Review Article

From Static to Dynamic: 4D Printing's Impact on Modern Dentistry

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ABSTRACT

4D printing, advancement from 3D printing, offers dynamic, adaptive materials through stimuli-responsive technology, with transformative potential in dentistry. Unlike traditional static 3D-printed structures, 4D-printed materials can change shape over time, addressing issues, such as microleakage, polymerization shrinkage, and dimensional changes in dental restorations. Applications extend across prosthodontics, implant dentistry, and temporomandibular surgeries, providing patient-specific, responsive solutions. However, material safety, regulatory hurdles, and high costs remain challenges. Continued research aims to enhance material biocompatibility, improve regulatory compliance, and reduce production costs for clinical adoption.

Key words: 4D printing applications, 4D printing dentistry, 4D printing prosthetics, 4D printing technology

INTRODUCTION

In the past 10 years, 3D printing has made it feasible for researchers to produce intricate designs that were previously unattainable through traditional manufacturing techniques. The term "conventional three-dimensional printing" refers to a method that builds a three-dimensional structure by layering on the material.

In the fields of orthodontics, implant dentistry, maxillofacial surgery, and current restorative and prosthetic dentistry, 3D printing has proved crucial. Specifically, 3D-built models have been crucial in corrective surgery for temporomandibular (TMJ) problems and facial reconstruction surgeries (such as zygomatic fractures). Furthermore, 3D printing has aided in the creation of trial prostheses, prosthetic mock-ups, and detachable dentures – all crucial for the everyday work of esthetic and restorative clinical practice.

Traditional 3D printing technologies that concentrate on creating static structures out of a single material are unable to satisfy all of the dynamic function requirements required for use in dentistry.[1]

With the goal of offering greater capabilities to transform restorative dentistry, attention has recently turned from 3D to 4D printing. According to current projections, 4D-printed goods will eventually replace 3D-printed ones. To create dynamic materials that can alter shape over time, Tibbitis first suggested 4D printing. The method of 4D printing involves using environmental stimuli to change a 3D-printed object into a different structure.[2]

The fourth dimension, or movement over time, is an extra-temporal component added to the 3D technology. This is made possible through the deft manipulation of a number of material properties, which are progressively changed by external stimuli, such as pH, ion concentration, glucose concentration, temperature, fluid, light, magnetic field of energy, and enzymes. In a variety of dental specialties where cutting-edge materials that can adjust to shifting environmental conditions are required, 4D printing technology is beneficial [Figure 1].

Among the drawbacks of dentistry that 4D printing can help with are polymerization shrinkage, microleakage, dimensional changes of dentures, continuous changes in the shape of the dental ridge, increased risk of damage to important structures during implant placement, and frequent follow-up visits.[2]

HOW DOES 4D PRINTING WORK?

Processing and programming are the two crucial processes in 4D printing. Before being programmed to change into a different shape in response to specific inputs (such as the body's moisture content or the temperature of the human body, which is 37°C), the model is first processed into its original shape.

It can be difficult to mix the microstructures into controlled measurements, while programming is the process by which materials go through pre-determined movements to become dynamic smart materials.[3]

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Components of 4D printing

- Multi-material 3D printing technology: Key to creating dynamic, programmable structures
- Smart materials: Include heat-responsive, moisture-responsive, auto-responsive, or electromagnetic-responsive materials
- Mathematical modeling: Forward and backward modeling methods to simulate transformations
- Interaction mechanism: Involves stimulation programming, supported by software, such as Autodesk, CATIA, or open-source alternatives
- Multi-material printers: These include Stratasys, ROVA, SolidView, and Geomagic, which print shape-memory alloys, self-healing polymers, etc.[4]

Additive manufacturing technologies

Various additive manufacturing techniques make 4D printing possible. Based on material deposition mode, they can be either extrusion-based methods or vat photopolymerization methods.

Extrusion-based methods, such as fusion deposition modeling (FDM), use heat and filaments are layered to form objects from materials, such as polylactic acid, acrylonitrile butadiene styrene, polycarbonate polycaprolactone, polyethylene terephthalate, and polyphenylene sulfone. While FDM is cost-effective and fast, it lacks the precision required for intricate details.[5]

Direct ink writing (DIW), another extrusion method, uses computer-controlled robotics to deposit metal, ceramic, or polymer ink, achieving high resolution. Inkjet printing utilizes electric, piezoelectric, or thermal nozzles for drop-on-demand printing onto a substrate using a computer-aided design. It sprays light-curable resins with fast output but suffers from frequent nozzle clogs.

Meanwhile, vat polymerization methods such as stereolithography (SLA), which was created by Charles Hull in 1986, use a light source (laser) to polymerize resin layers. It has high spatial resolution and speed, suitable for complex shapes and bioprinting using gamma rays, ultraviolet rays, and visible light. Recently magnetic assisted SLA has also developed, resulting in highly detailed shapes suited for bioprinting applications. Digital light processing emerging as a rapid prototyping technology essentially similar to SLA, but projects digital images of an entire layer onto the resin achieving rapid, precise prints, especially useful for custom medical implant precise surgical guides and 4D-printed structures. Used for self-folding, environmentally responsive structures from smart materials, such as polyethylene glycol dimethacrylate.[4]

Material systems in 4D printing

In terms of material systems, 4D printing heavily relies on smart materials, such as shape memory polymers (SMPs), shape memory alloys, and hydrogels, which respond to external cues for programmable changes. SMPs, for example, are engineered with segments that make them both elastic and capable of adjusting stiffness under stimuli. SMPs have become common in 4D printing as they enable functionalities such as self-deformation, self-assembly, and self-repair. Recent advancements in SMPs include nanocomposites, offering multi-functional and even reversible shape memory, allowing materials to alternate between shapes repeatedly. Different types of SMPs, such as thermally induced, light-responsive, and chemical-responsive variants, enable versatility in design and applications.[6]

Hydrogels are also significant due to their biocompatibility and reversible deformation capabilities. Their swelling behavior, controlled by factors, such as crosslinking density and hydrophilicity, makes them particularly adaptable for biomedical uses. Temperature-responsive hydrogels expand or contract with heat changes, making them suitable for sensors and actuators. Light-responsive hydrogels adjust properties, such as elasticity and shape based on light intensity, and pH-responsive hydrogels alter volume in response to hydrogen ion concentration, with notable applications in biomedicine [Figure 2].[7]

POTENTIAL APPLICATIONS IN DENTISTRY

Restorative material

The biomechanical properties of restorative dental materials include strength, color stability, adhesion, longevity, and failure.

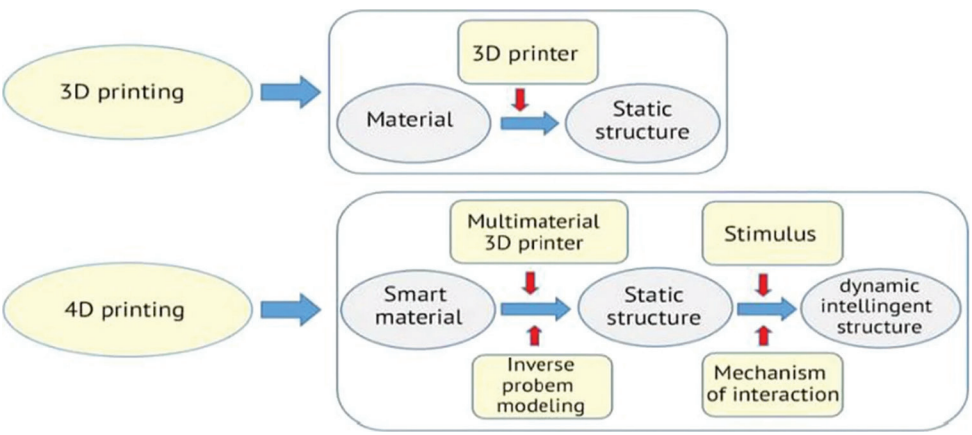

Figure 1: Differences between 3 and 4D printing technologies

The oral environment is a challenge for restoring damaged tooth structure due to its dynamic nature, balance, and functional demands. Dimensional alterations along the edges of restorative materials are often the cause of instability or complete loss of dental fillings. 4D printing can be used to create materials that continuously fold themselves or that may migrate toward the edges to stop microleakage or overhangs at the edges [Figure 3].

Only specific directions, pre-programmed before creation, can be moved by 4D-printed materials. The use of dental adhesives (etching and bonding systems) can be eliminated in restorative dentistry by modifying the motion of 4D-printed materials, which can rely more on mechanical retention than chemical assistance.

Removable prosthesis

Dentistry that uses detachable prosthetics can make advantage of 4D printing. The technology can create materials that resemble the soft and hard tissues seen in nature. 4D-printed materials can also adjust to the many kinds and orientations of stresses that exist in the oral cavity. Because they fold themselves, 4D-printed prosthetic materials can have excellent dynamic qualities and dependable fitting and retention characteristics. Similar to the periodontal ligaments or the mucosa that covers them, the denture base can be made of specific structures that meet flexibility and heat requirements. For patients with specific needs, a range of design choices can also be offered. To compensate for bone loss, extra materials might be installed in individuals who have areas of residual ridge resorption.[5]

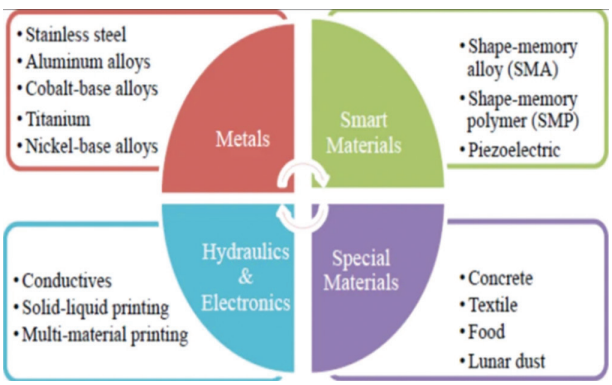

Figure 2: General overview of current research material for the additive manufacturing approaching era

Implant dentistry

By altering their apical section to serve as a soft substrate beneath implants, 4D-printed materials can be bonded to commercially accessible dental implants. By doing this, damage to important structures surrounding the implant site, including the maxillary sinus or inferior alveolar nerve, may be prevented. Therefore, when used for implant instances, the approach can overcome complex surgeries, such as sinus augmentation [Figure 4]. Furthermore, stem cells can develop into real teeth using scaffolds shaped, such as teeth or 4D-printed implants.[1]

TMJ

It is possible to use 4D-printed items in maxillofacial and TMJ operations. By replacing cartilage and enduring constant motion, 4D-printed materials can compensate for occlusion and articulation.[1]

Research and developments

New research opportunities for the application of 4D printing in dentistry have been made possible by recent developments in the technology and materials. According to studies, shape-memory polymers and hydrogels have a lot of potential for use in dentistry because of their compatibility with the oral environment and their responsiveness to temperature and moisture. In addition, these materials are being developed to enhance their mechanical qualities and biocompatibility, which will make them more appropriate for long-term oral usage.[8]

Zhang *et al.* investigated shape-memory polymers' potential in dental applications in 2022, pointing out that these materials could adapt dynamically to changing oral anatomies.[9] Additional research conducted by Choi and associates has concentrated on intelligent hydrogels that change size in reaction to moisture, potentially finding utility in self-adjusting retainers.[10]

Challenges and future directions

While 4D printing holds immense promise, there are challenges that need addressing before widespread clinical adoption. These include:

- Material safety: The biocompatibility of 4D materials must be thoroughly assessed, as many stimuli-responsive polymers still pose potential risks in biological environments.

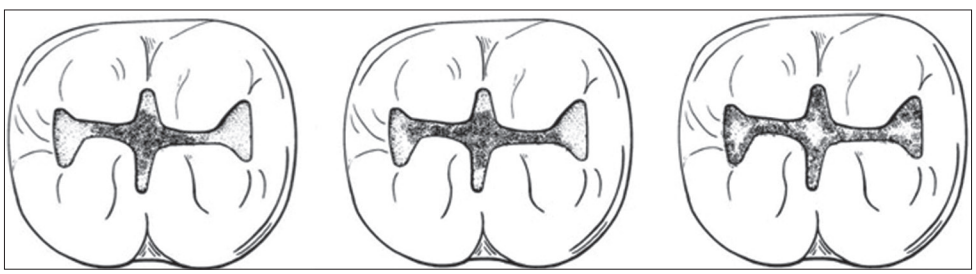

Figure 3: 4D-printed dental filling material continuously changes its shape and position from the centre to the margins over time to prevent any marginal leakage or fracture

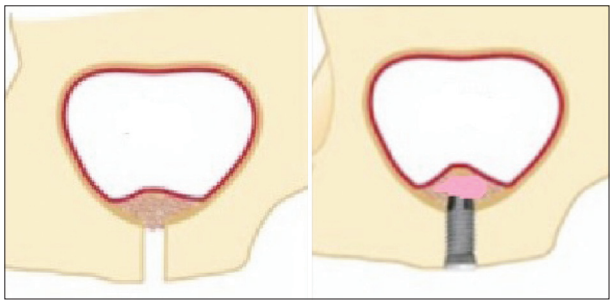

Figure 4: The application of 4D printing with implant dentistry. A 4D-printed membrane is applied between a dental implant and a vital structure (maxillary sinus) to act as a soft cushion to prevent injury

- Regulatory approval: 4D-printed devices must undergo rigorous testing to meet regulatory standards for medical devices, which can be a time-consuming process.
- Technical complexity and cost: 4D printing processes are more complex than conventional 3D printing, and thus, production costs are currently higher. Reducing these costs will be essential to make 4D applications viable for dental clinics.

Future research may focus on hybrid materials that combine the best features of various polymers to create safer, more efficient, and versatile devices.[5] In addition, advancements in digital scanning and dental imaging could be integrated with 4D printing processes to create truly customized and patient-specific devices, pushing the boundaries of personalization in dentistry.[11]

CONCLUSION

4D printing represents a revolutionary step in dental technology, with the potential to create devices and materials that are not only custom-fit but also adaptive, responsive, and possibly self-repairing. As research progresses, these dynamic, patient-centered solutions could become more accessible, transforming how dental care is delivered. However, further study and technological refinement will be needed to address current limitations and fully integrate 4D printing into routine dental practice.

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