

New horizons in dentistry and orthodontics with 4D printing technologies 4D printing and orthodontics

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Objective: This study aims to explain the mechanisms of the four-dimensional (4D) printing technique and its potential applications in dental and orthodontic practice.

General Information: Rapid advances in science and technology have led to significant developments in production systems. Described as additive manufacturing or rapid prototyping, a positive innovation has been the introduction of three-dimensional (3D) printers in the 1980s. The technology quickly became popular because it allowed complex structures to be produced using less material compared to traditional manufacturing methods. Objects are designed in three dimensions using dedicated computer programs and 3D printed using materials such as composites, resins, metals, and polymers. Orthodontics has also benefitted from 3D printing in the fields of clear aligner treatment, indirect bonding using bracket transfer trays, dental modelling, and the production of guides for mini-screw and implant placement, as well as the manufacture of removable appliances. As 3D printers continued to evolve and new 'smart' materials were specifically developed, 4D printing techniques emerged. 4D printing allows objects, produced by 3D printers to change shape in response to stimuli, usually in the form of heat and light, thereby enabling the performance of specific functions. The objects can also self-assemble into larger structures without external intervention. The applications of 4D printing are expanding across a wide range of clinical fields.

Conclusion: 4D printing is an evolving technology that requires further research. However, if integrated into dentistry, it holds great potential as an efficient printing method, similar to its applications in other fields.
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Introduction

Three-dimensional (3D) space can be defined as an environment in which the perceptions of width, length, and depth are fully present. Mathematical studies and philosophy suggest the existence of additional dimensions, noted as time or continuity, lay beyond the conventional three dimensions. A recent study has reported that four-dimensional (4D) geometry is possible¹ and when a fourth dimension is added to space, a closed material surface or shell can undergo a simple bending and tensile movement without stretching or tearing.¹

This technology has rapidly gained scientific interest as it enables the fabrication of complex structures with reduced material usage compared to traditional manufacturing methods. This method was first introduced in 2013 at the Massachusetts Institute of Technology by Tibbitts et al.² Inspired by nanotechnology's applications, particularly in medicine, biology, and pharmacology, the researchers aimed to produce large-scale materials that could change their shape, properties, and function autonomously. These materials were intended for use in industrial and environmental applications.²

4D printing may be defined as the capability of a material system or object to change its form and/or function under different external stimuli following the production printing stage.² 4D printing refers to the controlled progression of a printed 3D structure related to its shape, properties, and functionality over time. The process is printer-independent and predictable.³ The transformation time is referred to as the fourth dimension and indicates that printed structures are no longer simply static or inert objects, but are programmable and capable of independent transformation. In this context, it becomes possible to transition from a one-dimensional thread to a 3D form, from a two-dimensional (2D) surface to a 3D form, or from one 3D form to another through a single multi-material print.⁴

Distinctive features and benefits of 4D printing technology

Self-assembly and self-repair

In the process of combining raw materials into products, errors and energy losses may occur. To minimise these problems, the production aim is to add the assembly information directly to the raw material to induce spontaneous assembly in a process called 'self-assembly'. This method is widely used in biological systems involving proteins, DNA replication, and cell renewal. In industry, it is suggested that this system in biology should be taken as an example to ensure that products are composed of intelligent parts rather than complex machines.⁵

Many biological systems have mechanisms for error control, such as verification, error correction, and the elimination of failed attempts. Similar to biological systems, 4D-printed products can self-assemble, disassemble, and subsequently reassemble. The error correction and self-repair capabilities of these products offer many advantages. According to Tibbits et al., in the future, programmable products will not be discarded after failure as they have the capacity to repair themselves, adapt to new requirements, and be separated for recycling. This feature is expected to reduce the amount of material waste by increasing re-usability and recycling.⁴

Multi-functionality

Objects produced by 4D printing have a dynamic nature, as opposed to the fixed and unchanging

characteristics of objects produced by 3D printing. Products made using this technology can change their properties, shape and functions in response to various external physical, chemical or biological stimuli. This adaptability provides the object with the capability of responding to changing conditions and to perform different functions.⁶ These distinctive features therefore allow the objects produced using 4D printing technology to be dynamic structures with an adaptive capacity programmed by specific stimuli. This provides many advantages in the field of dentistry.^{7,8}

Advantages of 4D printing technology

Customisation and patient-focused approaches

The most significant advantage of incorporating 4D printing technology into dentistry lies in its unparalleled capability for customisation. This innovative approach enables the creation of structures and devices precisely adapted to a patient's individual anatomical features, enhancing fit, comfort, and functionality while ultimately improving patient satisfaction.^{7,9}

The ability to produce complex dental objects

4D printing makes it easier to produce dental devices with complex geometries that are difficult or impossible to achieve using conventional methods. This enables the development of dental implants, prostheses, and orthodontic devices thereby offering patients a wider range of treatment options.¹⁰

Material efficiency and environmental solution

4D printing works on an additive principle, using only the amount of material required, which is unlike conventional subtractive manufacturing approaches known to result in significant material waste.¹¹ The technology change reduces the environmental impact of dental manufacturing processes.

Optimised productivity and effective time utilisation

The integration of 4D printing into dental workflows offers the possibility of enhancing efficiency by consolidating multiple production stages into

a unified and cohesive process, even within the limitation of time constraints. The high level of efficiency saves time in the production and delivery process of dental devices, which therefore offers significant benefits for patients and dentists.⁷

Advanced technology materials

Advancing 4D printing technology has resulted in new materials being developed specifically for dental use. The advanced materials are biocompatible, durable and designed to flex. This enhances the efficiency and durability of manufactured dental devices, ensuring optimal performance over time.⁷

Techniques for minimally invasive approaches

4D printing technology enables minimally invasive treatment methods thanks to their dynamic and adaptive capabilities. They minimise the need for extensive surgical procedures by preserving the patient's anatomical contours. As a result, patients experience less trauma and a more rapid and improved overall healing process.¹²

Opportunities in innovation and scientific advancement

The inherent versatility of 4D printing technology provides a suitable infra-structure for dental research and development. The technology allows researchers to explore advanced designs, materials, and functions to address new solutions for challenging clinical needs.⁷

Production process of 4D printing technology

The basic components of 4D printing technology include 3D printing systems, mathematical modelling, stimuli, stimuli-responsive 'smart' materials, and the interactive mechanisms of these materials. The 4D printing process starts by designing the desired object using various computer programs and mathematical modelling according to required function. The designed object is produced by a system-compatible 3D printer using an appropriate stimulus-responsive 'smart' material. As a result, a passive object acquires a dynamic structure by undergoing a predicted feature or shape change by the triggering of interactive

mechanisms following activation by appropriate stimuli in the material's code.¹³

'Smart' materials

Materials with shape memory or shape-changing properties are defined as stimulus-responsive 'smart' materials. These materials demonstrate advanced sensing and response capabilities to environmental variations or external factors. The classification of a material or a system as 'smart' is evaluated via two fundamental mechanisms: energy exchange and property change. Property change refers to the process by which a material or system undergoes modifications at the molecular or micro-structural level upon exposure to a particular stimulus created by altered environmental conditions. These modifications lead to reversible changes in material properties including, but not limited to chemical, mechanical, electrical, magnetic, and thermal characteristics. Energy exchange involves a mechanism by which changes in environmental conditions induce a reversible shift in the energy state of the material or system without affecting its inherent properties.¹⁴

Shape memory materials intrinsically possess the characteristic, defined by an ability to be programmed into a temporary shape and to stably retain that configuration. The temporary configuration remains stable until a specific stimulus is applied, triggering the material to recover its original shape and allowing it to be reprogrammed. Shape memory is not an inherent property of the material itself but a functional property arising from the integration of its molecular architecture with specific processing and programming techniques.¹⁴ Materials utilised in 4D printing are classified according to their structural properties and can exist in single or multiple structures. Multi-material structures combine various polymers, obtained through precise geometric distributions and configurations facilitated by 3D printing technology.¹⁵

Shape memory alloy (SMA)

Shape memory alloys (SMAs) are defined as metallic materials with the ability to return to a pre-defined shape and size when activated by appropriate thermal changes. These materials are generally plastically deformable at low temperatures. When exposed to higher temperatures, they tend to return to their pre-deformed shape.¹⁶ The reversibility feature is

crucial for increasing the efficiency and versatility of SMAs. With the recent development of additive manufacturing techniques and material science, SMAs have been adapted into 4D printing systems, and their use in the production of complex and programmable objects has increased.¹⁷

'Smart' alloys were first discovered in 1932 and Vernon defined the term, shape memory, for a polymeric dental material in 1941. In 1962, the nickel-titanium (NiTi) alloy was discovered and became widely used because of its shape memory effect.¹⁸ In particular, NiTi-based shape memory alloys are widely used in orthodontics, especially for archwires and various force mechanisms, due to their mechanical properties of biocompatibility, corrosion resistance, low modulus of elasticity, super flexibility, and shape memory effect.¹⁹ In endodontics, NiTi instruments are widely used to provide the mechanical shaping of root canals of complex morphological structure. In prosthodontics, NiTi alloys are available in castings for the construction of crowns and dentures. The alloys are also used in surgery and implantology.²⁰ Shape memory alloys (SMAs) suitable for 4D printing applications include copper–aluminium–nickel, copper–zinc–aluminium, iron–manganese silicon, nickel–copper–titanium and copper–aluminium–zinc. These alloys offer a wide range of applications in various medical and industrial fields.¹⁷

Shape memory polymers (SMPs)

Beyond the limited applications of shape memory alloys, shape memory polymers (SMPs) are among the most common materials used in 4D printing. SMPs are a class of polymers capable of retaining a temporary shape and returning to their original shape when exposed to specific stimuli, such as heat or light. The deformation process of SMPs consists of two phases: the programming phase and the return phase. During the programming phase, the polymer is deformed by heating above its transition temperature (T_t) and then by fixing its shape by cooling below T_t . In the return phase, when the SMP is reheated above T_t , a return to its original shape occurs due to entropic elasticity.²¹ The active deformation capabilities and versatile material designs of SMPs offer several advantages over other materials and include low density, reduced cost, ease of programming, and easy control of the recycling

temperature. Biocompatibility and biodegradability can be achieved through chemical modification. However, the low mechanical strength, modulus values, and operating temperatures of these polymers can be considered disadvantages.²²

Many SMP components such as polyacrylate copolymers, segmented polyurethane ionomers, cross-linked polycyclooctene, polynorbornene, epoxy-based polymers, cross-linked ethylene-vinyl acetate copolymers are used in medicine and dentistry. Kawaguchi et al. stated that polyurethane (TPU) material, which belongs to the thermosensitive shape memory polymer family, has the potential to be used in orthodontic treatment. It was emphasised that its biomechanical and antibacterial properties need to be improved to increase its clinical use. The study investigated the effect of chitosan fibres on the mechanical and antibacterial properties of TPU. The results showed that the addition of chitosan fibres did not affect the glass transition temperature. However, they changed the crystal structure of the material from semi-crystalline to amorphous. In addition, the results showed that adding chitosan fibres contributed to improving the elastic modulus by maintaining the shape memory effect of TPU.²³ In a similar study, it was reported that glass fibre-reinforced shape memory polyurethane might be an alternative that eliminates the disadvantages of allergy and the unaesthetic appearance of metal orthodontic wires.²⁴ In an additional orthodontic material study, 1-butanol was added to PEMA-TA/HX resin and the resulting material, with its shape memory property, eliminated the plastic deformation that occurs during appliance placement plus can recover force.²⁵

Hydrogels

Hydrogels are used in medical applications due to their biocompatibility and bioabsorbability. In addition, hydrogels are similar to extracellular matrices due to their high hydrophilic nature, water permeability, and softness. They are also suitable materials for use as tissue scaffolds and have further applications in the food industry, architecture, robotics, tissue engineering, and as electronic sensors.²⁶

3D printers

The PolyJet technique is the most common type of 3D printer used for printing multi-material structures.

This printing system features multiple nozzles, enabling the simultaneous deposition of different materials. Consequently, multi-coloured materials with varying textures and hardness properties can be printed concurrently thereby facilitating the production of complex objects. The level of accuracy and precision offered by PolyJet printing is particularly high. Direct Ink Writing (DIW) technology, an alternative multi-material printing technique, is extensively employed, particularly in bioprinting, in which cell-based 'ink' is utilised. The rheological properties of the ink in DIW printers can be adjusted to ensure rapid shape acquisition and retention after exiting the nozzle. Complex structures can be formed through multiple nozzle sequences by applying ink materials such as colloidal particles, polyelectrolytes, hydrogels, and sol-gel oxides. DIW is a preferred method in medical device manufacture because it does not expose materials to harsh chemicals nor high temperatures.²⁷

The simplest approach to implementing 4D printing involves producing individual 'smart' materials using 3D printers. Technologies such as Stereo Lithography Apparatus (SLA) and Digital Light Processing (DLP), which are based on photopolymerisation, as well as Fused Deposition Modelling (FDM), and DIW printers, which utilise extrusion technology, can be employed to print these materials.²¹

4D printing technology in medicine, dentistry and orthodontics

Medical applications of 4D printing technique

4D printing has broad applications in tissue engineering, chemotherapy, and self-assembling biomaterials. 4D printing is particularly promising for medical devices, as it enables autonomous placement into challenging places in the human body. It can also produce stents and organs that can change shape over time if required. 4D printing can easily print smart medical tools and devices and has the potential to print skin grafts in their original colour which may then be used in complex surgeries with high success rates.⁸

4D printing technologies can be used to create matrices to support cells. Miao et al. used SLA printing to produce a memory scaffold to support the growth of human bone marrow mesenchymal stem cells to create a shape.²⁸ Mirani et al. produced pH-sensitive

GelDerm, a multifunctional hydrogel-based wound dressing material which detects the presence of infection by a pH-dependent colour change. A change in pH causes a corresponding colour change and facilitates the release of antibiotics into the wound. This advanced material therefore allows the infection of a wound to be diagnosed and treated.²⁹

Cardiovascular stents have also been produced by 4D printing technology. Cabrera et al. used FDM printers and active polymers to develop cardiovascular stents that adapt to the growth of paediatric patients.³⁰ In addition, peripheral nerve injury devices, orthopaedic implants, and tracheal stents are other examples of existing and applied medical 4D printing technology.³¹

Dental applications of 4D printing

Shape memory materials, which have long been actively utilised in dental applications, are the fundamental components of 4D printing technology.^{14,19,32} With the widespread adoption of evolving 3D printing systems, the integration of these materials has also increased.^{10,33} Hamza emphasised that materials produced using 4D printing technology possess the ability to move in predetermined directions. This innovative approach to restorative dentistry enables 4D-printed restorative materials to be programmed and guided toward the cavity walls for maximum adaptation.³⁴

In prosthodontics, the fit of fixed prosthetic restorations can be compromised by morphological changes in the surrounding hard and soft tissues. In such cases, the use of SMPs can help minimise potential complications by exploiting the material's adaptive capabilities. Additionally, 4D printing technology can be employed to create intelligent removable prosthetic restorations that dynamically adapt to variables related to chewing forces, age, and eating and drinking habits. Residual bone resorption, which can occur with the use of fully or partially removable dentures, necessitates the replacement of dentures over time. Prostheses produced using 4D printing technology can address this need for continuous adaptation, thereby reducing the frequency of revision procedures.^{10,34,35} Furthermore, 4D printing has the potential to advance dental implant technologies. Specifically, it is possible to design the apical parts of implants to form a soft base, thereby preventing damage to vital anatomical structures.^{34,35}

4D printing technology can be employed to develop intelligent bracket systems and wires that facilitate the movement of teeth to ideal positions and orientations based on the patient's malocclusion and treatment needs. This approach ensures that teeth can be moved to desired positions and angles without causing damage to periodontal tissues. Similarly, intelligent removable and functional appliances that change shape over time can be produced. Examples of smart appliance applications include the maxilla, mandible, arch expansion devices, and bite blocks.^{35,36}

By using multiple materials and a 4D printing technique,³⁷ Schweiger et al. focused on restorations which simulated the multilayer structure of the anterior teeth. However, Momeni et al. argued that the definition did not fully reflect 4D printing technology because the materials used lacked 'smart' properties.³

Tamaki et al. developed a manufacturing protocol for a sports mouthguard (MG) using 4D printing technology. The researchers designed a two-layer MG in a virtual model created by scanning the mouth. The outer MG layer was produced using a thermoplastic shape memory polyurethane elastomer, and the inner layer was produced using a thermoplastic elastomer and a 3D printer. The layers were bonded together with an adhesive after production. The internal surface data of the produced MG and the shape corrected MG were superimposed and deviation analysis was performed to verify the shape memory performance of the 4D printed MG. The root mean square error value (mm) was measured by calculating the distance between the data obtained from the deviation analysis. As a result, the researchers argued that 4D-printed MGs overcame the problems of conventional and 3D-printed MGs which were related to poor fit due to deformation, and that this method simplified the manufacturing process.³⁸

Pradhan et al. investigated the biomedical applications of 4D imaging and 4D printing systems and published a case study involving the restoration of a canine tooth. The dental models obtained from the patient were scanned and digitised, the crown region of the damaged tooth was selected, and a virtual restoration was performed. The process was completed with the fabrication of a shape memory alloy-based dental crown. As a result, the researchers predicted that shape memory biocompatible materials produced by 4D printing will have important

implications for dentistry as artificial intelligence and printing systems continue to evolve.³⁹

In recent years, research using 4D printing technology in orthodontics has focused on clear aligners produced using SMPs. The digital design software and 3D printers are widely used for fixed appliances, clear aligners, and removable appliances. Integrating 4D printing technology in orthodontics is facilitated by incorporating SMPs which offer several advantages, including ease of processing, low density, low cost, and an acceptable aesthetic appearance. Additionally, these materials can retain their shape memory properties for approximately three months. Due to their composition of hard and soft segments, their T_g is close to body temperature.^{34,40} Elshazly et al. described a new orthodontic clear aligner system based on a thermosensitive shape memory polyurethane-based thermoplastic material (Clear X; K Line Europe GmbH, Düsseldorf, Germany). Conducted on a typodont model, the clear aligner demonstrated an ability to return to its original shape when activated by heat, thus allowing tooth movement that would typically require three aligners, to be achieved using a single aligner.⁴¹ An additional study investigated the movement forces exerted by Clear X clear aligners made of SMP material after exposure to an appropriate thermal stimulus. The study found that the aligners could move teeth using biocompatible orthodontic forces.⁴²

Atta et al. evaluated the physico-chemical and mechanical properties of 3D-printed shape memory aligners in a study that compared the Tera Harz (TC-85) aligner with three different thermoformed materials using differential scanning calorimetry, dynamic mechanical analysis, and shape recovery tests. The results indicated that the Tera Harz (TC-85) aligner exhibited more favourable mechanical properties than the thermoformed materials. It was also reported that 4D aligners will continue to develop in orthodontics and that the ability to alter the design and thickness of the aligners will optimise workflow.⁴³ A further study utilised differential scanning calorimetry, dynamic mechanical analysis, and various experiments to evaluate an aligner's thermal, thermo-mechanical, and shape recovery properties. According to a cytotoxicity analysis performed on mouse fibroblast cells, the aligners were found to be non-cytotoxic *in vitro*.⁴⁴ Additionally, the shape memory properties of the material were evaluated using a crowded model, revealing that

this material could resolve crowding up to 3.5 mm. The authors believed that the use of this material in orthodontics would reduce the number of aligners, thereby minimising the formation of residual material.⁴⁴ Zhan et al. evaluated the mechanical properties of different sections of NiTi wires produced by laser powder bed fusion 4D printing technology. The study reported that the phase transformation behaviour of NiTi wire varied under different energy dissipations in different regions. It was also noted that the development of NiTi alloys produced by 4D printing technology would facilitate treatment.⁴⁵

Limitations of 4D printing technology

Although 4D printing technology enables the production of dynamic and personalised objects compared to traditional and 3D printing systems, additional development is still required. The system has design and production limitations and aspects that need to be advanced.

The complexity of the biological processes and feedback mechanisms required for the use of manufactured objects limits the adaptability of the 4D system. Adequate information on the response time of 3D structures and the controllability of the response of shape memory materials to stimuli is still lacking. These situations constitute design-based limits of the 4D printing system. Production-related limitations include the small number of 3D technologies and biocompatible 'smart' materials available for 4D printing. Printing systems aim for high resolution and high printing speed. In addition, the smart materials used must meet criteria such as biocompatibility, durability, and flexibility.⁴⁶ An extensive analysis of the long-term performance and biocompatibility of 4D printed dental materials is indicated and essential. Investigating the mechanical properties, degradation kinetics and tissue reaction of these materials is critical to assessing their suitability for long-term clinical use. In addition, 4D printing technology is relatively more expensive than conventional production methods commonly used in dentistry. The high cost of equipment and materials may limit its widespread application, particularly in smaller dental clinics or in developing regions.⁷

Conclusions

As in many other fields, 4D printing is an evolving technology in dentistry and is expected to be used

effectively once it can be integrated into clinical applications. These techniques and materials make it feasible to create dynamic objects that can change their 3D shape and behaviour over time. Additionally, by enabling the creation of complex multi-layered tissue structures, 4D printing offers significant advantages for future applications in tissue engineering and dentistry. Therefore, it is considered that further laboratory and clinical studies are necessary to evaluate the mechanical and physical properties of the materials used by 4D technology.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the author(s) used ChatGPT to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication. The manuscript received additional journal editorial correction.

Conflict of interest

The authors declare that there is no conflict of interest.

Availability of supporting data/Availability of data and materials

The data can be transmitted by the corresponding author in accordance with a reasonable request.

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