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Dental 4D Printing: An Innovative Approach

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ABSTRACT

Since the introduction of 4D printing in 2014, few research works has focused on the application of such revolutionary technique in the dentistry and medicine. 4D printing is the technology in which manufacturers can produce materials with self-folding interactions. The outcome of this technique are materials that are capable of undergoing motion criteria overtime. As most of the body's organs are in continuous movement, including structures in the oral cavity, the introduction of such materials as functional objects in medicine and dentistry can be highly valuable. This technique could enable clinicians to change the scope of dentistry and to provide more treatment options.

Overview

Over the last decade, 3D printing has enabled clinicians to improve their diagnostic and surgical procedures as it allowed for better visualization, realistic training and surgical planning. In dentistry, this technology has revolutionized the practice as it could provide maximum accuracy with little clinical setup and short operative time [1]. The use of 3D printing in dentistry has been essential in the modern restorative and prosthetic fields, orthodontics, implant dentistry as well as maxillofacial surgery. In particular, 3D-constructed models have played a principal role in facial reconstruction surgeries (e.g., zygomatic fractures) and temporomandibular disorders that require surgical intervention. 3D printing facilitated better visualization of deep structures and thus reduced the potential complications during surgery such as prolonged operative time with consequential infection and blood loss. In addition, 3D printing has helped in the production of removable dentures, prosthetic mock-ups and trial prostheses, which are all important in esthetic and restorative clinical daily work [2].

Skylar Tibbits and his coworkers had designed self-folding structures that reshape overtime under certain environmental conditions. They converted the stable 3D-printing materials into actively moving objects by the novel 4D-pritning approach. The printed models transform into a predetermined shape and function after fabrication. Self-folding materials is the name given for the outcome of the recently introduced 4D printing technology. 4D printing is based on adding a fourth dimension to the standard 3D printing, that is, motion over time [3, 4]. The aim of 4D printing is to produce functional objects rather than static ones.

In the medical field, the term "4D" has been linked to a scanning approach that is used for monitoring the dynamic characteristics of different organs and it has shown great advantages for the accurate positioning of dynamic tissues during radiotherapy; it also allowed orthopaedic clinicians to develop printed models of carpal and metacarpal bones to monitor thumb movement to help in arthroplasty procedures. Based on the concept of motion over time, 4D scanning could allow modelling complex anatomical structures improving the preoperative planning [5].

4D printing is the process of self-folding overtime under thermal and humidity changes. This concept relies on understanding how the microstructures of 3D-printed models can undergo spontaneous shape transformation under thermal and moisture changes. 4D printing relies on 3D printing of multi-materials followed by selective photo-curing to give the 4D-printed objects motility nature. The transformation mechanism can be assessed by evaluating the strain properties of each component within the printed model and putting them under a controllable pattern [6].

4D printing has 2 essential steps: processing and programming. The model is firstly processed into an original shape; then it is intermediately temporized into another shape and finally programmed to convert to another shape when exposed to certain stimuli (e.g., human body temperature 37°C or body moisture) in a self-folding pattern. Mixing the microstructures into controlled measures can be challenging, and the manner in which materials undergo programmed movements is not reported [6].

In dentistry, 4D printing would have a good impact on different specialties as the technology can produce dynamic and adaptable materials to be functional in the oral environment under the continuously changing thermal and humidity conditions. Undesired dimensional changes, thermal instability, polymerization shrinkage and microleakage are current concerns in dentistry that can be overcome utilizing the evolving 4D printing technology [7, 8].

In this work, the future applications of 4D printing in dentistry are highlighted.

Future Dental Applications of 4D Printing

4D printing can be used for the production of dental restorative materials (Figure 1). The biomechanical properties of restorative dental materials have long been a subject of interest: the important aspects of dental fillings are strength, color stability, adhesion, longevity and failure. The oral environment, in terms of its dynamic nature as well as functional and balancing forces, presents a challenge when replacing missing tooth structure. The common factor of failure of restorative materials is dimensional changes at the margins which lead to instability or total loss of dental fillings. The outcome of 4D printing can be restorative materials with continuous self-folding adjustment, that is, materials which are capable of moving toward the peripheries avoiding microleakage or overhangs at the margins. The technique would still rely on the advancing CAD/CAM technology, and, on the long term, the patient will need to see his dentist less frequently for follow up.

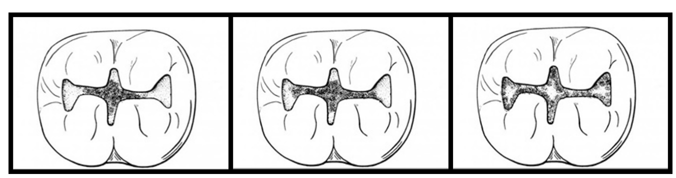

Figure 1: 4D-printed dental filling material continuously change their shape and position from the center to the margins over time to prevent any marginal leakage or fracture.

4D-printed materials can move only in certain directions as programmed before their production. Adjusting the path of motion of 4D-printed materials in restorative dentistry can eliminate the use of dental adhesives (etching and bonding systems) as the materials can rely more on mechanical means of retention rather than the chemical aids. In other words, 4D-printed filling materials can be programmed to move downward toward the fitting surface of the cavity to ensure

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maximum adaptation. In addition, 4D-printed fillings can be used for inaccessible areas in the oral cavity where manipulation and longevity of current restorative materials are difficult.

4D printing can be used in removable prosthetic dentistry. The technology can produce materials with similar properties of the natural hard and soft tissues. In addition, 4D-printed materials can adapt to the types and directions of forces in the oral cavity. 4D-printed prosthetic materials can have reliable fitting and retention characteristics and optimal dynamic properties according to their self-folding nature. The denture base can be fabricated of certain structures that encompass elasticity and thermal criteria similar to the periodontal ligaments or overlying mucosa. In addition, a variety of designing options can be provided for patients with individual demands. For example, patients with areas of residual ridge resorption can be managed by installing additional materials that compensate for bone loss.

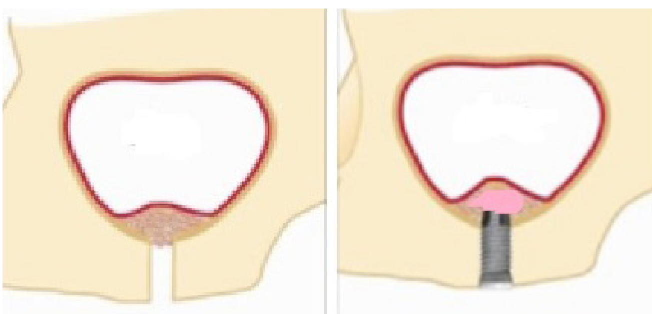

Figure 2: The application of 4D printing with implant dentistry. A 4D-printed membrane is applied between a dental implant and a vital structure (maxillary sinus) to act as a soft cushion to prevent injury.

In implant dentistry, 4D-printed structures can be used as fused to the currently available dental implants by modifying their apical portion to act as soft base under implants (Figure 2). This can help to avoid injury of vital structures around implant site such as maxillary sinus or inferior alveolar nerve. Thus, the technique can overcome sophisticated surgeries such as sinus augmentation when done for implant cases (Figure 2). In addition, stem cells can be carried on 4D-printed implants or tooth-shaped scaffolds to grow into natural teeth.

4D-printed objects can be used in TMJ and maxillofacial surgeries. 4D-printed materials can replace cartilage while undergoing continuous movements compensating for the articulation and occlusion.

The use of 4D printing in dentistry can also extend to orthodontics (Figure 3). Currently, the modern use of both removable appliances as well as fixed braces relies on data imported from 3D orthodontic software. The applicability to produce self-straining wires or self-folding removable can make the orthodontic appliances undergo continuous movement overtime ending up with positioning and aligning teeth in the desirable position and angulation.

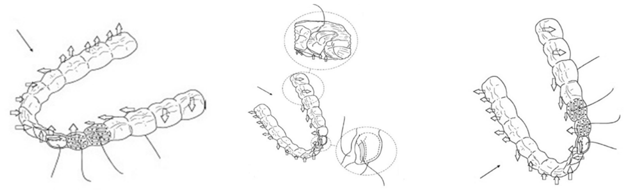

Figure 3: 4D-printed orthodontic appliances can be manufactured as to undergo controlled self-folding movement to take the teeth in certain direction and angulation in known time. The cross-section of the appliance showing the multilayered micro-constituents.

Discussion

4D printing is an interesting research topic and can have a positive, practical impact on medical and dental applications. A comprehensive understanding of the folding pattern is essential to produce functional appliances without harmful effects. This manufacturing technique relies on 3D printing of several materials with enhanced digital shape-memory properties that can alter over time under different thermal/physical conditions. 4D printing relies on important the sequence and path of movements, which determine the self-folding pattern [4].

The designing step should take into account the movement of the circumferential structures around the 4D-printed prosthetic appliance. For example, designing a cardiac valve should consider the contractile movements of the heart muscles together with the motion of cardiac and pulmonary vasculatures in addition to potential aspects of high/low blood pressure. In other words, designing 4D-printed appliances should be done on kinematic and dynamic bases [9–11].

Another important aspect is the shaping time under thermal/physical conditions. In this regard, patients who have newly introduced 4D-printed appliances should be closely monitored as the time of folding can range from minutes to days, and the success rate of the treatment procedures would rely on the time of transforming the material into its final shape and in final position while still being functional [4]. The self-folding time cannot be infinite, that is, the material should not keep undergoing dynamic changes continuously overtime. There should exist the so-called self-locking property, which is capable of controlling folding sequence [3].

The other major properties of ideal 4D-printing structures are biocompatibility, modulus of elasticity and coefficient of thermal expansion which should mimic those of body structures to hinder undesired body reactions such as swelling, inflammation or ischemic reactions. In addition, 4D-printing materials should have good strength properties to prevent their fracture overtime, which could necessitate revision surgery [5].

4D printing helps in the fabrication of shape-shifting materials over time or space with possibility to control their microscopic changes for use in biomedical engineering. 4D-printed structures should possess smart structures and high resolution so that they can be thermo-mechanically programmed to change into functional configurations. The shape-shifting behavior is resultant from the differences in dimensional changes' ratios (coefficient of thermal expansion, modulus of elasticity) of the internal ingredients. Modification of the materials behavior in microscale can allow for their use in stem cell and tissue-engineering research for the production of scaffolds [12].

More collaborative research work needs to focus on the introduction of 4D printing in dentistry; and further prospective analyses of the potential applications of this technique need to be discussed.

Conclusion

4D printing can have a significant impact on all aspects in dentistry. The author encourages researchers, academics and technicians to start discovering this interesting field. It can evolve in a similar manner to CAD/CAM and 3D printing and change the scope of dentistry.

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