Review Article

Rapid Prototyping and its Application in Dentistry

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Abstract :
Medical implants and biological models have three main characteristics: low volume, complex shape, and can be customized. These characteristics suit very well with Rapid Prototyping (RP) and Rapid Manufacturing (RM) processes. RP/RM processes are fabricated part layer-by-layer until complete shape finished from 3D model. Biocompatible materials, such as Titanium and Titanium alloy, Zirconium, Cobalt Chromium, PEEK, etc, are used for fabrication process. Reverse Engineering (RE) technology greatly affects RP/RM processes. RE is used to capture or scan image of the limb, cranium, tooth, and other biological objects. Three common methods to get the image are 3D laser scanning, Computer Tomography (CT), and Magnetic Resonance Imaging (MRI). Main RP/RM techniques used in Dentistry are Stereotype Lithography Apparatus (SLA), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and ink jet printing. This article reviews the changing scenario of technology in dentistry with special emphasis on Rapid Prototyping and its various applications in Dentistry.

Keyword: Rapid Prototyping, Stereolithography, Selective laser sintering, Inkjet printing

Introduction:

Rapid Prototyping is a process that creates parts in an additive, layer-by-layer manner. It is a special class of machine technology that quickly produces models and prototype parts from 3D data using an additive approach to form the physical models. Rapid prototyping (RP) is a relatively new class of technology used for building physical models and prototype parts from 3D CAD data. RP systems join together liquid, powder and sheet materials to form complex parts. Layer by layer, RP machines fabricate plastic, wood, ceramic, and metal objects based on thin horizontal cross sections taken from a computer model.

To fabricate a physical prototype (model) in industry and/or medicine; two different approaches have been utilized: subtractive and additive.[1,2] The subtractive technique is usually accomplished by the conventional NC machining, generally milling.[3] The input data for this method are principally from an optical or contact probe surface digitizer which can only capture the external surface data of the anatomy and not the internal tissue structure of the proposed object. NC machining is used typically in small model-making machines and this is the main reason for using them to fabricate metallic and/or ceramic crowns in dentistry.[1]

The additive technologies, on the other hand, can produce arbitrarily complex shapes with cavities; which is usually the case in human anatomy structures. The key idea of this innovative method which is also called "Layered manufacturing" or "solid free form fabrication," is that a solid 3D CAD model of an object decomposed into cross-sectional layer representations and then numerical files in the form of virtual trajectories guiding material additive processes for physically rapid building up of these layers in an automated fabrication machine to form the object called the prototype.[4] In this way, the captured 3D data set, rapidly slice into cross-sections, and construct layers from the bottom up, bonding one on top of the other, to produce models for applications. It was demonstrated that by using this method the overall production time will reduce considerably and complex models which are otherwise difficult and/or impossible to make by the conventional NC machining process could be build rather easily.[2] Owing to these capabilities, using additive methods for Medical Modeling (prototyping) is more advantageous and many problems usually accompanied by milling can be easily overcome. The main advantage of this type of model manufacturing in building the medical/dental parts is the ability of the technique to create minor details such as undercuts, voids, and complex internal geometries (neurovascular canals or sinuses, etc.) in the proposed model.

The capability of CT scans/MRI in providing detailed 3D pictures of the anatomy of the area of interest and gathering valuable data for diagnostic and therapeutic usage has very soon stimulated many clinicians.[5,6] It was also exciting that similar to CT scan data, MR scan data are also computed and presented in a layer-by-layer format. The layer data format of 3D scanners quickly prompted the realization that it should be possible to convert the data to be compatible with RP machine requirements, i.e. a physical model can be manufactured based on X-ray CT or MRI data. It is exciting that in spite of availability of CT scanners since 1973 [7], it was not until 1987 that this innovative technology became available for dental

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application.[8] It is also interesting that the main motivating factor for using CT in dentistry is the science of oral implantology.[9]

Advantages of Rapid Prototyping :

- The obvious benefit of rapid prototyping is speed.
- Rapid prototyping quickly delivers a better design communication tool, the physical prototype quickly and clearly communicates all aspects of a design.
- Rapid prototyping facilitates the early detection and correction of design flaws.
- In its simplest form, the benefit of rapid prototyping is confidence in the integrity of the design.

Rapid Prototyping in Dentistry :

As in many branches of medicine, rapid prototyping has been also used in dentistry for a range of dental specialties, including oral and maxillofacial prosthodontics and surgery [10-16], dental implantology as a surgical guide or physical model [17-21] and Prosthodontics. [22-27] The use of RP in dental branches has many other benefits of which only one of them is medical modeling construction; there are so many useful fields, in which RP can be helpful, i.e. mass production of patterns for casting purposes. In this way, time consuming and/or difficult parts in restoration making can be easily implemented even without human intervention. Common technologies used in dentistry are stereolithography (SLA), inkjet-based system (3D printing - 3DP), selective laser sintering (SLS) and fused deposition modeling (FDM). The materials that can be used are fairly diverse but, wax, plastics, ceramics and metals are all utilized by several teams for dental purposes.

Stereolithography:

The first process of this type of RP was patented by Hull (1984), for the production of 3D models from photopolymer resins.[28] This system consists of a bath of photosensitive liquid resin, a model-building platform, and an ultraviolet (UV) laser for curing the resin. The layers are cured sequentially and bond together to form a solid object beginning from the bottom of the model and building up. As the resin is exposed to the UV light, a thin well-defined layer thickness becomes hardened. After a layer of resin is cured, the resin platform is lowered within the bath by a small known distance. A new layer of resin is wiped across the surface of the previous layer using a wiper blade, and this second layer is subsequently exposed and cured. The process of curing and lowering the platform into the resin bath is repeated until the full model is complete. The self-adhesive property of the material causes the layers to bond to each other and eventually form a complete, en bloc 3D object. The model is then removed from the bath and cured for a further period of time in a UV cabinet (Fig.1 and 2).

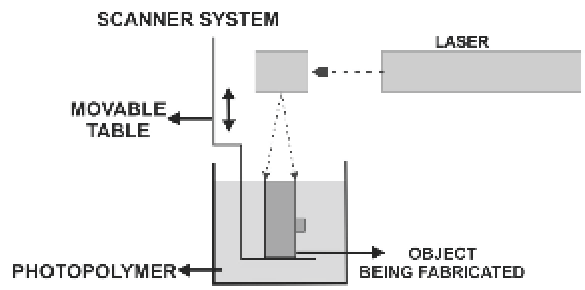

Fig 1. Schematic diagram showing stereolithography procedure.

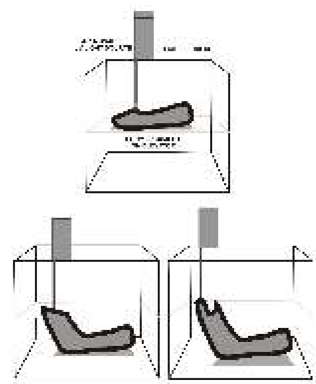

Fig 2. Schematic diagram showing stereolithography procedure.

Applications:

There is also some, who clearly demonstrated the possibility to use these systems for impression purposes in reconstructive surgeries and sub-periosteal dental implant surgery. [14, 15, 29-33] Nowadays, the main objective for using SLA models in dentistry is fabrication of surgical drilling templates during dental implant insertion. The high accuracy of SLA-made surgical drill guides has been proved by several well documented studies. [34-36] Furthermore, the transparency of the model and the recent development of color resins allow distinct visualization of anatomical structures.[37] The advantages of SLA are that it is highly accurate, has high mechanical strength and it gives a good surface finish. On the downside it requires post curing, material is costly and requires expensive equipment.[1]

Selective Laser Sintering:

SLS is a process of fusing together layers of specified powder material into a 3D model by a computer-directed laser. Thermoplastic powder is spread by a roller over the surface of a build cylinder. The piston in the cylinder moves down one object layer thickness to accommodate the new layer of powder. The powder delivery system is similar in function to the build cylinder. Here, a piston moves upward incrementally to supply a measured quantity of powder for each layer. A laser beam is then traced over the surface of this tightly compacted powder to selectively melt and bond it to form a layer of the object. The fabrication chamber is maintained at a temperature just below the melting point of the powder so that heat from the laser need only elevate the temperature slightly to cause sintering. This greatly speeds up the process. The process is repeated until the entire object is fabricated. After the object is fully formed, the piston is raised to elevate it. Excess powder is simply brushed away and final manual finishing may be carried out. No supports are required with this method since overhangs and undercuts are supported by the solid powder bed. SLS offers the key advantage of making functional parts in essentially final materials. However, the system is mechanically more complex than most other technologies (Fig. 3).

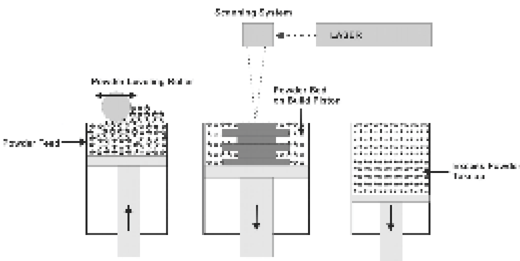

Fig 3. Schematic diagram showing selective lasering sintering.

The range of thermoplastic materials like nylon composite, investment casting wax, metallic materials, ceramics and thermoplastic composites that can be used on the SLS machine is a big advantage especially in the field of dentistry. The ability of this technology to build up removable partial denture (RPD) frameworks has been demonstrated. [22, 23] The material used was cobalt chrome spherical powder with a maximum particle size of 0.045mm (particle size range 0.005-0.045mm) and a mean particle size of approximately 0.030mm. The part proved successful and produced a complete cobalt-chrome RPD framework.[23] The possibility to preheat the SLS machines just below the temperature needed for metal powder sintering (melting) by lasers made this system very speedy. This minimizes thermal distortion and facilitates fusion to the previous layer.[38]

Applications of selective laser sintering in crown and bridge:

A high powered laser beam is focussed onto a bed of powdered metal (in this case medical grade Co-Cr) and these areas fuse into a thin solid layer. Another layer of powder is then laid down and the next 'slice' of the framework is produced and fused with the first. When every layer has been built up, the solid copings and bridge frameworks are taken from the machine, sand blasted, polished, inspected and ultrasonically cleaned. As the machine can create hundreds of units at a time the cost of each one is relatively low. The unused powder that remains is filtered and used in the next batch so there is very little waste, again helping keep running costs to a minimum. Laboratories have full control over their framework designs. Margin line placement, cement gaps, coping thickness and pontic designs can all be customised. Designs can be 'sectioned' on the computer screen and analysed for strength before committing to manufacture. Laser sintering is a precision, computer controlled process that ensures consistent framework integrity. There is no possibility of inclusions or defects that are commonly introduced in manual casting processes. Multi-unit cast frameworks can suffer from distortion as they cool. The DMLS process produces more consistent results with improved marginal fit. Switching to Laser porcelain fused to metal crowns means that a messy process can be removed from the lab, freeing up space and resources for higher-skilled ceramic work. Advantages of using selective laser sintering are that it can give 100% density and drawbacks are the cost.[1]

Fused Deposition Modeling (FDM):

FDM is the second most widely used rapid prototyping technology, after stereolithography. A plastic / wax filament is unwound from a coil and supplies material to an extrusion nozzle. The nozzle is heated to melt the plastic and has a mechanism which allows the flow of the melted plastic to be turned on and off. The nozzle is mounted to a mechanical stage which can be moved in both horizontal and vertical directions. As the nozzle is moved over the table in the required geometry, it deposits a thin bead of extruded plastic/wax to form each layer. The plastic/wax hardens immediately after being squirted from the nozzle and bonds to the layer below. The entire system is contained within a chamber which is held at a temperature just below the melting point of the material (Fig. 4).

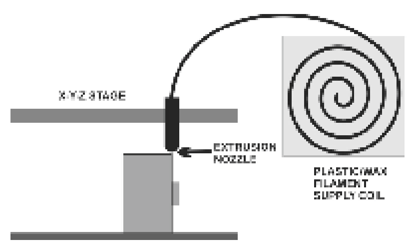

Fig 4. Schematic diagram showing fused deposition modelling.

Applications :

The FDM process allows a variety of modeling materials and colors, such as medical grade ABS, polycarbonates and investment casting wax. [5] FDM can produce models, as well as surgical guides and templates, out of medical grade ABS, which is gamma-sterilizable and translucent. ABS offers good strength, and more recently polycarbonate and poly (phenyl) sulfone materials have been introduced which extend the capabilities of the method further in terms of strength and temperature range. In one of them, the wax modeling process made completely automated and the system can easily produce over 150 units per hours (www.cynovad.com/html/produits/WaxPro/etapes.htm). Advantages of FDM are that this process gives direct wax patterns, and is fast and speedy. On the negative side it can be used only with thermoplastic materials, it gives rough surface and is not 100% dense.[1]

Inkjet (thermal Phase Change):

The working principle of this RP system is basically similar to the conventional 2D inkjet printer. This machine uses a single jet each for a plastic build material and a wax-like support material, which are held in a melted liquid state in reservoirs. The liquids are fed to individual jetting heads which squirt tiny droplets of the materials as they are moved in X-Y fashion in the required pattern to form a layer of the object. The materials harden by rapidly dropping in temperature as they are deposited. After an entire layer of the object is formed by jetting, a milling head is passed over the layer to make it a uniform thickness. Particles are vacuumed away as the milling head cuts and are captured in a filter. The process is repeated to form the entire object. After the object is completed, the wax support material is either melted or dissolved away. The most outstanding characteristic of inkjet systems is the ability to produce extremely fine resolution and surface finishes, essentially equivalent to CNC machines. The technique is very slow for large objects (Fig.5).

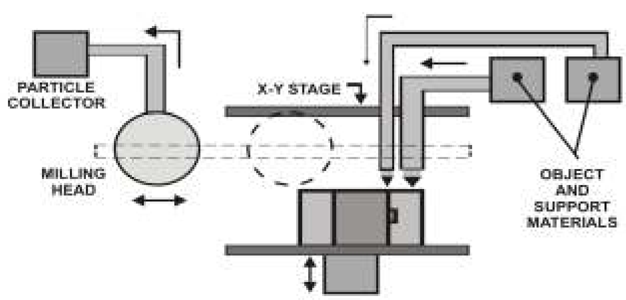

Fig 5. Schematic diagram showing Inkjet (Thermal phase change) procedure.

Applications :

Direct Inkjet Printing of Dental Prostheses Made of Zirconia direct inkjet printing. A tailored zirconia-based ceramic suspension with 27 vol% solid content was synthesized. The suspension was printed on a conventional, but modified, drop-on-demand inkjet printer. A cleaning unit and a drying device allowed for the build-up of dense components of the size of a posterior crown. A characteristic strength of 763 MPa and a mean fracture toughness of 6.7 MPam 0.5 were determined on 3D-printed and subsequently sintered specimens. The novel technique has great potential to produce, cost-efficiently, all-ceramic dental restorations at high accuracy and with a minimum of materials consumption.[39]

Conclusion:

It is noteworthy that working with RP technologies in the medical/dental field differs considerably from using them in the industrial environment. In manufacturing, only non existing models are usually virtually designed on the computer screen and then converted to physical models. In medical applications, the object or part to be modelled often, but not always, exists physically (anatomical structures of the patients body) and building medical models essentially starts with acquiring data such as CT cross-sectional images, pre-processing of collected data to provide a format that a CAD package or a RP system can recognize and finally linking with RP technologies to obtain the desired physical models. Although several attempts have been made to further customize the technique described above for using in dentistry but it seems that in near future many other methods will developed which could change the traditional dental practices. Some of the shortcomings which must be fully revolutionized in future are the delivery time which must be further shortened if RP and resin manufacturers can develop direct prototyping biomedical material, and the total cost of the finished product must be lowered in order to be used in everyday practice.[1]

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