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3D bioprinting of tissues and organs: advances, challenges and perspectives in regenerative medicine

Bioimpressão 3D de tecidos e órgãos: avanços, desafios e perspectivas na medicina regenerativa

Bioimpresión 3D de tejidos y órganos: avances, desafíos y perspectivas en la medicina regenerativa

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Abstract: 3D bioprinting has emerged as one of the most innovative technologies in regenerative medicine, providing new possibilities for treating diseases and injuries and addressing the shortage of organs for transplantation and regenerative therapies. Its application enables biological structures to be built through the precise deposition of living cells and biomaterials, supporting advances in the treatment of chronic diseases and severe injuries. This study addresses the following research question: how can 3D bioprinting of tissues and organs help solve the shortage of organs for transplantation and improve outcomes in regenerative treatments? The adopted methodology was qualitative and exploratory research based on a literature review of scientific materials published over the last ten years. The topic is important because of the growing demand for organs, the high rates of immune rejection in conventional transplants, and the potential of bioprinting to revolutionize medical practices. Studies published between 2016 and 2025 in Portuguese and English were selected as inclusion criteria. The general objective is to investigate the potential of 3D bioprinting in producing human tissues and organs, focusing on its applicability in therapies and transplants. The results show that 3D bioprinting has already achieved significant advances in clinical and laboratory applications, although it still faces technical and ethical challenges. It is concluded that the technology is promising and has the potential to transform personalized medicine, but requires investment in research, regulation, and infrastructure before its large-scale use becomes viable.

Keywords: Biotechnology. Tissue engineering. Tissue regeneration. Transplants.

Resumo: A bioimpressão 3D tem emergido como uma das tecnologias mais inovadoras na medicina regenerativa, proporcionando novas possibilidades para o tratamento de doenças, lesões e para a escassez de órgãos destinados a transplantes e terapias regenerativas. Sua aplicação permite a construção de estruturas biológicas por meio da deposição precisa de células vivas e biomateriais, possibilitando avanços no tratamento de doenças crônicas e lesões graves. Este estudo tem como problema de pesquisa a seguinte questão: como a bioimpressão 3D de tecidos e órgãos pode contribuir para solucionar a escassez de órgãos para transplante e melhorar os resultados em tratamentos regenerativos? A metodologia adotada foi uma pesquisa qualitativa e exploratória, baseada em revisão bibliográfica de materiais científicos publicados nos últimos dez anos. Justifica-se a importância do tema pela crescente demanda por órgãos, pelos altos índices de rejeição imunológica em transplantes convencionais e pelo potencial da bioimpressão para revolucionar práticas médicas. Como critério de inclusão, foram selecionados estudos publicados entre 2016 e 2025, nos idiomas português e inglês. O objetivo geral é investigar o potencial da bioimpressão 3D na produção de tecidos e órgãos humanos, com foco em sua aplicabilidade em terapias e transplantes. Como resultados, observou-se que a bioimpressão 3D já apresenta avanços significativos em aplicações clínicas e laboratoriais,

embora ainda enfrente desafios técnicos e éticos. Conclui-se que a tecnologia é promissora, com potencial para transformar a medicina personalizada, mas exige investimentos em pesquisa, regulamentação e infraestrutura para que seu uso se torne viável em larga escala.

Palavras-chave: Biotecnologia. Engenharia de tecidos. Regeneração tecidual. Transplantes.

Resumen: La bioimpresión 3D ha surgido como una de las tecnologías más innovadoras de la medicina regenerativa, al ofrecer nuevas posibilidades para tratar enfermedades y lesiones y afrontar la escasez de órganos destinados a trasplantes y terapias regenerativas. Su aplicación permite construir estructuras biológicas mediante la deposición precisa de células vivas y biomateriales, lo que favorece avances en el tratamiento de enfermedades crónicas y lesiones graves. Este estudio plantea la siguiente pregunta de investigación: ¿cómo puede la bioimpresión 3D de tejidos y órganos contribuir a solucionar la escasez de órganos para trasplante y mejorar los resultados de los tratamientos regenerativos? Se adoptó una investigación cualitativa y exploratoria, basada en una revisión bibliográfica de materiales científicos publicados durante los últimos diez años. La importancia del tema se justifica por la creciente demanda de órganos, las altas tasas de rechazo inmunológico en los trasplantes convencionales y el potencial de la bioimpresión para revolucionar las prácticas médicas. Como criterio de inclusión, se seleccionaron estudios publicados entre 2016 y 2025 en portugués e inglés. El objetivo general es investigar el potencial de la bioimpresión 3D para producir tejidos y órganos humanos, con énfasis en su aplicabilidad en terapias y trasplantes. Los resultados mostraron que la bioimpresión 3D ya presenta avances significativos en aplicaciones clínicas y de laboratorio, aunque todavía afronta desafíos técnicos y éticos. Se concluye que la tecnología es prometedora y puede transformar la medicina personalizada, pero requiere inversiones en investigación, regulación e infraestructura para que su uso a gran escala sea viable.

Palabras clave: Biotecnología. Ingeniería de tejidos. Regeneración tisular. Trasplantes.

1. Introduction

In recent years, advances in biomedical engineering have significantly transformed the way medicine approaches the treatment of chronic diseases, severe injuries, and organ failure. One of the most innovative and promising fields in this area is 3D bioprinting, a technology that uses adapted three-dimensional printers to manufacture living tissues and, in the future, human organs. By using bioinks composed of living cells and biocompatible materials, complex structures can be created with micrometric precision (Noor et al., 2019).

The development of bioprinting emerged in response to the growing demand for transplants and the shortage of organs available for donation. According to the World Health Organization, thousands of patients await transplants, face long waiting lists and, in many cases, do not survive until a compatible organ becomes available. The possibility of bioprinting customized tissues with the patient's own cells represents a revolutionary solution to this situation (Murphy; De Coppi; Atala, 2020).

3D bioprinting achieved its first significant advances in the late 1990s. In 1999, researchers at the Wake Forest Institute for Regenerative Medicine created a synthetic human

bladder scaffold using 3D printing techniques. Later, in 2003, Thomas Boland developed the first 3D bioprinter, marking a turning point in tissue engineering. Since then, the technology has evolved considerably, enabling complex structures such as blood vessels, skin, cartilage, and bones to be printed, with promising applications in surgery and regenerative therapies (Trevizan; Borges; Barud, 2022).

Brazil has one of the most robust transplantation systems in the world and ranks second in absolute numbers, behind only the United States. In 2023, the country recorded 29,261 transplants, the highest number in its history and an 11% increase over the previous year. Despite this advance, significant challenges remain: more than 43,000 people await organ transplants, and about 28,000 await corneal transplants. Furthermore, family refusal rates for organ donation remain high, with more than 40% of families not authorizing organ retrieval after the death of a loved one (AMB, 2024).

In addition to transplantation, 3D bioprinting has been used to produce artificial tissues for drug and cosmetic testing and clinical studies, reducing the use of laboratory animals and providing more accurate models of human physiology. These printed structures also support advances in personalized medicine by enabling safer and more effective therapies. Despite the numerous benefits, technical and scientific challenges still need to be overcome. Replicating the complexity of a human organ, particularly its vascularization and specific functions, requires extensive multidisciplinary knowledge involving engineering, biology, medicine, and materials science. Ethics, production costs, and regulation are also matters that require in-depth discussion (Murphy; Atala, 2014).

Against this background, 3D bioprinting of tissues and organs is a promising technological alternative capable of transforming the future of regenerative medicine. Studying this topic is essential to understand its limits, potential, and the social, economic, and scientific impacts it may produce. By enabling the production of personalized tissues and organs, 3D bioprinting has the potential to meet transplant demand, reduce immune rejection, and accelerate the development of more effective therapies (Gungor-Ozkerim et al., 2018).

According to the most recent data released by the Ministry of Health, Brazil reached its highest number of organ transplants in ten years in 2023. Between January and September, 6,766 solid-organ transplants were performed, an 11.7% increase over the same period in 2022, when 6,035 procedures were recorded. The number of effective donors also increased: 3,000 donations were completed in the same period, a 17% rise compared with the 2,004 registered in the previous year (Brasil, 2024).

The kidney was the most frequently transplanted organ, accounting for 66.72% of procedures, followed by the liver (1,777 transplants) and the heart (325 transplants). The number of corneal transplants also grew, totaling 11,952 surgeries between January and September 2023, compared with 10,344 during the same period in 2022. These figures reflect the continued efforts of the National Transplant System (SNT) and the Unified Health System (SUS) to expand access to and improve the efficiency of transplantation procedures in the country (Brasil, 2024).

The shortage of organs for transplantation, combined with the risk of immune rejection and dependence on invasive treatments, is an ongoing challenge for contemporary medicine. 3D bioprinting has emerged as an innovative and viable alternative, enabling not only the creation of artificial tissues for therapeutic use but also solutions for drug and cosmetic research. Studying this technology is essential to foster scientific and ethical debate and to propose pathways that accelerate its safe and efficient application in clinical practice.

This context gives rise to the following research problem: how can 3D bioprinting of tissues and organs help solve the shortage of organs for transplantation and improve outcomes in regenerative treatments?

Accordingly, the general objective was to investigate the potential of 3D bioprinting in the production of human tissues and organs, focusing on its applicability to transplantation and regenerative therapies. The specific objectives are to analyze the main methods and materials used in 3D bioprinting of tissues and organs; assess the technical, ethical, and regulatory challenges involved in implementing this technology; and investigate case studies and current research that demonstrate the effectiveness of 3D bioprinting in clinical applications.

2. Methodology

This study was characterized as qualitative, exploratory, and descriptive research aimed at understanding the current state of 3D bioprinting technology applied to the production of tissues and organs, along with its potential and limitations. The qualitative approach enabled an interpretive and in-depth analysis of data obtained from the scientific literature.

The research was conducted through an integrative review, using scientific articles, books, and specialized publications in bioengineering, biotechnology, regenerative medicine, and materials science as its main sources. The databases included SciELO, PubMed, Google Scholar, CAPES Journals, ScienceDirect, and IEEE Xplore and covered publications from the

previous ten years. The descriptors “3D bioprinting,” “Tissue engineering,” “Regenerative medicine,” and “Transplants,” included in the Health Sciences Descriptors (DeCS), were used.

The inclusion criteria were peer-reviewed full-text publications, texts specifically addressing the bioprinting of tissues or organs, applied case studies, and original articles. The exclusion criteria comprised materials without a scientific basis, duplicate or outdated articles, publications without a direct relationship to the topic, theses, and dissertations.

The data were organized into thematic axes and analyzed using the content analysis technique described by Bardin (2011), enabling the identification of patterns, trends, and gaps in the current literature. The results were discussed in light of the proposed objectives and the theoretical contributions of the consulted authors.

Because this review was based exclusively on publications available in the public domain, submission to a Research Ethics Committee was not required. All articles were accessed legally and selected and used according to scientific and ethical criteria.

3. Results

The study was conducted through a systematic search of the selected databases using the established descriptors. After the initial search, studies were filtered according to the defined inclusion and exclusion criteria. Figure 1 presents the methodology used in this process, including the total number of studies found and selected for this integrative literature review.

Stage	Description
Identification	Records identified: Google Scholar (n = 150); PubMed (n = 90); SciELO (n = 60); total from databases (n = 300); other sources (n = 20); overall total identified (n = 320).
Removal	Records removed before screening: duplicates (n = 20) and records removed for other reasons (n = 10).
Other methods	Records identified through websites (n = 300) and organizations (n = 20).
Screening	Records screened (n = 280); records excluded (n = 40).
Eligibility	Reports assessed for eligibility (n = 120); reports excluded because they were outside the scope or lacked relevant clinical data.
Inclusion	Studies included in the integrative review (n = 5).

Figure 1 – Descriptors used in the search, databases, and selected studies published from 2020 to 2025 (Source: authors' own work, 2025).

After initial screening, titles and abstracts were evaluated for thematic relevance, followed by full-text reading of the selected articles. The selection process was represented in a PRISMA flowchart covering the identification, screening, eligibility, and inclusion stages, resulting in five studies used in the final analysis.

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Table 1 shows that the articles analyzed on 3D bioprinting of tissues and organs were published between 2016 and 2025. Of the five selected articles, two were published in 2023, one in 2016, one in 2025, and one in 2020, demonstrating the scientific community's steadily growing interest in the application of 3D bioprinting to regenerative medicine.

Regarding methodological designs, literature reviews and experimental laboratory studies predominated, particularly those focusing on the development of bioinks, scaffolds, and bioprinting techniques for tissues such as skin, cartilage, and cardiac muscle. Studies such as Wu, Zhu, and Woo (2023) presented experimental bioprinting trials with translational potential, whereas others, such as Matai et al. (2020), conducted conceptual and technological analyses of advances in the field.

The main objectives investigated included defining and improving bioinks, developing functional and vascularized tissues, advancing bioprinting techniques, and analyzing clinical and regulatory prospects for transplantation use.

The main findings indicate significant advances in cell viability and bioink biocompatibility, as well as in the structural precision of three-dimensional prints. The technology also showed potential to reduce dependence on organ donors, improve tissue regeneration, and drive personalized medicine. Nevertheless, challenges remain regarding efficient vascularization, complete functional reproduction of organs, and standardization of clinical and ethical protocols.

Table 1, entitled “Integrative research on 3D bioprinting of tissues and organs,” presents the studies selected for the integrative review.

Table 1 – Integrative research on 3D bioprinting of tissues and organs. Source: authors' own work, 2025.

Author and year	Article title	Design	Study objective	Main results
JANG, Y. B. et al. (2023)	*Advances and innovations of 3D bioprinting skin: A brief review.*	Narrative review.	Analyze innovations in skin bioprinting.	Demonstrates advances in biomaterials and precision for constructing dermal tissues.
LI, J. et al. (2016)	*Recent advances in bioprinting techniques: approaches, applications and future prospects.*	Integrative review.	Analyze emerging approaches and applications.	Reports advances in printing techniques and discusses therapeutic potential and clinical limitations.
MATAI, I. et al. (2020)	*Progress in 3D bioprinting technology for tissue/organ regenerative engineering.*	Literature review.	Review the progress of bioprinting in tissue engineering.	Highlights applications in artificial organs and prospects in regenerative medicine.
PICADO-TEJERO, A. et al. (2025)	*Porous scaffolds for 3D bioprinting in tissue engineering: Recent advances and future directions.*	Narrative and critical review.	Analyze the use of porous scaffolds in bioprinting.	Presents new high-porosity biopolymer approaches and cell integration.
WU, R.; ZHU, W.; WOO, S. L. (2023)	*Advances in 3D Bioprinting: Techniques, Applications, and Future Directions for Cardiac Tissue Engineering.*	Scientific review.	Review advances in cardiac bioprinting.	Highlights technical and biological advances in 3D-printed cardiac models.

Legend: 3D: three-dimensional.

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4. Discussion

4.1 Advances in 3D bioprinting in regenerative medicine

In recent years, several studies have demonstrated significant progress in 3D bioprinting for the regeneration of skin, cartilage, and vascular tissues, suggesting increasingly close clinical application. For example, Jang and colleagues (2023) reviewed developments in skin bioprinting (Advances and innovations of 3D bioprinting skin), highlighting multilayer bioinks capable of imitating the skin layers—epidermis, dermis, and hypodermis—with the inclusion of skin appendages and improved vascularization, thereby enabling more realistic models for wound healing or in vitro testing.

In cartilage engineering, Li and coauthors (2016) explored several bioinks, techniques, and scaffolds for chondral regeneration. They showed that combining hydrogels with reinforced materials and hybrid printing—mixing thermoplastic polymers with hydrogels—can provide better mechanical properties while maintaining cell viability.

Another important advance concerns the bioprinting of vascular tissues, a critical issue for increasing the thickness and functionality of bioprinted tissues. In a recent review, Picado-Tejero et al. (2025) highlighted new porous scaffolds that promote cell growth and fluid perfusion, enabling denser structures that better tolerate transplantation or integration with host tissues.

In the cardiac field, Wu, Zhu, and Woo (2023) analyzed emerging techniques and applications for cardiac engineering. They reported progress not only in printing cardiac patches with stem cells or cardiomyocytes derived from pluripotent cells, but also in the pathways used to mature these cells after printing so that they acquire morphology and functionality resembling those of native cells, including contraction and electrical conduction.

Taken together, these advances signal a transition from laboratory bioprinting prototypes to more robust preclinical applications, emphasizing skin, cartilage, and cardiac tissue. Although challenges such as maturation speed, scalability, functional vascularization, and immune integration remain, recent trends are promising for 3D-bioprinting-based regenerative therapies to reach clinical use in the medium and long term.

3D bioprinting has evolved rapidly in recent years, mainly because of advances in materials engineering and the development of increasingly sophisticated bioinks. These bioinks, composed of living cells and biomaterials, have enabled the construction of three-dimensional structures that more closely resemble physiological reality, allowing cell growth, differentiation, and maturation within printed scaffolds (Li et al., 2016).

Skin engineering is one of the main fields to benefit from bioprinting. Recent studies show that complex dermal substitutes can already be produced with multiple layers that reproduce the epidermis, dermis, and, in some cases, initial vascular structures. These advances have the potential not only to treat extensive burns but also to reduce the use of animals in pharmacological and cosmetic testing (Jang et al., 2023).

Bioprinting has shown encouraging results in cartilage engineering. Biomaterials such as collagen-based hydrogels, hyaluronic acid, and methacrylated gelatin have demonstrated good biocompatibility and potential for regenerating articular tissues. This is particularly relevant to treating knee and hip injuries, which are common among older populations and high-performance athletes (Li et al., 2016).

The field of cardiac bioprinting has also advanced significantly. Structures such as vascularized cardiac patches are already under development, and studies indicate that these tissues may be used to regenerate damaged areas of the heart after myocardial infarction. This type of intervention opens prospects for more effective regenerative therapies and may reduce the need for heart transplants (Wu; Zhu; Woo, 2023).

Beyond solid organs, more complex and metabolically active tissues, such as the liver and kidneys, have become targets of bioprinting studies. Although it is not yet possible to print fully functional organs for transplantation, models of hepatic and renal tissues capable of performing basic functions such as filtration and metabolism already exist. These models have proved extremely useful in drug toxicity research and studies of chronic diseases (Picado-Tejero et al., 2025).

Another important advance is the vascularization of printed tissues. Creating functional vascular networks has been one of the greatest challenges in bioprinting because the absence of vessels limits tissue survival and integration. However, recent techniques such as coaxial printing and the use of angiogenic factors in bioinks have enabled significant progress in this area (Jang et al., 2023).

From a translational perspective, bioprinting has also become an essential tool for personalized medicine. Autologous cells can reduce the risk of immune rejection and enable tissues to be tailored to each patient. This potential makes bioprinting a promising alternative for the future of transplantation and regenerative therapy (Wu; Zhu; Woo, 2023).

Finally, 3D bioprinting is not limited to developing organs and tissues for transplantation; it also creates new avenues for scientific research. In vitro models of 3D-printed human tissues offer greater accuracy for simulating diseases, testing treatments, and studying

pharmacological interactions, representing a paradigm shift in biomedical research (Picado-Tejero et al., 2025).

4.2 Technological challenges and limitations of 3D bioprinting

Despite promising advances, 3D bioprinting still faces technological and scientific challenges that limit its immediate clinical application. One of the main obstacles is the structural and functional complexity of human organs, which contain not only different cell types but also dynamic interactions with vascular and nervous systems. Replicating this complexity in the laboratory requires highly advanced tissue engineering strategies (Matai et al., 2020).

Vascularization is considered one of the most critical barriers to large-scale bioprinting. Without a functional capillary network, thicker tissues experience hypoxia and cell necrosis after printing. Despite the development of coaxial printing techniques and the use of angiogenic growth factors, full integration of bioprinted tissues with the host circulatory system has not yet been achieved (Jang et al., 2023).

Another relevant challenge concerns the biocompatibility and mechanical stability of the biomaterials used. Hydrogels, for example, offer good cell compatibility but have low mechanical strength, which limits their application in structures that require greater support, such as bones and cartilage. The search for hybrid materials that combine biocompatibility with structural robustness is one of the main current research directions (Li et al., 2016).

Cell viability and differentiation also remain important concerns. During printing, cells are subjected to mechanical and thermal stresses that may compromise their survival. Maintaining cell functionality over time is essential for printed tissue to remain viable, particularly in therapeutic applications (Matai et al., 2020).

From a production-scale perspective, another major challenge is the transition from experimental bioprinting to large-scale production for transplantation. Most experiments currently take place in controlled laboratory environments, and the regulatory process for human use still requires protocol standardization and rigorous clinical trials (Picado-Tejero et al., 2025).

Ethical and regulatory issues are also obstacles to bioprinting. Manipulating human cells, particularly stem cells, raises debate over moral boundaries and equitable access to these technologies. In addition, clear regulatory frameworks are indispensable to ensure the safety and effectiveness of bioprinted organs intended for transplantation (Wu; Zhu; Woo, 2023).

Finally, economic factors must be considered. The high costs associated with developing bioprinters, bioinks, and tissue-engineering protocols make the technology inaccessible to many research centers and health systems. For bioprinting to be widely adopted, more affordable and scalable solutions must be developed to ensure its feasibility in public health settings (Jang et al., 2023).

Thus, although 3D bioprinting of tissues and organs represents a revolution in regenerative medicine, its consolidation as a clinical practice depends on overcoming technical, regulatory, and economic barriers. Addressing these challenges will determine whether the technology moves beyond a promise and becomes a reality in treating complex diseases.

5. Final considerations

The integrative study of 3D bioprinting of tissues and organs made it possible to understand the breadth of scientific and technological advances transforming regenerative medicine. Analysis of the studies showed that this technology has moved beyond the conceptual stage and has become a promising tool for creating functional tissues, with potential for future clinical application.

The field has evolved rapidly, driven by improvements in bioinks, biomaterials, and printing techniques that now enable increasingly complex and biocompatible structures to be constructed. Bioprinting has proved particularly relevant to developing biological models that simulate human tissues, expanding research possibilities in pharmacology, toxicology, and personalized therapies.

Despite this progress, considerable challenges remain. Obtaining fully functional and vascularized organs is still a major technical obstacle, as are process standardization and the ethical and legal regulation of the technology's clinical application. Furthermore, high costs and the need for highly qualified professionals indicate that establishing bioprinting as medical practice still requires time, investment, and interdisciplinary collaboration.

Overall, 3D bioprinting is one of the most promising frontiers of modern biotechnology. Its advances point toward a future in which it may be possible to reduce the shortage of organs for transplantation, minimize rejection, and offer therapeutic solutions tailored to each patient. Continued research and stronger partnerships among universities, medical centers, and industry will therefore be essential to turn this potential into clinical reality.

Conflicts of interest

Nothing to declare.

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