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Review Article

Rapid prototyping: A frontline digital innovation in dentistry

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ABSTRACT

The power, predictability and speed that today's digital solutions offer to human oral health care have gained a rapidly growing foothold in clinical dentistry. One such revolutionary innovation is the rapid prototyping technique. This technique facilitates the fabrication of physical models from computer aided design (CAD) data using 3D printers. This technique enables the dentist and laboratory technician to produce dental-related prosthesis with a greater speed and accuracy, thus making it a reliable alternative to the much labour intensive and time consuming hands on procedure. The present article reviews this current technology, its historical development, methods and applications in dentistry.

1. Introduction

The necessity of answering geometrical complexity has led to the introduction of Rapid Prototyping into the dental setup. It has the potential to become the next 'state-of-art fabrication technique in modern dentistry.[1] Rapid Prototyping equips us to broaden our vision in this era of digitalization, from conventional two-dimensional (2D) thinking to more informative three-dimensional (3D) thinking.[2]

Rapid Prototyping (RP) enables quick and automatic construction of a three-dimensional (3D) model of a part/product utilizing stereolithography machines or 3D printers.[1] Initially, slicing of digital models is done, then through automated layer-by-layer construction, transverse sections are produced and these 3D physical structures are known as rapid prototypes.[3]

RP is also termed as Layered manufacturing, Solid freeform fabrication, or Generative manufacturing.[4]

Digitalization in the form of Rapid Prototyping not only provides a brilliant break-through in various aspects of dentistry like orthodontics, prosthodontics, oral surgery, implantology and operative dentistry etc, but it also has created a great spur on the current time consumed on traditional laboratory design and procedures.[2]

The pivotal objective of this review is to focus on the types of Rapid Prototyping technique and its applications in the field of dentistry.

It provides fascinating opportunities in various aspects of dentistry like orthodontics, prosthodontics, oral surgery, implantology and operative dentistry etc. The key objective of this review is to focus on recent advancements of RP technology and its applications in dentistry.

2. Timeline

The concept of RP is not new and has seen development at various timelines.[5,6]

1. 1894 - Chuck Hull first introduced the concept of 3DP described it as stereolithography (SLA).

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2. 1957 - World's first CAM software program using a numerical control programming tool named PRONTO by Dr Patrick J. Hanratty.
3. 1971 - Computer-assisted production of dental restorations by Duret.
4. 1988 - Hull and the company 3D system developed the first 3D printer termed "SLA apparatus".
5. 1990 - Scott Crump engineered a technique called "FDM".
6. 1992 - Introduction of SLS.

3. Steps in RP Models Production

Rapid prototyping involves fabrication of a 3-D physical model directly from a computer-aided design model. Either contact or non-contact technique can do data acquisition.[7] They all start with a 3D computer-aided design (CAD) model of the anatomical area, which usually can be derived from X-ray CT or MRI data.[7] The steps involved in RP model production are summarised in Table I. Steps have been represented in Figure 1.

Table 1: Steps in RP models production

CAD-CAM steps	CAD-CAM system
Data acquisition	Contact or non-contact methods Example: Optical modeling, laser scanning, CT, MRI, digital photographs
Data processing	Digital data is processed to obtain a CAD model
Model fabrication	Rapid prototyping, CNC milling

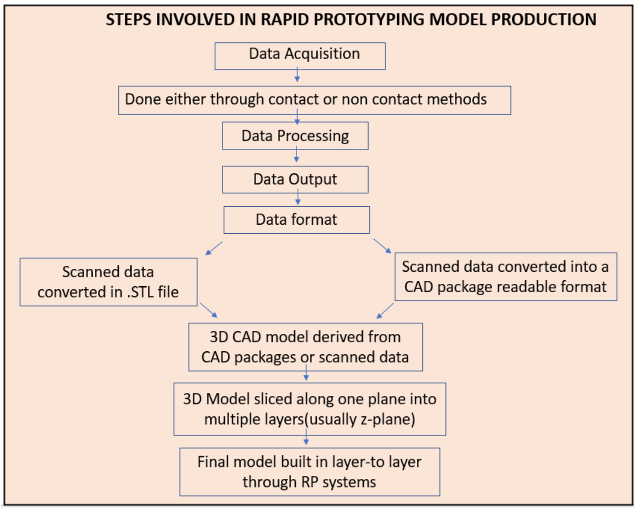

Fig. 1: Schematic flowchart of steps involved in RP model production

4. Digital Approaches for a Physical Prototype

The emergence of advanced digital technology has opened new perspectives in clinical dentistry.[8] To fabricate a physical prototype or a scale model through digital technology, two different approaches can be used:

1. Subtractive approach.
2. Additive approach.

Subtractive approach is usually facilitated using computer numerical control machining (CNC milling). The data principally obtained from an optical or contact probe surface digitizer captures the external surface data of the prescribed anatomy and not the internal tissue surface, hence less effective. This approach relies on milling an available larger blank using a CNC machine.[9] The CAM software automatically translates the designed CAD model into a tool path for the CNC machine. This involves series of procedures, including sequencing, milling tools, and tool motion direction and magnitude. The dental CNC machines are composed of multi-axis milling devices facilitating 3D milling of dental prosthesis.

4.1. 3-axis milling devices

These are the most commonly used. The milling burs move in three axes (x-, y- and z- axes) according to calculated path values. Therefore, 3-axis milling has the advantage of having minimal calculation and cumulative milling time.[9]

4.2. 4-axis milling devices

These machines allow for blank movements in an additional axis, which helps mill a larger blank producing long-span frameworks.[9]

4.3. 5-axis milling devices

The 5^{th} axis in this machine provides a rotating path of the milling tool or the blank. This facilitates the production of very complex geometries and smooth external surfaces such as acrylic denture bases.[9]

Keynote: For dental applications, the quality of the restoration is independent of the number of axes; instead, it reflects the method of processing the workpieces and CAD path of milling.

The Additive approach, on the other hand, can produce arbitrarily complex shapes with cavities such as human anatomical structures with the use of rapid prototyping. Additive manufacturing is defined as joining materials to make objects from 3D model data, usually layer upon layer. Once the CAD design is finalized, it is segmented into multislice images. The machine lays down 5–20 layers for each millimeter of material successively with liquid and powder that fuses to create the final shape. This is followed by workpiece refinement to remove the excess materials and supporting arms.[10]

4.4. Types of Rapid Prototyping Techniques:

Rapid Prototyping system commonly engaged in dentistry are:

1. Stereolithography (SLA,
2. Inkjet-based system (3D printing - 3DP,
3. Selective laser sintering (SLS and selective laser melting,
4. Fused deposition modeling (FDM).

Keynote: All the methods share the common work principle that distinguishes them from subtractive manufacturing:

1. Incremental vertical object build-up
2. No material wastage
3. Production of large objects
4. No application of force (passive production)
5. Production of fine details

4.5. Materials used for rapid prototyping

Wax, Plastics, Resins, Ceramics and Metals in the form of powder and liquid, Modeling materials and colors, such as medical-grade ABS, polycarbonates.[5]

4.6. Stereolithography

It creates a three-dimensional model using a computer-controlled moving laser beam to build up the required model from a liquid in a layer-by-layer manner. The first process of this type of RP was patented by Hull (1984).

4.7. Components of this system

A bath of photosensitive liquid resin, a model-building platform, and an ultraviolet (UV) laser for curing the resin.

4.8. Procedure

On the model-building platform, a layer of resin is exposed to UV light. After a resin layer is cured and hardened, the cured resin platform is lowered to the bath by a pre-fixed distance. A Wiper blade is used to wipe a new layer of resin across the previous layer, which is consequently exposed to the UV light and cured. The process of curing and lowering the platform into the resin bath is repeated until the complete model is built. (Figure 2)[4] The self-adhesive property of the material causes the layers to bond to each other and eventually form a 3D object. The model is then removed from the bath and for then placed in a UV cabinet for sometime.[11,12] The advantages and disadvantages of this technique are described in Table 2.

Table 2: Stereolithography

Advantages	Disadvantages
High accuracy	Expensive equipment
Good surface finish	High Material cost
Can be made transparent	Can be used only for polymers
100 percent density possible	Requirement of Post - cure
High-mechanical strength	
Fine building detail	

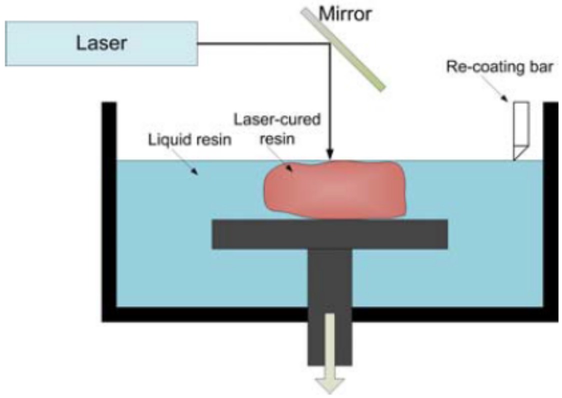

Fig. 2: Schematic diagram of stereolithography

5. Inkjet-Based System (3D printing - 3DP)

A measured quantity of powder is dispensed from a supply chamber by incremtal upward movement of piston. The roller then distributes and compresses the powder at the top of the fabrication chamber. Then a multi-channel jetting head subsequently deposits a liquid adhesive in a 2D pattern onto the layer of the powder, which becomes bonded in the areas where the adhesive is deposited to form a layer of the object. Once a layer is finished, the piston that supports the powder bed and the part lowers so that the next powder layer can be spread and selectively joined. This layer-by-layer technique is gradually continued until the prototype is completely built up. (Figure 3)[4] The unbound powder is swept off with a heat treatment process, leaving the fabricated part intact.[13] The advantages and disadvantages of this technique are described in Table 3.

Table 3: Inkjet based system

Advantages	Disadvantages
Fast fabrication time	Large tolerance
Low material cost	Lower strength models
The capability of being colored	Rough surface finish
Build models can be used for casting	
Low toxicity	
Relative material variety	

6. Fused Deposition Modeling (FDM)

In this system, a temperature-controlled head extrudes thermoplastic material layer by layer. A filament of a

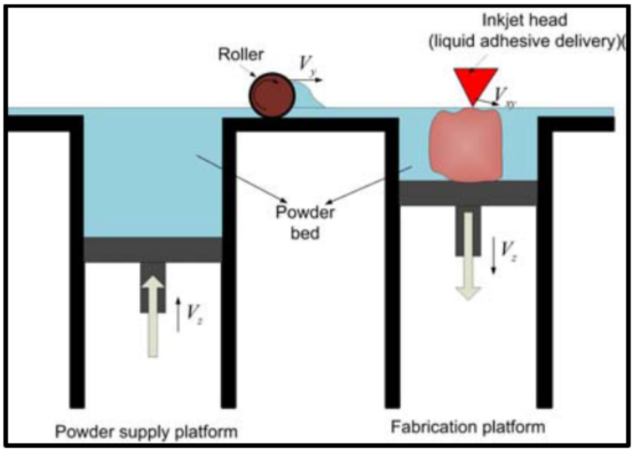

Fig. 3: Schematic diagram of Inkjet-based system

thermoplastic polymer material feeds into the temperature-controlled FDM extrusion nozzle head, where it is heated to a semi liquid state. The motion of the nozzle head is computer controlled and is used to trace and deposit the material in ultra-thin layers onto a fixtureless base. The final model is built up layer by layer, and the material solidifies within 0.1s after being ejected from the nozzle and bonds to the layer beneath. This entire system works within a chamber that is held at a temperature just below the melting point of the proposed material. The supporting structures and overhanging geometries are later removed by cutting them out from the object.[14] The advantages and disadvantages of this technique are described in Table 4.

Table 4: Fused deposition modelling

Advantages	Disadvantages
Direct wax pattern	Support structure must be removed
Multi-color part	Rough surface finish
Speedy procedure	Thermoplastic material only
	Not 100 percent dense

7. Selective Laser Sintering (SLS)

In the SLS method, layers of a particular powder material are fused into a 3D model using a computer-directed laser (Figure 4).[4] A roller distributes the powdered material over the surface of a build cylinder. The powder is spread layer-by-layer on top of the preceding hardened layer and sintered repeatedly with a laser beam.[15] The advantages and disadvantages of this technique are described in Table 5.

8. Selection of RP System

As discussed above, every RP system has its strengths and limitations. A suitable RP machine needs to be chosen such that it matches up to satisfy maximum requirements. Criteria quoted by Zein et al.[16] and Xiong Z et al.[17] for system selection include: Application purpose, time constraint, cost, materials availability, accuracy, surface finish, and so on.

Table 5: Selective laser sintering

Advantages	Disadvantages
Fast fabrication time	Large tolerance
Low material cost	Lower strength models
Capability of being colored	Rough surface finish
Build models can be used for	
Casting purposes directly	
Low toxicity	
Relative material variety	

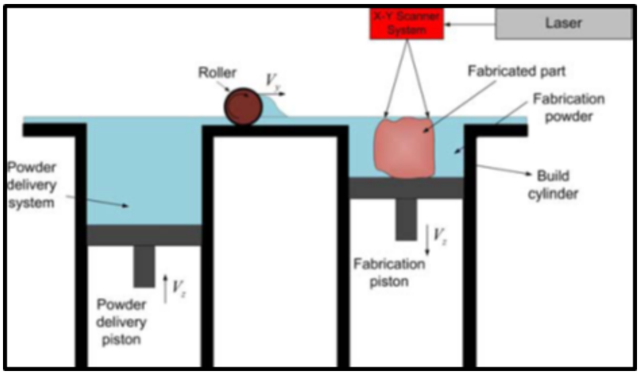

Fig. 4: Schematic diagram of selective laser sintering

8.1. *For example*

While planning a surgery, an RP system, like SLA or FDM, enables us to use different colours to highlight and enhance the visualization of critical structures; hence, be preferable. Similarly, for designing a drilling guide for implants, SLA built model resins have visualization benefits due to their translucent nature.

When building speed is a consideration, the SLA machine is more opted for than the FDM machine. When surface quality and detailing is a significant concern, SLA followed by SLS is preferred. The FDM serves as an economical option.

9. Applications of RP in Dentistry

9.1. *Applications in endodontics*

The invention of RP has found tremendous applications in endodontics.[18]

9.1.1. *Guiding the canal*

Successful endodontic therapy requires a thorough understanding of root canal anatomy and its variations. In cases of complex root canal anatomies, 3D visualization of the canal through digital reconstruction of tooth model can be simulated through RP technology to achieve the precise working path of the root canal.[19]

9.1.2. Accurate diagnosis of the lesions

In cases of root resorption, clinical and radiographic examination provides only a rough outline of the lesion that may not be continuous with the pulpal cavity. Rapid prototyping in these kinds of scenarios provides three dimensional view of the lesion and assists accurate diagnosis.[20]

9.1.3. Autotransplantation

Earlier in cases of autotransplantation, the extracted donor tooth is used a guided template for the preparation of the recipient site. But with the advent of rapid prototyping, fabrication of a computer-aided surgical guide for the recipient site is possible. Adopting this new technique has led to a decrease in procedural duration and intraoperative errors.[21]

9.1.4. Endodontic training and research

It can evaluate the efficacy of the newer root canal systems in preparing curved canals of 3d printed tooth models.[18]

9.2. Applications in prosthodontics

9.2.1. Wax pattern fabrication

Traditionally, wax pattern making is the most labor-intensive step during the fabrication of crowns and RPD frameworks. With this technology, a new approach to automated wax patterns is now available in the field of prosthodontics. This simplified the traditional age-old technique of hand-made wax patterns. The advantages of automatic wax-up include:

1. High production rate of 150 crowns/hr by dental laboratories
2. Quality control of the wax copings is improved, resulting in the high precision fit of the crowns in the oral cavity.[22]

9.2.2. Direct metal prosthesis

Fabrication of high precision metal parts with RP technologies such as selective laser melting (SLM) and SLS technology are used. Dental prostheses processed by employing SLS/SLM technique are appropriate for their complex geometry and their capability to be customized. This procedure eliminates the extensive manual pre and post-processing steps.[22]

9.2.3. All ceramic restoration fabrication

The direct inkjet fabrication process has been anticipated using a slurry micro-extrusion process for the fabrication of an all-ceramic crown. This innovative method is a good CAD/RP system with a remarkable ability to produce high precision fit all-ceramic crowns. The other advantages include cost competence and minimum material intake.[22]

Complete dentures:

In complete denture situations, RP technology can be used for:

1. Establishing a 3D graphic database of artificial teeth positioning.
2. Getting 3D data of edentulous models and rims in centric relation.
3. Exploring a CAD route and developing software for complete denture finishing.

9.2.4. Maxillofacial prosthodontics

A wax prototype sculpted on the stone cast by using the free-hand technique can be eliminated using this RP technique. The 3D model of the patient's face (reconstructed with the CT data) can be used, and the technology can be applied in the following areas.[22]

9.2.5. Fabrication of obturators, auricular and nasal prosthesis

1. Manufacturing of surgical stents for patients with large tumors scheduled for excision
2. Manufacturing of lead shields to protect healthy tissue during radiotherapy treatment
3. Fabrications of burn stents, where the burned area can be scanned rather than subjecting delicate, sensitive burn tissue to impression-taking procedures.

9.2.6. Implants

Achieving an ideal implant position is one of the key criteria determining implant success. Computer-aided designing and fabrication techniques employing implant simulation software provide a preoperative view of anatomical structures and restorative information, thus improving the procedure's outcome.

Guided implant surgery applies these digital techniques using drill guides processed by stereolithographic rapid prototyping through which implants are positioned with minimal surgical exposure of bone or even with a flapless approach. The advantages of the less invasive flapless surgical procedure include the following:

1. Shorter duration and facilitation of the surgical procedure.
2. Faster and less complicated recovery.
3. Enhanced esthetic results.

9.3. Application in Oral and Maxillofacial Surgery

The length and shape of the grafts to be used in surgical procedures are estimated through the surgical models. Customized plates can be pre-produced to hold the future bone graft, thus facilitating the surgical procedure and saving intra-operating time. Also, the tumor areas can be coloured using stereolithographic techniques to visually establish their extension and clarify their relationship to the alveolar nerve in the mandible and hard surrounding structures, such as paranasal sinuses, orbit, etc.[23]

Prototypes can and should be used in several situations such as: -

1. Evaluation of asymmetrical features
2. Reconstruction of symmetrical structures using mirroring
3. Fracture assessment
4. Modelling rigid internal fixation plates and screw selection
5. Modelling osteogenic distracters
6. Calculation and adaptation of bone grafts
7. Tumor assessment
8. Fabrication of surgical guides

9.4. Applications in Orthodontics and Dentofacial Orthopaedics

1. **Diagnosis and Treatment Planning**- Faber et al. state that RP is especially beneficial in cases with impacted teeth and helps understand the impacted tooth's exact position in relation to its surrounding structures.[24]
2. **Fabrication of Removable Appliances and aligners** is easier and more accurate using the CAD/CAM technology. Lee et al.[25] described a technique where a polyvinyl chloride impression was used and converted into a 3D model in STL format directly using a CBCT image. This method was cheaper, with fewer manual errors when compared to the conventional technique of laser scanning and digitization of human tissues. The prototype is created using the SLA technique, and the aligner is built-in layered fashion using photosensitive liquid resin.
3. **Custom-made Trays**- It assists in the fabrication of custom-made trays in case of indirect bonding. Here, virtual bracket positioning is done on the software-generated digital model. Then using RP technology, trays are created.
4. **Lingual Orthodontics-** Customised lingual brackets can be produced using knowledge of RP technology. This facilitates direct bonding and easier positioning of the brackets onto the tooth surface.
5. **Orthognathic Surgery**- 3D models made using SLA helps understand the accurate positions of anatomical landmarks. Computerized orthognathic surgeries serve special importance in asymmetric cases where discrepancies can be measured and manipulated directly on the models. Mock surgery done on these models can help achieve more efficient post-operative results. Literature also suggests using the RP technique to create a 3D model of the jaws in Distraction Osteogenesis cases.

10. Bioengineering Research in Dentistry

Tissue engineering is an important genre of treatment when attempting craniofacial reconstruction. RP technique has been proposed for bioprinting of tissue analogs and organ analogs. Features such as the possibility for multicolour printing provide us with added benefits during the arrangement and positioning of multiple cells.[5]

11. Scope of RP

Rapid Prototyping is comparatively a recent advancement with much scope for improvising the exactness, speed, and consistency. Further research needs to be conducted to widen the horizon for materials used in prototype construction. The current cost of the RP system is another area that needs to be dealt with.[5]

12. Conclusion

The ever-growing arena of digital services used for the automated production of dental prosthesis requires knowledge, skill sets and time to master the technology. As dentistry continues to move from analog to digital workflow, it may be time to evaluate state of the art and realize that it is not the computer that makes the decisions-it's only a tool to help clinicians make appropriate decisions and improve their decision with clinical outcomes.

13. Source of Funding

None.

14. Conflict of Interest

None.

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