 48: 341-370.
- [19] Özkol E, Ebert J, Uibel K, Wätjen AM, Telle R. Development of high solid content aqueous 3Y-TZP suspensions for direct inkjet printing using a thermal inkjet printer. *J Eur Ceram Soc* 2009; 29: 403-409.
- [20] Noguera R, Lejeune M, Chartier T. 3D fine scale ceramic

- components formed by ink-jet prototyping process. *J Eur Ceram Soc* 2005; 25: 2055-2059.
- [21] Potamianos P, Amis AA, Forester AJ, McGurk M, Bricher M. Rapid prototyping for orthopaedic surgery. *Proc Inst Mech Eng H* 1998; 212: 383-393.
- [22] Petzold R, Zeilhofer HF, Kalender WA. Rapid prototyping technology in medicine--basics and applications. *Comput Med Imaging Graph* 1999; 23: 277-284.
- [23] Webb PA. A review of rapid prototyping (RP) techniques in the medical and biomedical sector. *J Med Eng Technol* 2000; 24: 149-153.
- [24] Swan S. Integration of MRI and Stereolithography to Build Medical Models. A Case Study. *Rapid Prototyping J* 1996; 2: 41-46.
- [25] Jamieson R, Holmer B, Ashby A. How rapid prototyping can assist in the development of new orthopaedic products - a case study. *Rapid Prototyping J* 1995; 1: 38-41.
- [26] Kai CC, Meng CS, Ching LS. Rapid prototyping assisted surgery planning. *Int J Adv Manuf Technol* 1998; 149: 624-630.
- [27] Klein HM, Schneider W, Alzen G, Voy ED, Günther RW. Pediatric craniofacial surgery: comparison of milling and stereolithography for 3D model manufacturing. *Pediatr Radiol* 1992; 22: 458-460.
- [28] Esses SJ, Berman P, Bloom AI, Sosna J. Clinical applications of physical 3D models derived from MDCT data and created by rapid prototyping. *AJR Am J Roentgenol* 2011; 196: 683-688.
- [29] Goiato MC, Santos MR, Pesqueira AA, Moreno A, dos Santos DM, Haddad MF. Prototyping for surgical and prosthetic treatment. *J Craniofac Surg* 2011; 22: 914-917.
- [30] Hierl T, Arnold S, Kruber D, Schulze FP, Hümpfner-Hierl H. CAD-CAM-assisted esthetic facial surgery. *J Oral Maxillofac Surg* 2013; 71: e15-23.
- [31] Stoetzer M, Rana M, von See C, Eckardt AM, Gellrich NC. Reconstruction of defects of maxillary sinus wall after removal of a huge odontogenic lesion using prebended 3D titanium-mesh and CAD/CAM technique. *Head Face Med* 2011; 7: 21.
- [32] Olszewski R, Reychler H. Three-dimensional surgical guide for frontal-nasal-ethmoid-vomer disjunction in Le Fort III osteotomy. *J Craniofac Surg* 2011; 22: 1791-1792.
- [33] Feng ZH, Dong Y, Bai SZ, Wu GF, Bi YP, Wang B, et al. Virtual transplantation in designing a facial prosthesis for extensive maxillofacial defects that cross the facial midline using computer-assisted technology. *Int J Prosthodont* 2010; 23: 513-520.
- [34] Yu Q, Gong X, Wang GM, Yu ZY, Qian YF, Shen G. A novel technique for presurgical nasoalveolar molding using computer-aided reverse engineering and rapid prototyping. *J Craniofac Surg* 2011; 22: 142-146.
- [35] Haung X, Ye M, Zhang W, Wang C, Jiao T. Fabricating auricular prostheses based on rapid prototyping and the FreeForm modelling system. *Int J Adv Manuf Technol* 2004; 24: 873-878.
- [36] Zhou L, He L, Shang H, Liu G, Zhao J, Liu Y. Correction of hemifacial microsomia with the help of mirror imaging and a rapid prototyping technique: case report. *Br J Oral Maxillofac Surg* 2009; 47: 486-488.
- [37] Mavili ME, Canter HI, Saglam-Aydinatay B, Kamaci S, Kocadereli I. Use of three-dimensional medical modeling methods for precise planning of orthognathic surgery. *J Craniofac Surg* 2007; 18: 740-747.
- [38] da Rosa EL, Oleskovicz CF, Aragão BN. Rapid prototyping in maxillofacial surgery and traumatology: case report. *Braz Dent J* 2004; 15: 243-247.
- [39] Coward TJ, Watson RM, Wilkinson IC. Fabrication of a wax ear by rapid-process modeling using stereolithography. *Int J Prosthodont* 1999; 12: 20-27.
- [40] Lal K, White GS, Morea DN, Wright RF. Use of stereolithographic templates for surgical and prosthodontic implant planning and placement. Part II. A clinical report. *J Prosthodont* 2006; 15: 117-122.
- [41] Ganz SD. Presurgical planning with CT-derived fabrication of surgical guides. *J Oral Maxillofac Surg* 2005; 63: 59-71.
- [42] Bentz RM, Balshi SF. Complete oral rehabilitation with implants using CAD/CAM technology, stereolithography and conoscopic holography. *Implant Dent* 2012; 21: 8-12.
- [43] Ozan O, Seker E, Kurtulmus-Yilmaz S, Ersoy AE. Clinical application of stereolithographic surgical guide with a handpiece guidance apparatus: a case report. *J Oral Implantol* 2012; 38: 603-609.
- [44] Jeng JY, Chang KY, Dong DR, Shih HS. Tooth crown fabrication using reverse engineering technology and model maker rapid prototyping system. *Rapid Prototyp J* 2000; 6: 136-145.
- [45] Bibb R, Eggbeer D, Williams R. Rapid manufacture of removable partial denture frameworks. *Rapid Prototyping J* 2006; 12: 95-99.

- [46] Han J, Wang Y, Lü P. A preliminary report of designing removable partial denture frameworks using a specifically developed software package. *Int J Prosthodont* 2010; 23: 370-375.
- [47] Eggbeer D, Bibb R, Williams R. The computer-aided design and rapid prototyping fabrication of removable partial denture frameworks. *Proc Inst Mech Eng H* 2005; 219: 195-202.
- [48] Williams RJ, Bibb R, Rafik T. A technique for fabricating patterns for removable partial denture frameworks using digitized casts and electronic surveying. *J Prosthet Dent* 2004; 91: 85-88.
- [49] Lee SJ, Jung IY, Lee CY, Choi SY, Kum KY. Clinical application of computer-aided rapid prototyping for tooth transplantation. *Dent Traumatol* 2001; 17: 114-119.
- [50] Morea C, Hayek JE, Oleskovicz C, Dominguez GC, Chilvarquer I. Precise insertion of orthodontic miniscrews with a stereolithographic surgical guide based on cone beam computed tomography data: a pilot study. *Int J Oral Maxillofac Implants* 2011; 26: 860-865.
- [51] Tampos AL, Lope JEC, Hesthaven JS. Accurate reconstruction of discontinuous functions using the singular pade-chebyshev method. *IAENG International Journal of Applied Mathematics* 2012; 42: 242-249.
- [52] Ciocca L, De Crescenzo F, Fantini M, Scotti R. Rehabilitation of the nose using CAD/CAM and rapid prototyping technology after ablative surgery of squamous cell carcinoma: a pilot clinical report. *Int J Oral Maxillofac Implants* 2010; 25: 808-812.
- [53] Ciocca L, Fantini M, De Crescenzo F, Corinaldesi G, Scotti R. Direct metal laser sintering (DMLS) of a customized titanium mesh for prosthetically guided bone regeneration of atrophic maxillary arches. *Med Biol Eng Comput* 2011; 49: 1347-1352.
- [54] Cohen A, Laviv A, Berman P, Nashef R, Abu-Tair J. Mandibular reconstruction using stereolithographic 3-dimensional printing modeling technology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009; 108: 661-666.
- [55] Ciocca L, Fantini M, Marchetti C, Scotti R, Monaco C. Immediate facial rehabilitation in cancer patients using CAD-CAM and rapid prototyping technology: a pilot study. *Support Care Cancer* 2010; 18: 723-728.
- [56] Salles F, Anchieta M, Costa Bezerra P, Torres ML, Queiroz E, Faber J. Complete and isolated congenital aglossia: case report and treatment of sequelae using rapid prototyping models. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2008; 105: 41-47.
- [57] Klammert U, Böhm H, Schweitzer T, Würzler K, Gbureck U, Reuther J, et al. Multi-directional Le Fort III midfacial distraction using an individual prefabricated device. *J Craniomaxillofac Surg* 2009; 37: 210-215.
- [58] Robiony M, Salvo I, Costa F, Zerman N, Bazzocchi M, Toso F, et al. Virtual reality surgical planning for maxillofacial distraction osteogenesis: the role of reverse engineering rapid prototyping and cooperative work. *J Oral Maxillofac Surg* 2007; 65: 1198-1208.
- [59] Sarment DP, Sukovic P, Clinthorne N. Accuracy of implant placement with a stereolithographic surgical guide. *Int J Oral Maxillofac Implants* 2003; 18: 571-577.
- [60] Chen YY, Chang YL, Shiao YY. Accuracy of Surgical Drilling Guide SurgiGuide System. IADR/AADR/CADR 82nd General session, Hawaii, 10-13 Mar 2004. Available at: http://oo.simplantacademy.org/index.php?option=com_simplant_publications&id=678&task=view&lang=en-US
- [61] Chen X, Yuan J, Wang C, Huang Y, Kang L. Modular preoperative planning software for computer-aided oral implantology and the application of a novel stereolithographic template: a pilot study. *Clin Implant Dent Relat Res* 2010; 12: 181-193.
- [62] Jayme SJ, Muglia VA, de Oliveira RR, Novaes AB. Optimization in multi-implant placement for immediate loading in edentulous arches using a modified surgical template and prototyping: a case report. *Int J Oral Maxillofac Implants* 2008; 23: 759-762.
- [63] Paspaspyridakos P, Lal K. Complete arch implant rehabilitation using subtractive rapid prototyping and porcelain fused to zirconia prosthesis: a clinical report. *J Prosthet Dent* 2008; 100: 165-172.
- [64] Lal K, White GS, Morea DN, Wright RF. Use of stereolithographic templates for surgical and prosthodontic implant planning and placement. Part I. The concept. *J Prosthodont* 2006; 15: 51-58.
- [65] Di Giacomo GA, Cury PR, de Araujo NS, Sendyk WR, Sendyk CL. Clinical application of stereolithographic surgical guides for implant placement: preliminary results. *J Periodontol* 2005; 76: 503-507.
- [66] Wu M, Tinschert J, Augthun M, Wagner I, Schädlich-Stubenrauch J, Sahm PR, et al. Application of laser measuring, numerical simulation and rapid prototyping to titanium dental castings. *Dent Mater* 2001; 17: 102-108.

- [67] Williams RJ, Bibb R, Eggbeer D, Collis J. Use of CAD/CAM technology to fabricate a removable partial denture framework. *J Prosthet Dent* 2006; 96: 96-99.
- [68] Bassoli E, Gatto A, Luliano L, Violente MG. 3D printing technique applied to rapid casting. *Rapid Prototyping J* 2007; 13: 148-155.
- [69] Sykes LM, Parrott AM, Owen CP, Snaddon DR. Applications of rapid prototyping technology in maxillofacial prosthetics. *Int J Prosthodont* 2004; 17: 454-459.
- [70] Cheah CM, Chua CK, Tan KH. Integration of laser surface digitizing with CAD/CAM techniques for developing facial prostheses. Part 2: Development of molding techniques for casting prosthetic parts. *Int J Prosthodont* 2003; 16: 543-548.
- [71] Al Mardini M, Ercoli C, Graser GN. A technique to produce a mirror-image wax pattern of an ear using rapid prototyping technology. *J Prosthet Dent* 2005; 94: 195-198.
- [72] Kanazawa M, Inokoshi M, Minakuchi S, Ohbayashi N. Trial of a CAD/CAM system for fabricating complete dentures. *Dent Mater J* 2011; 30: 93-96.
- [73] Sun Y, Lü P, Wang Y. Study on CAD&RP for removable complete denture. *Comput Methods Programs Biomed* 2009; 93: 266-272.
- [74] Williams RJ, Bibb R, Eggbeer D, Collis J. Use of CAD/CAM technology to fabricate a removable partial denture framework. *J Prosthet Dent* 2006; 96: 96-99.
- [75] Karatas MO, Cifter ED, Ozenen DO, Balik A, Tuncer EB. Manufacturing implant supported auricular prostheses by rapid prototyping techniques. *Eur J Dent* 2011; 5: 472-477.
- [76] Hazeveld A, Huddleston Slater JJ, Ren Y. Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques. *Am J Orthod Dentofacial Orthop* 2014; 145: 108-115.