Adding extra dimension to digital dentistry: 4D printing.

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Abstract

3D printing also called additive manufacturing (AM) has rapidly evolved over the last few decades due to its various advantages over traditional fabrication methods. Recent advancement in 3D printing is 4D/four-dimensional printing. It includes fourth dimension i.e time. Basically, 4D printing adds time to the 3D printing and this addition provides reconfiguration to a printed object, that is, 4D printed structure will reconfigure itself to the pre-determined shape with time on exposure to various stimuli. It is a recent evolving technology, rapidly emerging in various fields like medical, engineering, automobile industry, chemistry, material science, basic sciences, computer science etc.[1] In Dentistry ,moving on from traditional fabrication methods to 3D printing and now to 4D printing would be a boon to various treatment procedures and so to the prognosis as well. The objective of 4D printing is to fabricate functional objects in contrast to 3D printing techniques which produce static objects. The main focus of this article is to review basic aspects of 4D printing technology and its application in dentistry.

Keywords: 4D Printing, 3D printing, Digital dentistry, Smart materials.

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Introduction

Over the last few decades, 3D printing techniques has rapidly evolved over the traditional fabrication methods because of their capability to print complex shapes and the advancement of material they utilize. With these techniques, unique and complicated shapes and configurations can be constructed and thus overcome the procedural difficulties in traditional methods. With the evolution of smart materials, a new technological innovation, 4D printing has now arisen which has high capability to change the restorative dentistry.4D printing basically differs from the 3D printing technique by the nature of the structure being fabricated.4D printed structures are dynamic, adaptable and functional in nature whereas 3D printed structures are static in nature. In contrast to 3D printing, this recent printing technique permits the smart materials to convert into pre-programmed shape as a function of time on exposure to different external stimuli.[2] 4D printing uses the same additive manufacturing technique but with the addition of smart materials that undergoes structural changes with time.[3] The stimulus may be of different nature. Various stimuli are temperature, humidity, pH, and light intensity (Figure 1).

In 2013, the Tibbits' group at MIT (Massachusetts Institute of Technology) defined 4D printing technology and following this, extensive investigations and studies have been done related to stimulus mechanism, the smart materials, 3D printers, advanced design and applications.[4] As because most of the body's organs including components of oral cavity shows continuous physiological changes or continuous physiological movement, the utilization of smart materials for 4D printed functional structures in medical discipline can have major impact on the prognosis of the treatment.

Mechanism:

4D printing consists of 5 major components according to Momeni et al. These are printing technique, stimulus, smart materials, mathematical modeling, and interaction mechanism.[5] This technique consists of two primary steps. First step is processing followed by second step i.e programming. Processing of the structure is initially done into an original form, followed by intermediate temporization into other shape and finally programming is done to transform to other shape on exposure to stimuli (e.g., human body temperature or moisture).[6] 4D printing technology provides structures with active and responsive functions in contrast to 3D printed structures.[7]

4D Printing materials:

Smart materials also known as Stimulus-responsive material are programmable, highly dynamic in form and functions.[8] They respond to different stimuli and are the key to 4D printing. Example of smart materials are Shape memory materials. Various materials that fall into this category are Shape memory materials.[9] which include SMpolymers (SMPs), SMalloys (SMAs), SMceramics (SMCs), SMgels (SMGs), and other shape memory hybrid (SMHs).[10]

Shape memory polymers (SMPs)– These polymers change their shape on exposure to external stimuli.[11,12] Polylactic acid, polyurethane acrylonitrile butadiene styrene and polyvinyl alcohol are some examples of SMPs. SMPs should possess two components : one is switching part and another is network structure. Each of these components plays different role like switching part brings significant changes in the mobility of the polymer network (transitory shape) and network structure dictates the permanent structure (memory).[13,14]

Shape memory alloys (SMAs)– These alloys on exposure to temperature or load changes show multiple unique phases or states.[15] Some examples are Fe-Mn-Si alloy system[16], NiTiHf based SMAs[17]; NiMn based SMA systems, y Ni-Ti SMAm (nitinol)[18].Nitinol is biocompatible mainly because of its nano-structuring which makes it more safe to be used in biomedical implants.[19]

Both SMPs and SMAs are extensively used materials. But, SMPs are more flexible, lighter and more biocompatible than SMAs.[20] During designing or shape memory programming, SMPs consume less energy and also have ability to restore a larger amount of strain.[21,22]

Hydrophilic polymeric materials/Hydrogels- Hydrogels are also used in 4D printing because on exposure to stimuli they can change their volume to the greater extent.[23] Examples are hydrogels composed of sodium alginate and PEG[24], hydrogel inks consists of crosslinked pHEMA(poly(2-hydroxyethyl methacrylate)) and HEMA (2-hydroxyethyl methacrylate) chains[25], PNIPAAm (Poly(N-isopropyl acrylamide)) hydrogels. PNIPAAm hydrogels are used in biomedical (drug delivery, tissue engineering) and engineering (sensors and actuators) systems [26]

Shape memory ceramics: Ceramics are very brittle in nature but shape memory ceramic that serves as smart material have fine structure with few grain junctions. This enables it to sustain greater amount of stress without cracking.[13,18]

First known dental laboratory material to utilize 4d printing is lucitone digital print 3D dentureresin.it was seen that in complete denture fabricated from this material fracture toughness increases from 2.86 ± 0.24MPa at room temp. to 3.68 ± 0.20MPa at body temperature, flexural strength increases, it also prevents the worsening of any existing cracks. Its composition is Urethane methacrylate, organic methacrylate and acrylate monomers and photoinitiator.[27]

4d printing techniques:

Over the last few decades, moving onto 3D printing/additive manufacturing techniques over traditional fabrication methods have make it possible to print various complicated and unique shapes. 4D printing of smart materials utilizes the same 3D techniques but with certain modifications to it.

Some of these techniques include extrusion-based methods, traditional and contemporary methods like in situ fabrication, stereolithography, fused deposition modeling, electron beam melting, inkjet printing and selective laser melting.[28-30]

Inkjet printing- In this technique, data of the structure is read from a computer followed by reconstruction of structure by deposition of small ink drops.[31]

Fused deposition modeling (FDM)- In this technique, 3D structure is fabricated by deposition of material in a layer by layer manner. In this , base material is melted and then melted material is extruded through a nozzle to build 3D structure. Modified FDM techniques were created by incorporating an air circulation system for printing of the smart material.[32]

Direct ink writing (DIW) In this technique, viscoelastic inks are deposited through nozzles under much pressure to form 3D structures.[33,34]

Stereolithography (SLA)is the more commonly used method for printing of shape memory polymer. It has very high accuracy. In this, a laser is used to polymerize the material layer by layer to form the 3D structure.[35]

Applications:

4D printing can produce dynamic, self adaptable and programmable materials that functions in the oral environment where temperature and moisture conditions continuously vary. This would have major impact in the treatment prognosis of different fields of dentistry. Major concerns seen in practice are undesired changes in dimensions, thermal instability, curing shrinkage and microleakage etc. These drawbacks can be minimized using the rapidly developing 4D printing techniques.[36,37] Various applications are :

Removable Prosthetic Dentistry: With 4D printing technique, materials that possess properties similar to natural hard and soft tissues can be used to fabricate removable prosthesis in such a way that this prosthesis fabricated that adapts to the directions of forcesin the oral environment. The denture base fabricated with 4D printed structures have elastic and thermal properties alike pdl or overlying mucosa.[6] As both hard and soft tissues of the oral cavity undergoes changes with age so dentures that can adapt to the altered hard and soft tissues are desirable to avoid the need of denture relining[38]. This can be fulfilled by prosthesis made up of SMP.

Fixed Partial Dentures: As continuous changes occur in the surrounding hard and soft tissues, so with time, gap may be present between the tissue surface of the pontic and the corresponding part of the ridge that ultimately leads to inadequate fitting of the pontics thus affects the esthetic and biological value.[39] Pontics made up of smart materials can adapt to the surrounding altering hard and soft tissues so prevents its suboptimal fitting.

Implants: 4D-printed structures can be used as soft base under implants (S M P s have similar resiliency like pdl), that is, this structure can be fused to apical portion of dental implants after certain modification in that portion to have cushioning effect. In this way injury to vital structures like maxillary sinus and ID nerve can be avoided. This can overcome sinus augmentation surgeries.[5,6]

Stem cells can be placed along with 4D-printed implants or tooth-shaped scaffolds so that these stem cells can grow into natural teeth. Custom designing and printing surgical drill guides may also use these 4D printable smart materials.[5,6]

Temporo-mandibular joint and Maxillofacial Surgeries :

- Materials used in 4D-printing technique can be used as a replacement of cartilage while undergoing continuous movement.[5,6]
- Can be used to cover maxillofacial defects.[40,41]

Dental Restorative Materials: Failure of the restorations is commonly seen at the margins of the cavity. One of the reasons is dimensional changes occurring at the margins leading to microleakage and further loss of restoration. This can be avoided with the help of 4D printing materials. These materials because of continuous self folding movement have ability of moving towards the peripheries of the cavity and thus, avoiding microleakages and further loss of restoration.[5,6]

4D-printed restorative materials can be pre- programmed to direct their movement towards the cavity walls to ensure maximum adaptation and thus prognosis of the conservative treatment can be improved.[5,6]

Root Canal Instrumentation: Instrument separation is the commonly seen complication while doing RCT procedure. Root canal instruments made up of shape memory metals takes the shape of the curved canals and adapts to it. In this way it minimizes the occurrence of instrument separation.[42,43]

Orthodontic Appliances: 4D-printed technique can also be used for the fabrication of orthodontic appliances. In these 4D printed appliances, continuous movement occurs because of self folding nature of the smart material. The movement of the appliance are controllable and are used to position and align teeth in planned position and direction in specific duration of time.[5,6]

Summary:

As tissues of the oral cavity (both hard and soft tissues) undergoes changes with growth and also after completion of growth with age so we need materials that can self adapt with changing surrounding environment to avoid interventions.

This is fulfilled by 4D printing technology that can give dynamic, self adaptable material that give response on exposure to stimuli in contrast to 3D printed objects.

Another important parameter is to monitor time. That means, after delivery of the 4D appliance to the patient, timely follow-up should be done as because transforming time of the appliance to the preprogrammed shape varies. The prognosis of the planned treatment depends on the time taken by the 4D printed material to transform into final pre determined functional shape and in final position.[44] Continuous dynamic changes for the smart material with time are not desirable, that i.e., the self-folding time cannot be infinite. In other words, hence every smart material should possess self-locking property that can control its folding sequence.[45] Other factor to be considered during designing or programming step of the material is structures present around 4D printed appliance and their movement. For example, along with the monitoring of blood pressure, contractile movements of the heart muscles and physiological movement of heart and lungs vessels should be considered during designing a cardiac valve. To summarize, both kinematic and dynamic factors has to be considered while designing a 4D printed structure.[46-48].

So 4d printing technology is a quantum leap because of its potential applications not only for prosthodontics but also for all the branches of medical field.

Conclusion:

4D printing is an innovative revolution that can have significant impact on all branches of dentistry. But as it is a new technique, it needs more collaborative scientific research work and further prospective analysis of its potential applications.

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FIGURES

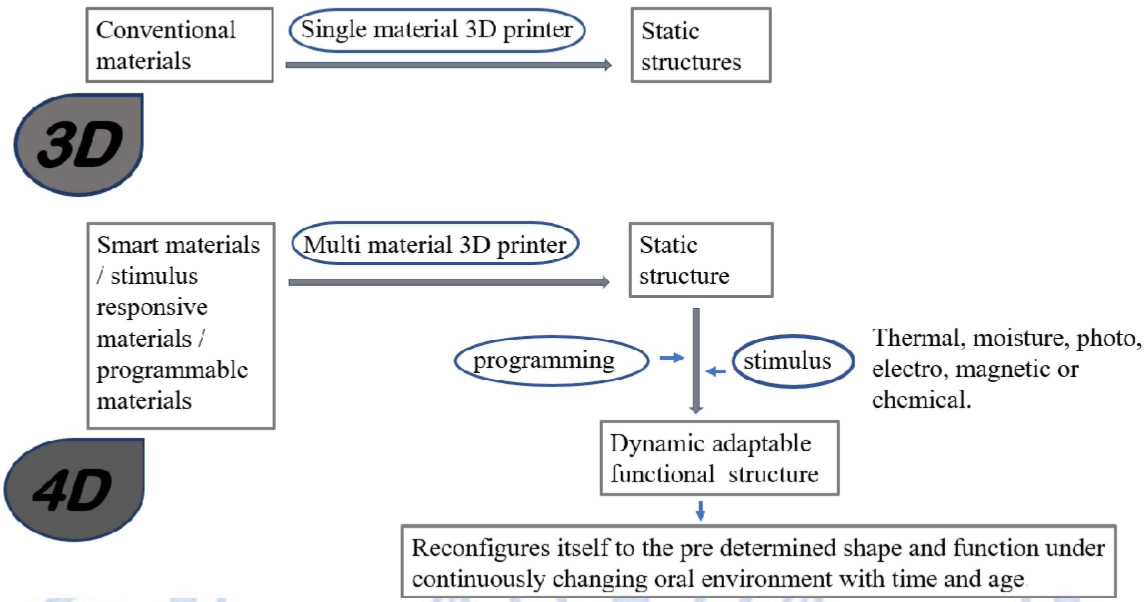

Figure 1