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BEYOND 3D PRINTING: THE EMERGING ROLE OF 4D TECHNOLOGIES IN DENTAL APPLICATIONS

ALÉM DA IMPRESSÃO 3D: O PAPEL EMERGENTE DAS TECNOLOGIAS 4D EM APLICAÇÕES ODONTOLÓGICAS

MÁS ALLÁ DE LA IMPRESIÓN 3D: EL PAPEL EMERGENTE DE LAS TECNOLOGÍAS 4D EN APLICACIONES DENTALES

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ABSTRACT

Objective: To explore the emerging role of 4D printing in dentistry, focusing on smart materials, potential clinical applications, and current technological challenges.

Methods: A narrative review of the literature was performed, including studies on 4D printing technologies, smart biomaterials, and digital dentistry innovations. Experimental, preclinical, and conceptual reports were analysed to provide a comprehensive overview of the state of the art and future directions.

Results: 4D printing represents an evolution of additive manufacturing by incorporating time-dependent material transformation into printed structures. In dentistry, programmable materials capable of responding to environmental stimuli, such as temperature, humidity, and pH have demonstrated potential for creating adaptive and self-adjusting devices. Proposed applications include shape-morphing orthodontic appliances, self-fitting prostheses, and responsive biomaterials for tissue engineering. Preliminary findings suggest that these technologies may enhance prosthetic fit, reduce the need for manual

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adjustments, and improve patient comfort. However, the field remains largely experimental. Key limitations include restricted availability of biocompatible smart materials, challenges in controlling predictable transformations in the oral environment, high production costs, and the absence of standardized clinical protocols and regulatory pathways.

Conclusion: 4D printing has the potential to transform digital dentistry by enabling dynamic, patient-responsive devices. Despite promising early results, substantial technological refinement, material development, and clinical validation are required before widespread clinical implementation becomes feasible.

Keywords: 4D Printing. Smart Materials. Digital Dentistry. Adaptive Prostheses. Additive Manufacturing.

RESUMO

Objetivo: Explorar o papel emergente da impressão 4D na odontologia, com foco em materiais inteligentes, potenciais aplicações clínicas e desafios tecnológicos atuais.

Métodos: Foi realizada uma revisão narrativa da literatura, incluindo estudos sobre tecnologias de impressão 4D, biomateriais inteligentes e inovações em odontologia digital. Relatos experimentais, pré-clínicos e conceituais foram analisados para fornecer uma visão abrangente do estado da arte e das direções futuras.

Resultados: A impressão 4D representa uma evolução da manufatura aditiva ao incorporar a transformação de materiais dependente do tempo nas estruturas impressas. Na odontologia, materiais programáveis capazes de responder a estímulos ambientais, como temperatura, umidade e pH, demonstraram potencial para a criação de dispositivos adaptativos e autoajustáveis. As aplicações propostas incluem aparelhos ortodônticos com mudança de forma, próteses autoajustáveis e biomateriais responsivos para engenharia de tecidos. Resultados preliminares sugerem que essas tecnologias podem melhorar o ajuste protético, reduzir a necessidade de ajustes manuais e aumentar o conforto do paciente. No entanto, o campo ainda é amplamente experimental. As principais limitações incluem a disponibilidade restrita de materiais inteligentes biocompatíveis, desafios no controle de transformações previsíveis no ambiente oral, altos custos de produção e a ausência de protocolos clínicos padronizados e vias regulatórias.

Conclusão: A impressão 4D tem o potencial de transformar a odontologia digital ao permitir dispositivos dinâmicos e responsivos ao paciente. Apesar dos resultados iniciais promissores, são necessários avanços tecnológicos substanciais, desenvolvimento de materiais e validação clínica antes que sua implementação clínica em larga escala se torne viável.

Palavras-chave: Impressão 4D. Materiais Inteligentes. Odontologia Digital. Próteses Adaptativas. Manufatura Aditiva.

RESUMEN

Objetivo: Explorar el papel emergente de la impresión 4D en la odontología, con énfasis en materiales inteligentes, posibles aplicaciones clínicas y desafíos tecnológicos actuales.

Métodos: Se realizó una revisión narrativa de la literatura, incluyendo estudios sobre tecnologías de impresión 4D, biomateriales inteligentes e innovaciones en odontología digital. Se analizaron informes experimentales, preclínicos y conceptuales para proporcionar una visión integral del estado del arte y las direcciones futuras.

Resultados: La impresión 4D representa una evolución de la fabricación aditiva al incorporar la transformación de materiales dependiente del tiempo en las estructuras impresas. En odontología, materiales programables capaces de responder a estímulos ambientales, como temperatura, humedad y pH, han demostrado potencial para crear dispositivos adaptativos y autoajustables. Las aplicaciones propuestas incluyen aparatos ortodónticos con cambio de forma, prótesis autoajustables y biomateriales responsivos para ingeniería de tejidos. Los hallazgos preliminares sugieren que estas tecnologías pueden mejorar el ajuste protésico, reducir la necesidad de ajustes manuales y aumentar la comodidad del paciente. Sin embargo, el campo sigue siendo en gran medida experimental. Las principales limitaciones incluyen la disponibilidad limitada de materiales inteligentes biocompatibles, desafíos en el control de transformaciones predecibles en el entorno oral, altos costos de producción y la ausencia de protocolos clínicos estandarizados y vías regulatorias.

Conclusión: La impresión 4D tiene el potencial de transformar la odontología digital al permitir dispositivos dinámicos y sensibles al paciente. A pesar de los prometedores resultados iniciales, se requieren importantes avances tecnológicos, desarrollo de materiales y validación clínica antes de que su implementación clínica generalizada sea viable.

Palabras clave: Impresión 4D. Materiales Inteligentes. Odontología Digital. Prótesis Adaptativas. Fabricación Aditiva.

1 INTRODUCTION

Additive manufacturing has profoundly transformed modern dentistry by enabling highly customised and digitally driven workflows. Three-dimensional (3D) printing technologies are now widely applied in prosthodontics, orthodontics, implantology and maxillofacial surgery, offering advantages such as rapid prototyping, reduced material waste and improved manufacturing precision (Javaid & Haleem, 2019; Tahayeri et al., 2018). Despite these advances, most 3D-printed dental devices remain structurally static after fabrication, limiting their ability to adapt to the dynamic biological and functional conditions of the oral environment.

Four-dimensional (4D) printing has recently emerged as a significant evolution of additive manufacturing. The fourth dimension refers to the incorporation of time-dependent transformation, enabling printed objects to change shape, properties or function in response to external stimuli such as temperature, moisture, light or pH (Momeni et al., 2017). This capability is primarily achieved through the use of smart or stimuli-responsive materials, including shape-memory polymers and hydrogels, which can be programmed during fabrication to undergo controlled post-printing transformations.

In dentistry, the oral cavity represents a particularly suitable environment for responsive biomaterials because of its fluctuating temperature, humidity, enzymatic activity and mechanical loading. Recent experimental studies have suggested potential applications of 4D printing in orthodontic aligners, self-adjusting prostheses and adaptive tissue engineering scaffolds (Miao et al., 2021; van Manen et al., 2018). These technologies may improve prosthetic fit, reduce chairside adjustments and enhance patient comfort by enabling devices to dynamically conform to anatomical changes over time.

Despite its promise, the clinical translation of 4D printing in dentistry remains in an early developmental stage. Challenges include limited availability of biocompatible smart materials suitable for intraoral use, difficulties in achieving predictable shape transformation under oral conditions, high production costs and the absence of standardized regulatory frameworks (Momeni et al., 2017; Miao et al., 2021).

Given the rapid evolution of digital dentistry, a comprehensive understanding of the opportunities and current limitations of 4D printing is essential to guide future research and clinical adoption.

2 METHODOLOGY

A narrative review was undertaken to evaluate the current landscape of 4D printing technologies and their potential applications in dentistry. A comprehensive literature search was performed in PubMed/MEDLINE, Scopus and Web of Science, supplemented by manual searches of reference lists from key publications in digital dentistry and biomaterials research. Search terms combined keywords and controlled vocabulary related to “4D printing”, “smart materials”, “shape-memory materials”, “additive manufacturing”, and “dentistry” or “oral applications”. The search aimed to capture experimental studies, preclinical investigations, proof-of-concept reports and relevant technological reviews describing time-responsive materials applicable to dental practice.

Studies were eligible if they discussed programmable or stimuli-responsive materials with potential dental relevance, including orthodontics, prosthodontics, implantology or oral tissue engineering. Purely industrial or non-biomedical applications, as well as reports lacking relevance to oral healthcare, were excluded. Screening was performed by two reviewers, and relevant information was extracted regarding material types, triggering mechanisms, proposed clinical applications, advantages and current limitations. Findings were synthesised qualitatively to provide a critical overview of technological readiness and future research needs.

3 RESULTS

The literature analysed in this narrative synthesis indicates that 4D printing in dentistry is an emerging but still predominantly experimental field. The compiled evidence converges on four major thematic domains: (1) material responsiveness and transformation mechanisms, (2) proof-of-concept dental applications, (3) performance advantages over static 3D devices, and (4) translational barriers limiting clinical adoption.

3.1 MATERIAL RESPONSIVENESS AND TRANSFORMATION MECHANISMS

Across experimental and engineering studies, the defining feature of 4D printing is the integration of stimuli-responsive materials capable of time-dependent transformation. The most frequently investigated material classes include:

1. shape-memory polymers (SMPs)
2. stimuli-responsive hydrogels
3. composite smart biomaterials

Momeni et al. (2017) describe that these materials can be pre-programmed during fabrication to undergo controlled geometric or functional changes when exposed to triggers such as temperature, moisture, pH, or light. In dental contexts, temperature- and moisture-responsive behaviors are particularly relevant due to the dynamic oral environment.

Experimental work demonstrates that shape-memory polymers can recover predetermined configurations after thermal activation, while hydrogels exhibit swelling-induced morphing when exposed to aqueous environments. Miao et al. (2021) reported successful fabrication of smart biomedical scaffolds capable of predictable structural transformation, supporting the feasibility of programmable dental biomaterials.

Proof-of-concept dental applications

Although clinical trials remain absent, multiple preclinical and conceptual studies propose high-impact dental uses. The most frequently reported applications include:

Adaptive orthodontic appliances

Several proof-of-concept models suggest that 4D-printed aligners could deliver time-modulated orthodontic forces without the need for sequential appliance replacement. Theoretical modeling indicates that shape-memory materials may allow progressive tooth movement through programmed force release, potentially reducing the number of aligner stages.

Self-adjusting prosthetic devices

Preliminary investigations propose that responsive prostheses could improve marginal adaptation by compensating for minor dimensional discrepancies after insertion. Van Manen et al. (2018) demonstrated programmable shape-shifting behavior in soft materials, supporting the conceptual feasibility of self-fitting intraoral devices.

Tissue engineering scaffolds

Responsive hydrogels and smart scaffolds have been explored for regenerative dentistry. Experimental studies indicate that 4D scaffolds may dynamically adapt to the defect microenvironment, potentially enhancing cell infiltration and tissue maturation.

Despite these promising directions, the review found that virtually all evidence remains at proof-of-concept or preclinical stage, with no robust human clinical trials currently available.

Performance advantages over conventional 3D printing

Compared with static additive manufacturing, the literature suggests several theoretical and experimentally supported advantages:

Improved prosthetic adaptation

Dynamic post-printing transformation may compensate for minor inaccuracies in scanning, printing, or intraoral conditions. Tahayeri et al. (2018) previously demonstrated that even conventional 3D materials exhibit variability in fit, highlighting a clinical gap that 4D systems aim to address.

Reduced chairside adjustments

Programmable self-adjustment could decrease the need for manual modification of prostheses and appliances, potentially improving clinical efficiency.

Enhanced patient comfort

Adaptive devices may better accommodate anatomical changes, thermal fluctuations, and functional loading, theoretically improving long-term comfort and compliance.

However, it is critical to note that most of these advantages remain theoretical or based on laboratory simulations, not clinical outcome data.

Translational and technical barriers

The synthesis consistently identifies substantial obstacles to clinical implementation.

Material limitations

The most prominent barrier is the scarcity of biocompatible smart materials suitable for long-term intraoral use. Many currently available shape-memory polymers and hydrogels were developed for industrial or short-term biomedical applications and lack:

1. long-term hydrolytic stability
2. resistance to enzymatic degradation
3. proven oral biocompatibility
4. adequate mechanical strength for mastication

Momeni et al. (2017) emphasize that material development remains the primary bottleneck for medical translation of 4D printing technologies.

Predictability in the oral environment

The oral cavity presents complex and fluctuating conditions, including:

1. temperature variation
2. salivary enzymes
3. mechanical loading
4. pH changes
5. biofilm formation

Controlling precise and reproducible shape transformation under these conditions remains technically challenging. Miao et al. (2021) note that achieving reliable actuation in vivo is substantially more difficult than in controlled laboratory settings.

Economic and regulatory constraints

The review also highlights non-technical barriers:

1. high cost of smart materials
2. limited availability of specialized printers
3. absence of standardized validation protocols
4. unclear regulatory pathways for dynamic devices

These factors collectively slow clinical translation despite strong conceptual promise.

Evidence maturity and research gaps

Overall, the field demonstrates high innovation potential but low clinical maturity. Key gaps include:

1. lack of randomized clinical trials
2. limited long-term biocompatibility data
3. absence of standardized testing frameworks
4. insufficient in vivo validation
5. minimal cost-effectiveness analyses

The current evidence therefore supports technological feasibility and conceptual promise, but not yet clinical readiness.

4 DISCUSSION

The findings of this review highlight the transformative potential of 4D printing within digital dentistry while simultaneously underscoring the considerable gap between experimental promise and clinical reality. The integration of time-responsive behaviour into additively manufactured dental devices represents a conceptual shift from static prosthetic solutions toward adaptive, patient-responsive systems.

One of the most compelling advantages of 4D printing lies in its capacity to produce structures capable of self-adjustment in response to intraoral stimuli. In theory, this could address longstanding clinical challenges such as prosthetic misfit, orthodontic force decay, and the need for repeated chairside adjustments. Shape-memory polymers and responsive hydrogels appear particularly promising in this regard, given their programmable behaviour and compatibility with additive manufacturing workflows.

However, the current body of evidence remains predominantly preclinical and proof-of-concept in nature. Significant material science barriers persist, especially concerning the availability of biocompatible smart materials suitable for long-term intraoral use. The oral cavity presents a highly complex environment characterised by fluctuating temperature, humidity, enzymatic activity, and mechanical loading. Achieving predictable and durable shape transformation under these conditions remains a major technical challenge.

Economic and regulatory considerations also represent important translational barriers. The cost of advanced materials, specialised printers, and validation processes may limit near-term accessibility in routine dental practice. Furthermore, the absence of standardised testing protocols and regulatory pathways for dynamic printed devices creates uncertainty for manufacturers and clinicians alike.

Future research should prioritise material optimisation, long-term biocompatibility testing, and controlled clinical trials. Interdisciplinary collaboration between dental researchers, materials scientists, and biomedical engineers will be essential to accelerate responsible clinical translation.

5 CONCLUSION

4D printing represents a promising evolution of additive manufacturing with the potential to enable adaptive and patient-responsive dental devices. Early experimental findings suggest meaningful applications in orthodontics, prosthodontics, and tissue engineering.

Despite this potential, the technology remains in an early developmental stage, with important challenges related to material performance, predictability, cost, and regulatory approval. Substantial technological refinement and clinical validation are required before widespread implementation in routine dental care becomes feasible. Continued interdisciplinary research will be critical to unlocking the full clinical value of 4D printing in dentistry.

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