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A DEEP LEARNING OF 4D PRINTING IN DENTISTRY: AN UNPRECEDENTED QUANTUM LEAP IN INNOVATIVE TECHNOLOGIES

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ABSTRACT:

"Necessity is the mother of all inventions." The need for more stable, functional and durable dental materials has paved the way for many researchers, scientists and dental clinicians to enter into new era of 4D dentistry. The goal is towards enhancement of oral health care management with newer biomimetic modalities of treatment to restore the teeth as close as possible to its original state & structure.

Today's world of endless opportunities has opened up avenues for revised versions of 3D printing, incorporating a new dimension "TIME". The time variable adds additional functional dynamics to the existing 3D technology, making it a game changer in this fast-evolving field.

Recent technological advances coupled with clinician's skills can effectively deliver the finest dental care, while maintaining the treatment standards and meeting the patient's growing demands. Its applications are diverse in the dental stream ranging from restorative dentistry to the most complex surgical and maxillofacial prosthesis. This paper highlights the various materials used in 4D technology, its applications at present and the scope of 4D in the future of dentistry.

INTRODUCTION:

3D structures have always been constructed by cutting out the bulk of a solid structure, either natural or man-made, which is known as the SUBTRACTIVE MANUFACTURING METHOD. After the advent of 3D printers, ADDITIVE MANUFACTURING OR RAPID-PROTOTYPING has been possible, where in solids with variable lattice structures can be created through computer programming, with the material being deposited as layers on top of each other; thereby reducing the wastage of resources.

3D-printing has created ample possibilities and treatment modalities in the field of dentistry by improving treatment planning and lessening the treatment time, while enabling patient specific designs. Over the last decade, many recent advances of 3D-printing have come into existence with emerging technologies, one such advancement being 4D printing.

4D-printing is a new dimension of interest which uses similar techniques of rapid prototyping, with the resultant object able to morph in response to environmental stimulus. 4D-printing in akin to 3D-printing with an additional advantage of the dimension time, which helps is retaining the shape memory of a particular entity that is printed in 3D [1]. This added advantage helps in the designing and manufacturing of a wide variety of structures ranging from drugs and therapeutics, bones of face and the jaw, dental materials, facial prosthesis; in their most advanced forms that are more durable and can withstand more forces than their 3D counterparts [2].

The dynamic nature of the oral cavity makes 4D technology the most suitable alternative to the old school methods, which are static in nature. Initially the required object is printed using special materials, which stays inert till the external stimulus is applied and thereafter the stimulus-responsive material adapts to the dynamics accordingly.

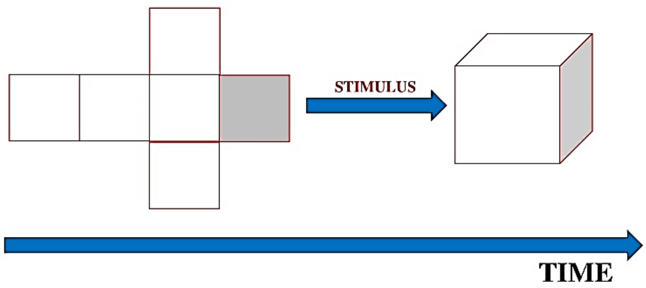

Figure 1: Deformation behaviours in 4-D printing

REASONS TO CHOOSE 4D OVER 3D:

4D materials are dynamic in nature and work through stimulation, rather than mere simulation of tissue structures. The time dimension adds to the adaptability due to the external stimulus, making them comparatively more durable than static products.

The ability to control external stimuli and thereby the internal environment around them leads to high functionality. The raw material required for 4D manufacturing results in reduced cost in the long run as the necessity to print multiple 3D printed structures is compensated by a functional 4D printed structures, as well as increased manufacturing efficiency [3].

The 4D printed material can be stimulated with the best suitable one with in a variety of variable external stimuli, making it practical for everyday functionality.

Structures that are larger in size than the printers can be manufactured at once as they can be programmed initially and later adapted according to the applied stimulus, in contrast to printing smaller structures using 3D printer and assembling them [2].

MATERIALS USED:

The materials used in 4D printing are known as "SMART MATERIALS" or "INTELLIGENT" or "RESPONSIVE MATERIALS"; whose properties can be controlled via application of external stimuli [1,4].

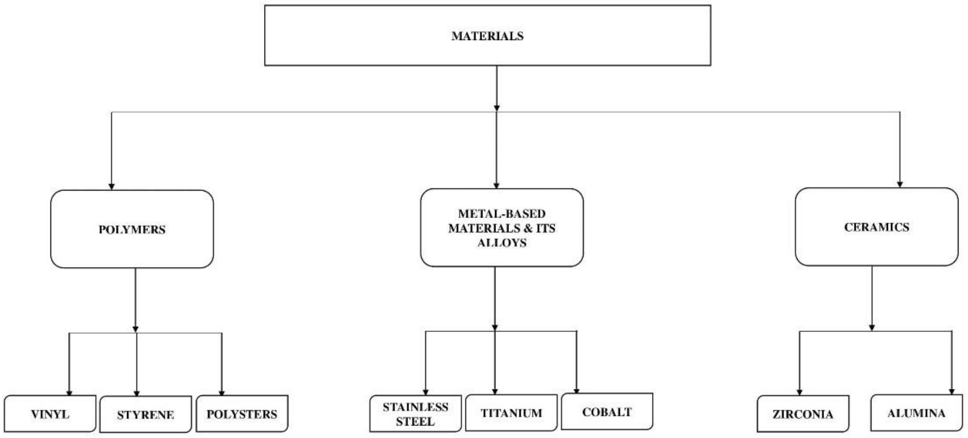

Figure 2: Materials used for 4D printing in dentistry

They are also known to possess other functions like self-cleansing, self-responsiveness, self-repair, shape-memory and even shape-changing properties according to the stimulus they receive [5]. There are different types of stimuli to which these materials respond ranging from, physical, chemical, biological or a combination of any of these [6].

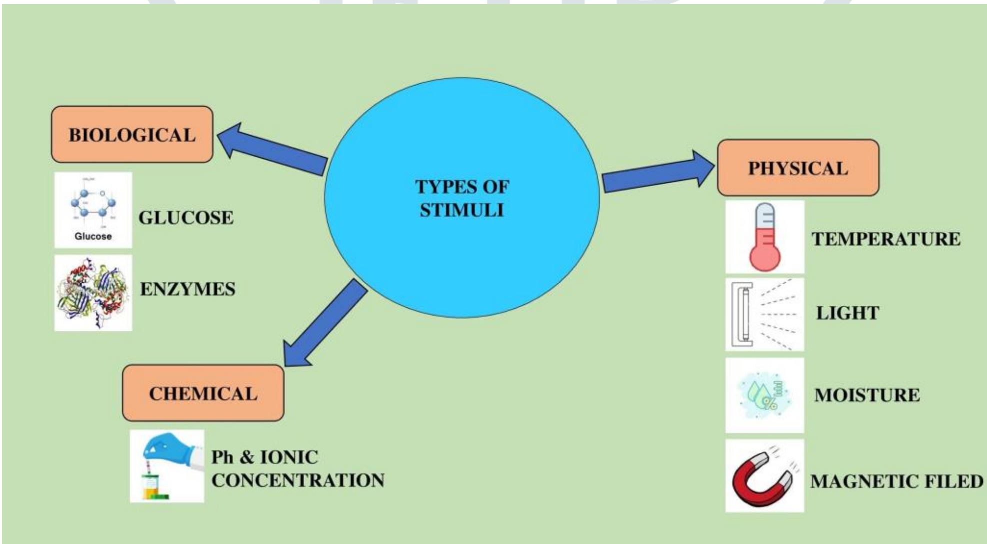

Figure 3: Different types of stimuli that act on 4D printed materials

Thermo-responsive materials change their lattice structure according to the temperature difference. The 4D printed structure is activated with the varying temperatures of the body and its internal environment.
For example, Thermo-responsive heart stents were developed using a polymer through FDM technique which expand by immersion in the water at a controlled temperature of 37 degrees Centigrade, which is as same as normal body temperature [7]. In endodontics, Gutta-Percha (GP) is re-engineered to Trans-1,4- polyisoprene GP, which can firmly seal the entire endodontic space [8].

Photo-responsive materials react differently compared to others, the materials may contain a colour pigment called as chromophore which absorbs the light and gets heated up, leading to the desired response. The method of action is indirect, where the light energy is converted into heat energy to in turn bring changes in the structure of the 4D printed object. Sources of light include UV light and visible light. For example, photoreactive materials are used in photo-therapy, photo-actuators and reversible adhesives [9].

Moisture responsive materials absorb the water and change their configuration, they greatly differ in the type of material used based on their water kinetics and diffusion rates through the material, that helps the material to swell and perform required function. For example, Optical humidity detection devices [9,10].

Some polymers have magnetic components embedded in them, which respond to the magnetic field in its presence, and return to their original state when the magnetic field is turned off, known as magneto-responsive materials. For example, Magnetic particles can be combined with certain gel to make “FERRO-GELS”, commonly used in ultrasonography, which have phenomenal potential in the bio-medical field [9,11].

The variations in the pH can greatly affect the molecular structure of the materials printed sophistically using 4D, these materials contain ionic groups which respond to the microenvironment in the human body and expand their functional potential by swelling or deswelling. This is possible due to the ionic gradients and the osmotic pressure present around them [9,12].

Another type of materials that can be manufactured using 4D printing are those that respond to glucose and enzymes, they are commonly used for the targeted drug delivery systems, with the level of glucose or enzymes in blood triggering the release of these therapeutic agents in a sustained flow. They play a key role in drug-delivery systems, especially cancer drugs, due to the varying pH of tumour cells [9,13].

Targeted drug-delivery systems could play an important role, as general systemic administration might create resistance over a period of time, or may lead to side effects. For example, in case of Endodontic infections and periodontal problems, anti-biotics are available in advanced forms such as sprays, fibres, films etc.

In case of local anaesthetics, the efficacy of topical local anaesthesia might be decreased due to the salivary clearance. To tackle this problem, local anaesthetics are supplied with the help of biomaterials acting as carrier molecules such as hydrogels, films, nano-fibres and others that help in improving drug targeting [14].

In addition, targeted drug deliveries with bio-mimetic scaffolds are being used for “BONE TISSUE ENGINEERING” (BTE), which supply the stem cells, bone regenerative cells and drugs to the targeted area with the help of carrier molecules [15].

TECHNIQUES OF ADDITIVE MANUFACTURING:

- STEREOLITHOGRAPHY
- FUSED DEPOSITION MODELLING
- DIGITAL LIGHT PROJECTION
- SELECTIVE LASER SINTERING
- PHOTOPOLYMER JETTING
- POWDER BINDER PRINTER
- COMPUTED AXIAL LITHOGRAPHY
  Of which “STEREOLITHOGRAPHY” and “FUSION DEPOSITION” are the most commonly employed techniques owing to less expenditure [16].

STEREOLITHOGRAPHY (SLA):

This technology uses light as a stimulus to activate the polymerisation process. U.V light is used as the polymerising agent; the successive layers of polymerisation take place on top of the previously polymerised layer [17]. SLA in dentistry is used in preparation of restorations, crowns and bridges, and also anti-microbials can be added to the resins, such as nano-particles, chlorhexidine and chitosan [18].

FUSED DEPOSITION MODELLING:

Also known as the “FUSION DEPOSION METHOD”, or “FUSED FILAMENT FABRICATION”. In this technique, thermoplastic materials are used, which are heated and ejected from the printer in the required shape. It is employed in the fabrication of temporary structures like crowns and bridges [19]. They also exhibit shape-memory due to heat transfer within the materials.

Table 1: Comparison of Stereolithography and Fused deposition modelling [1,19]

STEREOLITHOGRAPHY	FUSED DEPOSITION MODELLING
• Polymerizing resins are used.	• Thermoplastic materials are used.
• Comparatively expensive.	• Affordable technique.
• Complex methodology.	• Comparatively simple.
• Used to manufacture durable structures in dentistry.	• Used to manufacture temporary structures in dentistry.
• Limited shape memory.	• Superior shape memory.
• Superior surface replication of details and smooth texture of the finish.	• Reasonable replication os surface details; tendency for more voids and rougher finish.
• Better adaptability to contours of bone/teeth; Hence wider applications.	• Modest adaptability
• Used in manufacturing units.	• Used in scientific research and teaching modalities.

SCOPE OF 4-D PRINTING IN DENTISTRY:

4D printing promises evolutionary changes in the dental field in near future. The medical field has witnessed exceptional results with 4D printed devices. In 2015, a medical team from Michigan could save 3 infants with customised patient specific respiratory implants [20]. Scope has broadened in manufacturing of newer, stimuli responsive, adaptive cardio-vascular stents, targeted drug delivery systems; 4D bioprinting for grafts, scaffolds, organs and implants [21].
In-vitro studies of cardio-vascular implants have been proved to be promising [22]. A successful smart material has demonstrated its potential of being used as a vascular graft by a research team from University of Missouri [23].

In the dental field, it is well known that the use of 4D printing is not far, with every speciality of dentistry having its own possible and endless applications. The use of nanomaterials for 4D printing could innovate better dental materials with superior mechanical properties [24].
In a new generation of composites known as the "SELF-HEALING COMPOSITES", the filler particles when combined with the shape-memory photo-curable monomer, lower the curing time, and enhance the mechanical properties. A breakthrough in the field of restorative dentistry has been marked with the discovery of 4D printed Zeolite/polymer-based composite, which can reversibly alter its shape according to the presence of absence of water [25].

Just like the dynamic oral environment, restorative materials could be made to be dynamic, therefore shape-shifting according to the stimulus within the oral cavity, leading to decrease in micro-leakage and overhanging restorations [26].
Due to the self-folding nature of certain smart materials, prosthesis may be manufactured using them to contact the bone during resorption, without the need for relining dentures.
Shape memory metals have taken over the present technology of rotary instruments for root canal instrumentation procedures [19].

The possible use of 4D printing for implants can be proved effective due to the equal stress distribution around the implant site [26].Traditional implants are made of hard materials leading to fatigue failure, whereas implants made with PEEK(Polyether ether ketone) /CHAP(calcium hydroxyapatite) polymer have a higher modulus of elasticity, thereby distributing the stresses over the implants uniformly, instead of forces being concentrated at the apex.
Additionally, biomaterials can also be added as scaffolds to implants so as to promote cellular proliferation [27].

Grafts can be used in TMJ and other maxillofacial surgeries. Smart materials promise to be better orthodontic appliances compared to the arch-wires, as shape memory polymers have greater elastic modulus compared to shape-memory arch-wires such as Ni-Ti [19].

This self-regulating technology has its fair share of drawbacks. The number of smart materials discovered until now is limited and lack variety. The technology itself is in novice stage and would require more clinical trials for commercial manufacturing, which brings us to the next drawback of researches being expensive and require the need for huge funding.

Overall, the scope of 4D printing technology using the smart materials seems to be colossal in dentistry.

CONCLUSION:

Since the past decade, additive manufacturing technology has opened doors of innovation, cutting-edge functional application and advancements in patient specific customized treatment modalities. It has revolutionized the standard of patient care by enabling clinicians to enhance their key diagnostic and decision-making skills as it permits superior visualization and pragmatic treatment planning. By virtue of its benefits in manufacturing technology, 4D printed programmable materials with superior shape memory properties which vary over time under different stimuli is made possible.

This shape-shifting behaviour over a period of time when subjected to dynamic forces can influence its performance in various areas of dentistry. From the introduction of recent shape memory polymers and self-folding adaptive stimuli responsive materials in restorative dentistry, the enhanced tissue adaptive 4D printed prosthetic rehabilitations, the self-straining wires for orthodontic movement to the 4D augmented scaffolds for bioengineering regenerative techniques the possibilities of 4D design and function are endless.

4D printing is rapidly gaining advantage in futuristic technological developments paving the way for newer bio-smart novel materials and exploring the benefits of curating customized dental care in accordance with patient needs and demands. In due course of its evolvement and realistic use 4D printing will allow for more interceptive and preventive minimalistic modalities of therapy instead of reparative dentistry.

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