



3D BIOPRINTING OF HUMAN TISSUE

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Received: 10 July 2026

Revised: 16 August 2026

Accepted: 11 September 2026

Published: 30 September 2026

DOI: <https://doi.org/10.5281/zenodo.23308700>

Abstract:

Three-dimensional (3D) bioprinting has emerged as a promising technology in tissue engineering and regenerative medicine, offering the ability to fabricate complex biological structures through the controlled deposition of cells, biomaterials, and bioactive components. This review discusses recent developments in 3D bioprinting with particular emphasis on bioprinting technologies, bioink development, stem-cell integration, and their applications in tissue and organ regeneration. Different bioinks, including naturally derived, hydrogel-based, and extracellular matrix-reinforced materials, are examined in relation to their printability, biocompatibility, mechanical properties, and ability to support cellular growth and tissue maturation. The review also considers major bioprinting approaches, including extrusion-based, inkjet, laser-assisted, and other advanced fabrication techniques. The application of 3D bioprinting in the development of tissues such as neural, hepatic, cardiac, bone, cartilage, and other biological models is discussed, along with its potential in regenerative medicine, disease modelling, drug screening, and personalized medicine. Despite significant advances, challenges including vascularization, cell viability, tissue maturation, mechanical stability, reproducibility, standardization, ethical considerations, and clinical translation remain important barriers. Recent progress toward clinically relevant tissue fabrication and organ bioprinting highlights the potential of this technology to address limitations associated with conventional tissue engineering and transplantation. Overall, continued advances in bioink design, stem-cell technology, bioprinting strategies, and regulatory frameworks are expected to improve the functionality and clinical applicability of 3D-bioprinted tissues and organs.

Keywords 3D Bioprinting, Tissue Engineering, Regenerative Medicine, Bioinks, Stem Cells, Tissue Regeneration, Organ Bioprinting, Hydrogel, Personalized Medicine, Clinical Translation.

1. Introduction

1.1 Definition of 3D bioprinting

3D bioprinting is an advanced biofabrication technique used to construct three-dimensional biological structures through the controlled, layer-by-layer deposition of biomaterials, living cells, and biological components. It

combines principles of tissue engineering, biomaterials science, cell biology, and computer-aided manufacturing. Unlike conventional three-dimensional printing, 3D bioprinting focuses on the fabrication of structures containing living cells and biologically active materials with the objective of producing tissue-like constructs for regenerative medicine, disease modelling, and other biomedical applications (1–3).

1.2 Evolution of 3D bioprinting

The development of 3D bioprinting has progressed from conventional scaffold fabrication towards the controlled deposition of cells, hydrogels, and extracellular-matrix-derived materials. Advances in computer-aided design, printing technologies, biomaterials, and stem-cell research have enabled the fabrication of increasingly complex tissue-like structures. Recent developments have also focused on multi-material printing, vascularization, tissue maturation, organ fabrication, and clinical translation (1, 4, 5).

1.3 Need for tissue and organ regeneration

The shortage of suitable donor organs and the limitations associated with conventional transplantation have increased the need for alternative approaches to tissue and organ regeneration. Tissue engineering attempts to develop biological substitutes capable of replacing, repairing, or supporting damaged tissues. 3D bioprinting provides an approach for producing organized tissue constructs with controlled architecture and cellular distribution (2, 6, 7).

1.4 Role of 3D bioprinting in tissue engineering

3D bioprinting supports tissue engineering by allowing cells and biomaterials to be deposited at predefined locations. The technique can be used to reproduce aspects of the extracellular environment and tissue architecture. Bioinks containing cells, hydrogels, extracellular matrix components, and other biomaterials can be printed to produce tissue-specific constructs (1, 8, 9).

1.5 Advantages of 3D bioprinting over conventional tissue engineering

Conventional scaffold-based tissue engineering may have limitations in controlling cellular distribution and complex three-dimensional architecture. 3D bioprinting provides greater control over the spatial deposition of cells and biomaterials. It also enables patient-specific design, fabrication of complex structures, and incorporation of multiple materials or cell types (3, 5, 10).

1.6 Aim and scope of the review

This review discusses the basic principles, major components, bioinks, printing technologies, and design strategies used in 3D bioprinting. It also summarizes applications in tissue engineering and organ fabrication, the role of stem cells, post-printing maturation, therapeutic applications, advantages, limitations, ethical considerations, clinical translation, and future developments.

2. Basic principles of 3D bioprinting

2.1 Concept of 3D bioprinting

The basic concept of 3D bioprinting involves converting a digital design into a physical biological construct through controlled deposition of bioink. The process generally includes design development, material preparation, printing, and post-printing maturation (1, 3).

Figure 1 illustrates the 3D bioprinting workflow, comprising human cell isolation and expansion, medical imaging (MRI/CT), CAD scaffold modelling and slicing, bioink preparation, robotic 3D bioprinting, and compression bioreactor stimulation for functional tissue maturation.

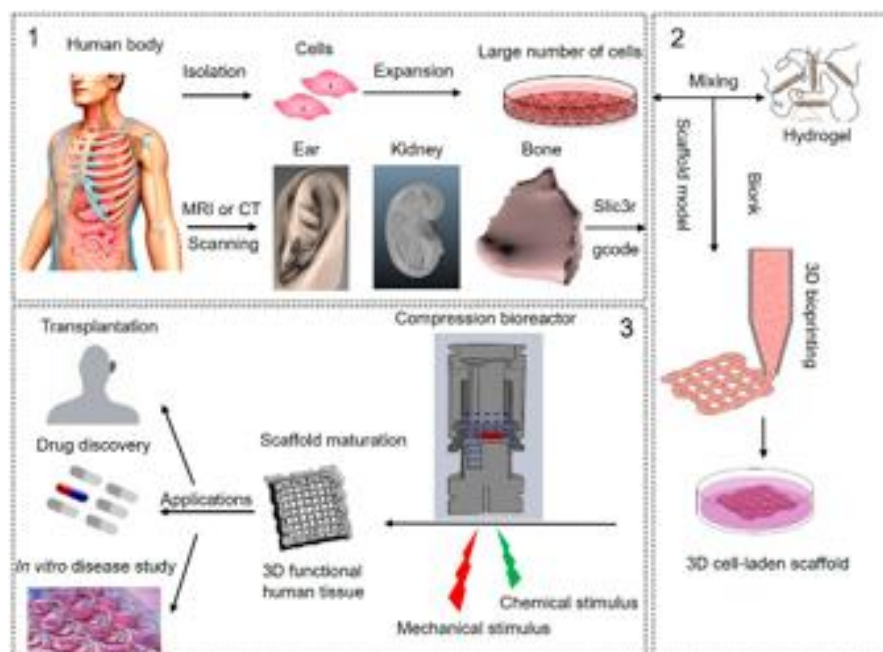


Figure 1: Overall workflow of 3D bioprinting, illustrating the major stages from digital design and bioink preparation through printing and post-printing tissue maturation (1).

2.2 Computer-aided design and digital models

Computer-aided design is used to create the required three-dimensional architecture before printing. Digital models can define the shape, dimensions, and internal architecture of the construct. Patient-specific imaging data may also be used to develop customized structures.

2.3 Layer-by-layer fabrication

In 3D bioprinting, materials are deposited sequentially in thin layers. Each deposited layer contributes to the final three-dimensional structure. Precise positioning of the material is important for reproducing the desired tissue architecture (1, 15).

2.4 Cell-bioink interaction

Cells must remain viable and functional during bioink preparation and printing. Bioink properties such as viscosity, mechanical characteristics, cross-linking behaviour, and biocompatibility influence cell survival and subsequent tissue formation (9, 13).

2.5 Scaffold formation

Printed biomaterials can form temporary or permanent three-dimensional scaffolds that provide structural support to cells. Scaffold architecture can influence cell attachment, proliferation, differentiation, and tissue organization.

2.6 Post-printing tissue maturation

After printing, the construct generally requires a maturation period during which cells proliferate, differentiate, and produce extracellular matrix. Bioreactors and mechanical or biochemical stimulation can be used to support tissue development (1, 4).

3. Major components used in 3D bioprinting

3.1 Living cells

Living cells are one of the major components of bioprinted tissue constructs. Depending on the target tissue, different cell types can be incorporated into bioinks to reproduce tissue-specific functions (1, 11).

3.2 Stem cells

Stem cells are important because of their ability to proliferate and differentiate into specialized cell types. Their incorporation into bioprinting approaches provides opportunities for developing tissue constructs with regenerative potential (11).

3.3 Mesenchymal stem/stromal cells

Mesenchymal stem/stromal cells have attracted considerable interest in regenerative medicine because of their differentiation potential and compatibility with tissue-engineering approaches. They can be incorporated into biomaterial-based constructs for tissue regeneration (11, 12).

3.4 Extracellular matrix components

The extracellular matrix provides structural and biochemical signals to cells. ECM-derived components can be incorporated into bioinks to improve cellular interactions and create a more tissue-like microenvironment (8).

3.5 Bioinks

Bioinks are printable biomaterials, often containing living cells, that are used to fabricate three-dimensional biological structures. Their printability, biocompatibility, mechanical properties, and ability to support cell function are important considerations (1, 9).

3.6 Growth factors

Growth factors can provide biochemical signals that regulate cellular proliferation, differentiation, and tissue development. Their controlled incorporation into bioprinted constructs can support tissue maturation.

3.7 Cross-linking agents

Cross-linking agents are used to stabilize printed hydrogels and maintain the desired three-dimensional structure. Cross-linking may occur through physical, chemical, or light-mediated mechanisms depending on the bioink.

3.8 Scaffolds and biomaterials

Scaffolds provide structural support for cells and developing tissues. Both natural and synthetic biomaterials have been investigated for producing scaffolds with appropriate mechanical and biological properties (1, 9).

4. Bioinks for 3D bioprinting

4.1 Definition and characteristics of bioinks

Bioinks are materials designed for use in bioprinting to generate three-dimensional biological constructs. An appropriate bioink should possess suitable printability, biocompatibility, mechanical properties, and structural stability while supporting cell viability and function (9, 13).

4.2 Natural bioinks

Natural bioinks are derived from biological sources and can provide biological signals that support cellular activity.

4.2.1 Alginate

Alginate is widely investigated because it can form hydrogels through ionic cross-linking and can be processed under relatively mild conditions.

4.2.2 Gelatin

Gelatin is derived from collagen and provides cell-interactive properties. It is frequently used in hydrogel-based bioinks.

4.2.3 Collagen

Collagen is a major component of the natural extracellular matrix and can provide a biologically relevant environment for cells.

4.2.4 Fibrin

Fibrin is associated with natural wound healing and has been investigated as a biomaterial for tissue regeneration.

4.2.5 Hyaluronic acid

Hyaluronic acid is an extracellular matrix component involved in cellular interactions and tissue homeostasis.

4.2.6 Chitosan

Chitosan is a natural polymer investigated for biomedical applications because of its biological and structural properties.

4.2.7 Silk fibroin

Silk fibroin has attracted interest because of its mechanical properties and potential use in tissue-engineering applications (9, 13).

4.3 Synthetic bioinks

Synthetic materials such as polyethylene glycol (PEG), polycaprolactone (PCL), polylactic acid (PLA), and poly(lactic-co-glycolic acid) (PLGA) can provide greater control over material properties. However, synthetic materials may require modification or combination with biological components to improve cellular interactions (1, 2).

4.4 Hydrogel-based bioinks

Hydrogels are important materials for 3D bioprinting because they can provide a hydrated environment suitable for cells. Hydrogel-based bioinks can be designed to support cell encapsulation, proliferation, and tissue formation (9).

4.5 Extracellular matrix-derived bioinks

ECM-derived bioinks attempt to reproduce aspects of the native tissue microenvironment. ECM reinforcement can improve biological interactions and provide tissue-specific signals to cells (8).

4.6 Cell-containing bioinks

Cell-containing bioinks combine biomaterials with living cells. The selection of cell type, cell concentration, and printing conditions is important for maintaining cell viability and supporting subsequent tissue development (11).

4.7 Properties of an ideal bioink

An ideal bioink should demonstrate the following characteristics (9, 13):

- Good printability.
- High biocompatibility.
- Adequate mechanical strength.
- Appropriate viscosity.
- Suitable cross-linking ability.
- High cell viability.

- Support for cell proliferation.
- Support for cell differentiation.
- Appropriate degradation behaviour.
- Ability to maintain structural stability.

4.8 Advantages and limitations of different bioinks

Natural bioinks generally provide favourable biological interactions but may have limitations in mechanical strength and printing stability. Synthetic materials can provide better control over mechanical properties but may have limited biological functionality. Therefore, combinations of natural, synthetic, and ECM-derived materials are frequently investigated to balance biological and mechanical requirements (8, 9).

5. 3D bioprinting technologies

5.1 Inkjet bioprinting

Inkjet bioprinting deposits small droplets of bioink onto a substrate. It can provide relatively precise deposition and has been investigated for cell and biomaterial printing.

5.2 Extrusion-based bioprinting

Extrusion-based bioprinting uses pressure to continuously deposit bioink through a nozzle. It is widely used because it can process relatively viscous bioinks and different cell-containing materials (1, 2).

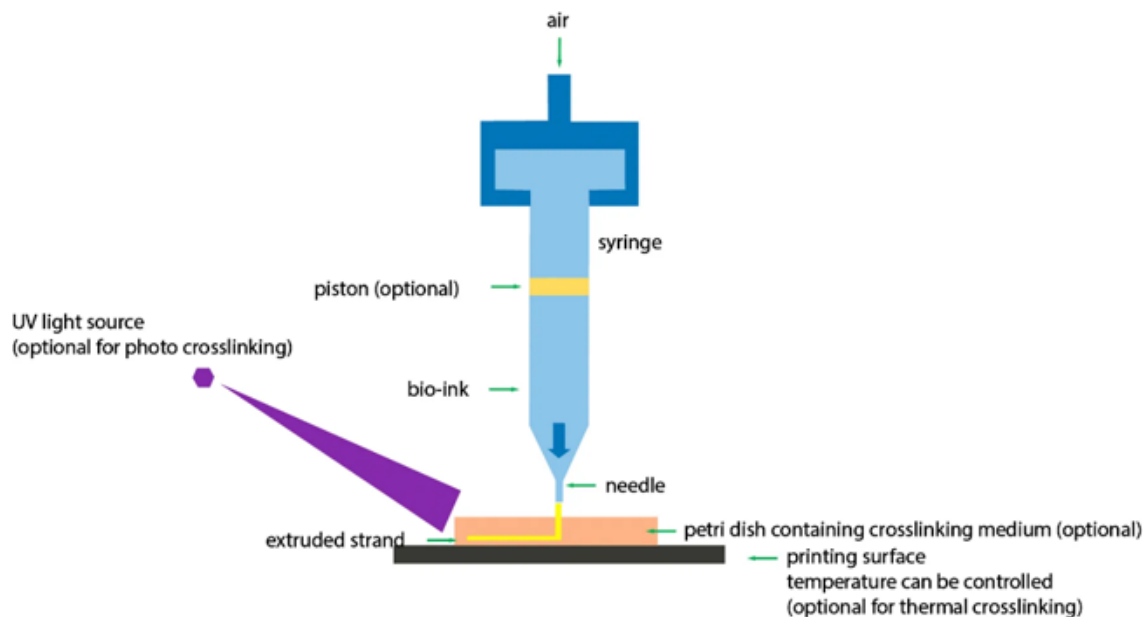


Figure 2: Schematic representation of extrusion-based 3D bioprinting, showing continuous deposition of bioink through a nozzle to construct a three-dimensional tissue structure (3)

5.3 Laser-assisted bioprinting

Laser-assisted bioprinting uses laser energy to transfer biomaterials or cells from a donor layer to a receiving substrate. The technique can provide high-resolution deposition.

5.4 Stereolithography

Stereolithography uses light to selectively polymerize photosensitive materials. It can produce complex structures with high spatial control.

5.5 Digital light processing

Digital light processing uses projected light patterns to polymerize photosensitive bioinks. It can enable rapid fabrication of complex geometries.

5.6 Microfluidic bioprinting

Microfluidic approaches allow controlled manipulation of cells and biomaterials at small scales. They can be useful for producing organized structures and complex bioink systems.

5.7 Complex 3D bioprinting methods

Complex bioprinting approaches combine different printing strategies or materials to overcome the limitations of individual techniques. Such approaches are important for fabricating complex tissues containing multiple cell types and structural features (14).

Table 1: Comparison of different bioprinting technologies

Technology	Major feature	Important consideration
Inkjet	Droplet deposition	Bioink viscosity
Extrusion	Continuous material deposition	Printing pressure and cell viability
Laser-assisted	High-resolution deposition	Equipment complexity
Stereolithography	Light-based polymerization	Photocrosslinking
Digital light processing	Patterned light exposure	Photosensitive materials
Microfluidic	Controlled microscale fabrication	System complexity

Different technologies provide different combinations of resolution, speed, material compatibility, and cell viability (1, 14).

6. Design and printing strategies

6.1 Computer-aided design

Computer-aided design allows the desired geometry of the tissue construct to be digitally developed before fabrication.

6.2 Scaffold architecture

Scaffold architecture influences mechanical behaviour, cell distribution, and tissue organization. Pore structure and overall geometry are important considerations.

6.3 Cell distribution

Uniform or tissue-specific distribution of cells can be achieved through controlled printing strategies. Appropriate cellular organization is important for developing functional tissue constructs (15).

6.4 Printing resolution

Printing resolution determines the ability to reproduce small structural features. Higher resolution can improve structural precision but may influence printing speed and cell viability.

6.5 Printing speed

Printing speed must be balanced with structural accuracy and cell survival. Excessively slow printing may affect fabrication efficiency, whereas inappropriate high-speed printing can affect deposition accuracy.

6.6 Cell viability during printing

Cells may experience mechanical stress during printing. Therefore, printing pressure, nozzle diameter, bioink viscosity, and processing conditions must be optimized to maintain cell viability (11, 15).

6.7 Cross-linking strategies

Cross-linking stabilizes printed structures. Selection of cross-linking conditions depends on the composition of the bioink and the requirements of the target tissue.

6.8 Multi-material and multi-cell printing

Multi-material and multi-cell printing can reproduce the complexity of native tissues by placing different biomaterials and cell types at specific locations. These approaches are particularly important for complex tissue and organ fabrication (14, 15).

7. Applications of 3D bioprinting in tissue engineering

7.1 Skin tissue

3D bioprinting can be used to construct skin-like structures containing cells and biomaterials. The controlled arrangement of cells and extracellular components may support the development of tissue-engineered skin.

7.2 Bone tissue

Bioprinting approaches for bone regeneration aim to combine suitable biomaterials and cells to produce structures with appropriate architecture and mechanical properties.

7.3 Cartilage tissue

Cartilage has limited natural regenerative capacity. 3D bioprinting can provide controlled fabrication of cartilage-like constructs containing cells and hydrogels.

7.4 Neural tissue

3D bioprinting has been investigated for neural tissue engineering, where cellular organization and the development of tissue-specific microenvironments are important (16).

7.5 Cardiac tissue

Bioprinting approaches can be used to develop cardiac tissue models containing relevant cells and biomaterials. Such constructs may also be useful for disease modelling and drug testing.

7.6 Liver tissue

The liver is a complex organ requiring organized cellular interactions and vascular support. 3D bioprinting has been explored for developing liver tissue models, including co-culture systems (17).

7.7 Blood vessels

Vascularization is a major requirement for the development of larger tissue constructs. Bioprinting can provide controlled fabrication of vascular-like structures and channels.

7.8 Other tissue models

3D bioprinting has also been investigated for the development of tissue models for regenerative medicine, disease modelling, and drug screening (3, 5, 6).

8. Role of stem cells in 3D bioprinting

8.1 Embryonic stem cells

Embryonic stem cells possess broad differentiation potential and can theoretically contribute to the generation of various specialized cell types. Their use also involves important ethical considerations (11).

8.2 Adult stem cells

Adult stem cells can contribute to tissue regeneration and are being investigated as cell sources for bioprinted tissue constructs.

8.3 Mesenchymal stem cells

Mesenchymal stem/stromal cells are widely investigated in regenerative medicine and can be incorporated into bioinks and tissue-engineering systems (11, 12).

8.4 Induced pluripotent stem cells

Induced pluripotent stem cells can provide a source of cells capable of differentiation into multiple specialized lineages. Their potential application in bioprinting is particularly relevant for personalized tissue models.

8.5 Stem-cell differentiation

Successful tissue fabrication requires appropriate differentiation of stem cells into the desired cell type. Biochemical signals, extracellular matrix components, and environmental conditions can influence differentiation.

8.6 Stem-cell viability and functionality

Maintaining stem-cell viability during bioink preparation and printing is essential. Printing conditions should minimize mechanical stress and maintain a suitable cellular microenvironment (9).

8.7 Stem-cell-based tissue regeneration

The combination of stem cells and 3D bioprinting provides an approach for generating tissue constructs with regenerative potential. Naturally derived bioinks can further provide biological signals that support stem-cell behaviour (12).

9. Post-printing tissue maturation

9.1 Cell proliferation

After printing, cells must proliferate to increase cellular density and contribute to tissue development.

9.2 Cell differentiation

Stem and progenitor cells may require appropriate biochemical and physical signals to differentiate into tissue-specific cell types.

9.3 Vascularization

Vascularization is essential for supplying oxygen and nutrients and removing metabolic waste from developing tissue. It remains a major challenge for large tissue constructs (2, 4).

9.4 Tissue organization

Cells must organize into tissue-specific structures after printing. Appropriate scaffold architecture and extracellular matrix interactions can support this process.

9.5 Mechanical stimulation

Mechanical stimulation can influence cellular behaviour and tissue maturation, particularly in mechanically active tissues.

9.6 Bioreactors

Bioreactors provide controlled environments for tissue maturation by regulating parameters such as nutrients, mechanical stimulation, and other culture conditions (1).

9.7 Functional maturation

The final objective of post-printing maturation is to obtain a construct that demonstrates appropriate tissue-specific structure and function.

10. Therapeutic and biomedical applications

10.1 Regenerative medicine

3D bioprinting provides a platform for developing tissue constructs intended to repair or replace damaged tissues (5, 6).

10.2 Disease modelling

Bioprinted tissues can reproduce selected characteristics of human tissues and may therefore be used to study disease mechanisms.

10.3 Drug screening

Bioprinted tissue models can provide platforms for evaluating drug responses in three-dimensional biological environments.

10.4 Drug toxicity testing

Human tissue models may help investigate potential toxic effects of therapeutic compounds.

10.5 Personalized medicine

Patient-specific cells and anatomical information may be incorporated into bioprinting approaches, providing opportunities for personalized tissue models and therapeutic strategies.

10.6 Organ transplantation

The long-term goal of organ bioprinting is to develop functional tissues and organs that could potentially address limitations associated with donor-organ availability (4, 7).

10.7 Treatment of human diseases

3D bioprinting has been investigated as a potential approach for preventing or treating human diseases through tissue replacement, disease modelling, and therapeutic development (6).

11. Advantages of 3D bioprinting

The major advantages of 3D bioprinting include:

- Patient-specific tissue fabrication.
- Precise placement of cells.
- Controlled biomaterial deposition.
- Fabrication of complex tissue architectures.
- Ability to combine multiple materials.
- Ability to combine different cell types.
- Potential for personalized medicine.
- Development of tissue and disease models.
- Potential reduction in some animal-based experimental requirements.
- Potential development of replacement tissues and organs (3, 5, 10).

12. Limitations and challenges

12.1 Poor vascularization

Insufficient vascularization limits the survival and development of thick bioprinted tissues.

12.2 Low cell viability

Cells may be exposed to mechanical stress, pressure, or other adverse conditions during printing.

12.3 Bioink limitations

No single bioink currently provides all the required biological, mechanical, and printing properties for every tissue.

12.4 Printing resolution

There is a need to balance high resolution with printing speed and cell viability.

12.5 Mechanical strength

Many hydrogel-based materials provide suitable biological environments but may not possess sufficient mechanical strength for load-bearing applications.

12.6 Tissue maturation

Printed constructs may require long periods of culture and maturation before achieving tissue-specific function.

12.7 Long-term functionality

Long-term survival, integration, and function of bioprinted tissues remain important research requirements.

12.8 Reproducibility

Variations in cells, biomaterials, printing conditions, and culture environments can affect reproducibility.

12.9 Standardization

Standardized methods, materials, testing procedures, and quality-control systems are required to support reliable development and clinical translation (18).

12.10 High cost

Advanced bioprinting equipment, specialized biomaterials, cell culture facilities, and quality-control procedures can increase research and manufacturing costs.

13. Ethical and regulatory considerations**13.1 Ethical issues in stem-cell use**

The use of certain stem-cell sources can raise ethical questions concerning cell procurement, research use, and potential clinical applications (19, 20).

13.2 Patient consent

Patient-derived cells and biological information require appropriate informed consent and ethical oversight.

13.3 Safety of bioprinted tissues

Bioprinted tissues must be evaluated for biological safety, functionality, contamination, and potential adverse effects before clinical use.

13.4 Genetic and biological risks

The use of genetically modified cells or advanced cellular technologies may create additional biological and regulatory concerns.

13.5 Ownership of bioprinted tissues

Questions may arise concerning ownership and control of patient-derived biological materials, digital anatomical models, and manufactured tissue constructs (20).

13.6 Regulatory requirements

Bioprinted tissues intended for clinical use must satisfy relevant regulatory requirements concerning manufacturing, quality, safety, and efficacy (18).

13.7 Medico-legal considerations

The use of bioprinted organs and tissues raises medico-legal questions involving responsibility, consent, safety, intellectual property, and clinical accountability (20).

14. Clinical translation

14.1 From laboratory research to clinical application

Translation of 3D bioprinting from laboratory research to clinical applications requires reliable manufacturing, reproducible outcomes, and appropriate safety evaluation (18, 21).

14.2 Safety and efficacy testing

Bioprinted constructs require systematic evaluation of biocompatibility, structural integrity, cell function, tissue integration, and therapeutic effectiveness.

14.3 Manufacturing standards

Standardized manufacturing procedures are required to produce consistent bioprinted products.

14.4 Quality control

Quality control should address cell characteristics, biomaterial properties, printing parameters, sterility, structural properties, and biological performance.

14.5 Regulatory approval

Clinical products require appropriate regulatory assessment before use in patients. Regulatory pathways depend on the nature and intended use of the bioprinted product (18).

14.6 Patient-specific applications

Patient-specific anatomical information and cells may allow customized tissue fabrication, representing an important potential application of bioprinting.

14.7 Challenges in clinical transplantation

Major challenges include vascularization, long-term functionality, manufacturing consistency, safety, immune compatibility, and regulatory approval (18, 21).

15. Future perspectives

15.1 Artificial intelligence in bioprinting

Artificial intelligence may support optimization of printing parameters, design of tissue architectures, and analysis of bioprinting data.

15.2 4D bioprinting

4D bioprinting extends three-dimensional fabrication by incorporating structures capable of changing their properties or shape in response to appropriate stimuli.

15.3 Multi-material bioprinting

Future systems are expected to increasingly combine multiple biomaterials with different mechanical and biological properties within a single construct.

15.4 Vascularized organ printing

Development of hierarchical vascular networks remains an important requirement for successful fabrication of large and complex organs.

15.5 Personalized bioprinting

Combining patient-specific imaging with patient-derived cells may support customized tissue fabrication and personalized biomedical models.

15.6 Advanced stem-cell technologies

Advances in stem-cell differentiation, induced pluripotent stem cells, and cell culture systems may improve the development of functional tissue constructs (11).

15.7 Large-scale organ fabrication

Future research aims to overcome the technical limitations associated with the size, complexity, and vascularization of bioprinted organs (4, 7).

15.8 Integration with robotics and automation

Automation and robotic systems may improve printing precision, reproducibility, and manufacturing scalability.

16. Conclusion

3D bioprinting is an emerging biofabrication technology that combines living cells, biomaterials, and computer-controlled manufacturing to produce organized three-dimensional biological constructs. Advances in bioinks, stem cells, ECM-derived materials, hydrogel systems, and printing technologies have expanded its applications in tissue engineering, regenerative medicine, disease modelling, and drug testing (1, 5, 8, 12).

Despite considerable progress, important challenges remain, particularly in vascularization, cell viability, tissue maturation, mechanical properties, reproducibility, standardization, and clinical translation. Ethical, regulatory, and medico-legal considerations must also be addressed before widespread clinical application (18–20).

The future of 3D bioprinting is expected to involve integration with advanced stem-cell technologies, artificial intelligence, multi-material printing, automation, and personalized medicine. Continued development of bioinks, printing technologies, and tissue-maturation strategies may contribute to the long-term goal of producing functional tissues and organs for biomedical and regenerative applications (4, 21, 22).

References

1. Zhang, J., Wehrle, E., Rubert, M., & Müller, R. (2021). 3D bioprinting of human tissues: Biofabrication, bioinks, and bioreactors. *International Journal of Molecular Sciences*, 22(8), 3971. <https://doi.org/10.3390/ijms22083971>
2. De Santis, M. M., Alsafadi, H. N., Tas, S., Bölükbas, D. A., Prithiviraj, S., Da Silva, I. A. N., Mittendorfer, M., Ota, C., Stegmayr, J., Daoud, F., Königshoff, M., Swärd, K., Wood, J. A., Tassieri, M., Bourguine, P. E., Lindstedt, S., Mohlin, S., & Wagner, D. E. (2021). Extracellular-matrix-reinforced bioinks for 3D bioprinting human tissue. *Advanced Materials*, 33(3), 2005476. <https://doi.org/10.1002/adma.202005476>
3. Agarwal, S., Saha, S., Balla, V. K., Pal, A., Barui, A., & Bodhak, S. (2020). Current developments in 3D bioprinting for tissue and organ regeneration—A review. *Frontiers in Mechanical Engineering*, 6, 589171. <https://doi.org/10.3389/fmech.2020.589171>
4. Ji, S., & Guvendiren, M. (2021). Complex 3D bioprinting methods. *APL Bioengineering*, 5(1), 011508. <https://doi.org/10.1063/5.0034901>
5. Tan, B., Gan, S., Wang, X., Liu, W., & Li, X. (2021). Applications of 3D bioprinting in tissue engineering: Advantages, deficiencies, improvements, and future perspectives. *Journal of Materials Chemistry B*, 9(27), 5385–5413. <https://doi.org/10.1039/D1TB00172H>

6. Yi, H.-G., Kim, H., Kwon, J., Choi, Y.-J., Jang, J., & Cho, D.-W. (2021). Application of 3D bioprinting in the prevention and the therapy for human diseases. *Signal Transduction and Targeted Therapy*, 6, 177. <https://doi.org/10.1038/s41392-021-00566-8>
7. Moghaddam, A. S., Khonakdar, H. A., Arjmand, M., Jafari, S. H., Bagher, Z., Moghaddam, Z. S., Chimera, M., Sisakht, M. M., & Shojaei, S. (2021). Review of bioprinting in regenerative medicine: Naturally derived bioinks and stem cells. *ACS Applied Bio Materials*, 4(5), 4049–4070. <https://doi.org/10.1021/acsabm.1c00219>
8. Sekar, M. P., Budharaju, H., Zennifer, A., Sethuraman, S., Vermeulen, N., Sundaramurthi, D., & Kalaskar, D. M. (2021). Current standards and ethical landscape of engineered tissues—3D bioprinting perspective. *Journal of Tissue Engineering*, 12, 20417314211027677. <https://doi.org/10.1177/20417314211027677>
9. Scognamiglio, C., Soloperto, A., Ruocco, G., & Cidonio, G. (2020). Bioprinting stem cells: Building physiological tissues one cell at a time. *American Journal of Physiology-Cell Physiology*, 319(3), C465–C480. <https://doi.org/10.1152/ajpcell.00124.2020>
10. Reddy, V. S., Ramasubramanian, B., Telrandhe, V. M., & Ramakrishna, S. (2023). Contemporary standpoint and future of 3D bioprinting in tissue/organs printing. *Current Opinion in Biomedical Engineering*, 27, 100461. <https://doi.org/10.1016/j.cobme.2023.100461>
11. Ramiah, P., du Toit, L. C., Choonara, Y. E., Kondiah, P. P. D., & Pillay, V. (2020). Hydrogel-based bioinks for 3D bioprinting in tissue regeneration. *Frontiers in Materials*, 7, 76. <https://doi.org/10.3389/fmats.2020.00076>
12. Cadena, M., Ning, L., King, A., Hwang, B., Jin, L., Serpooshan, V., & Sloan, S. A. (2021). Three-dimensional bioprinting of neural tissues. *Advanced Healthcare Materials*, 10(15), e2001600. <https://doi.org/10.1002/adhm.202001600>
13. Loukelis, K., Koutsomarkos, N., Mikos, A. G., & Chatzinikolaidou, M. (2024). Advances in 3D bioprinting for regenerative medicine applications. *Regenerative Biomaterials*, 11, rbae033. <https://doi.org/10.1093/rb/rbae033>
14. Gungor-Ozkerim, P. S., Inci, I., Zhang, Y. S., Khademhosseini, A., & Dokmeci, M. R. (2018). Bioinks for 3D bioprinting: An overview. *Biomaterials Science*, 6(5), 915–946. <https://doi.org/10.1039/C7BM00765E>
15. Agarwal, T., Onesto, V., Banerjee, D., Guo, S., Polini, A., Vogt, C., Viswanath, A., Esworthy, T., Cui, H., O'Donnell, A., Vajanthri, K. Y., Moroni, L., Ozbolat, I. T., Panoskaltsis-Mortari, A., Zhang, L. G., Costantini, M., & Maiti, T. K. (2025). 3D bioprinting in tissue engineering: Current state-of-the-art and challenges towards system standardization and clinical translation. *Biofabrication*, 17(4), 042003. <https://doi.org/10.1088/1758-5090/ade47a>
16. Dey, M., & Ozbolat, I. T. (2020). 3D bioprinting of cells, tissues and organs. *Scientific Reports*, 10, 14023. <https://doi.org/10.1038/s41598-020-70086-y>
17. Ricci, G., Gibelli, F., & Sirignano, A. (2023). Three-dimensional bioprinting of human organs and tissues: Bioethical and medico-legal implications examined through a scoping review. *Bioengineering*, 10(9), 1052. <https://doi.org/10.3390/bioengineering10091052>
18. Mirsky, N. A., Ehlen, Q. T., Greenfield, J. A., Antonietti, M., Slavin, B. V., Nayak, V. V., Pelaez, D., Tse, D. T., Witek, L., Daunert, S., & Coelho, P. G. (2024). Three-dimensional bioprinting: A comprehensive review for

- applications in tissue engineering and regenerative medicine. *Bioengineering*, 11(8), 777. <https://doi.org/10.3390/bioengineering11080777>
19. Liu, S., Cheng, L., Liu, Y., Zhang, H., Song, Y., Park, J.-H., Dashnyam, K., Lee, J.-H., Khalak, F. A.-H., Riester, O., Shi, Z., Ostrovidov, S., Kaji, H., Deigner, H.-P., Pedraz, J. L., Knowles, J. C., Hu, Q., Kim, H.-W., & Ramalingam, M. (2023). 3D bioprinting tissue analogs: Current development and translational implications. *Journal of Tissue Engineering*, 14, 20417314231187113. <https://doi.org/10.1177/20417314231187113>
 20. Thakur, K. K., Lekurwale, R., Bansode, S., & Pansare, R. (2023). 3D bioprinting: A systematic review for future research direction. *Indian Journal of Orthopaedics*, 57(12), 1949–1967. <https://doi.org/10.1007/s43465-023-01000-7>
 21. Lee, J. M., & Yeong, W. Y. (2016). Design and printing strategies in 3D bioprinting of cell-hydrogels: A review. *Advanced Healthcare Materials*, 5(22), 2856–2865. <https://doi.org/10.1002/adhm.201600435>
 22. Subramaniam, V., Abraham, C., Higgins, B. R., Chisolm, S. J., Sweeney, B., Duraivel, S., Balzano-Nogueira, L., Monjure, T., Wang, C.-Y., Palmer, G. D., & Angelini, T. E. (2025). A functional human liver tissue model: 3D bioprinted co-culture discoids. *Biomaterials Advances*, 173, 214288. <https://doi.org/10.1016/j.bioadv.2025.214288>