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Chapter 15

Vision for the Future

Pola Kranthi Kumar
Joginpally B.R. Pharmacy College, Moinabad, Ranga Reddy, Telangana 500034, India
Shibu John
Founder, 3D Graphy LLP, 804/ B, Building 68. 13th Road, Tilaknagar, Mumbai, India
Ananda Kumar Chettupalli
School of Medical and Allied sciences, Galgotias University, Greater Noida, Uattar Pradesh-203201
Banapuram Srinivas
Indira College of Pharmacy, Vishnupuri, Nanded, Maharashtra 431606, India

Abstract: As 3D bioprinting moves beyond foundational research into clinical translation, the next decade will witness a transformative expansion in its scope and capabilities. This chapter outlines a forward-looking perspective on how the convergence of genomics, artificial intelligence, regenerative medicine, space exploration, and open-source innovation will redefine the boundaries of tissue engineering and personalized medicine. Central to this future is the promise of personalized bioprinting, wherein genomic data will guide the fabrication of individualized tissues, offering unmatched therapeutic precision. In parallel, the synergistic integration of gene editing and stem cell therapies within bioprinted constructs is anticipated to revolutionize regenerative medicine for chronic, degenerative, and genetic disorders. The chapter also explores the prospects of bioprinting in microgravity, enabling organogenesis and tissue culture in space vital for extraterrestrial healthcare and long-term colonization missions. Whole organ printing, though still aspirational, is rapidly approaching feasibility with advances in vascularization, neural integration, and multi-material bioprinting. Further, global collaboration through open-source platforms is likely to democratize access and accelerate innovation across borders. Finally, as bioprinting reshapes clinical practices, it will catalyze a transformation in medical education and pose new societal, ethical, and economic challenges that require anticipatory governance. This chapter envisions bioprinting not just as a technological evolution, but as a paradigm shift in human health, longevity, and planetary adaptation.

Keywords: Personalized Bioprinting, Regenerative Medicine, Space Bioprinting, Whole Organ Fabrication, Open-Source Collaboration.

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15.0 INTRODUCTION

15.0.1 Roadmap for the Next Decade

The evolution of 3D bioprinting from a research-intensive niche to a potentially routine clinical application has marked a pivotal turn in biomedical science. As we stand at the threshold of the third decade of bioprinting innovation, it is increasingly clear that the next phase will be defined not solely by incremental improvements but by radical, systemic shifts in application, scalability, and societal integration. The roadmap for the next decade is expected to build upon current advances in bioink formulations, tissue maturation, and vascularization, while incorporating disruptive technologies such as real-time AI-assisted bioprinting, quantum modeling of biomolecular interactions, and robotic automation of post-print tissue conditioning. Parallel progress in complementary domains such as genomics, CRISPR-Cas gene editing, stem cell biology, organ-on-chip systems, and computational modeling will allow 3D bioprinting to evolve into a core tool in precision and regenerative medicine. More futuristically, 3D bioprinting is poised to address global healthcare inequities, support long-duration space travel, and even redefine philosophical questions around human enhancement and synthetic life. However, realizing this vision demands coordinated investment, global regulatory alignment, and careful navigation of bioethical concerns. This chapter aims to elucidate the technological, clinical, and societal milestones necessary to unlock the full potential of 3D bioprinting in the coming decades.

15.1 Personalized Bioprinting

15.1.1 Genomic-Guided Fabrication

Personalized medicine has become a cornerstone of 21st-century therapeutics, and 3D bioprinting is uniquely positioned to advance this field through genomic-guided tissue fabrication. In this model, a patient’s own genomic and epigenetic data inform the design of bioinks, scaffold architectures, and cellular compositions to generate tissue constructs that are immunologically compatible, functionally optimized, and tailored to the individual's disease profile. The integration of next-generation sequencing (NGS) with bioprinting design tools allows for the encoding of patient-specific mutations, SNPs, or epigenetic markers into the bioprinting workflow. For example, in cancer immunotherapy, bioprinted tumor models with embedded neoantigens derived from patient genomes can be used to test personalized vaccine strategies ex vivo before clinical application [1]. Similarly, in cardiac tissue repair, polymorphisms in genes such as TNNT2 or MYH7 can be factored into the mechanical and electrical tuning of the bioprinted patch, potentially reducing arrhythmia risks post-implantation [2]. AI-driven data analysis pipelines are further improving the resolution with which bioprinting parameters can be personalized, incorporating dynamic feedback from real-time biosensors, metabolic flux data, and even microbiome interactions [3]. Despite these advances, significant challenges remain. These include ensuring the reproducibility of patient-specific constructs, safeguarding genomic data privacy, and navigating the ethical implications of personalized organ fabrication. Looking ahead, the advent of cloud-based design platforms and interoperable databases will make personalized bioprinting accessible even in remote or resource-constrained environments. These developments suggest a future in which “off-the-shelf” organs give way to custom-printed, autologous tissues that are optimized for individual physiology, disease burden, and therapeutic outcomes.

15.2 Regenerative Medicine Integration

15.2.1 Combining Gene and Stem Cell Therapies

The integration of regenerative medicine with 3D bioprinting marks one of the most transformative intersections in biomedical science. Traditionally, stem cell therapies and gene editing have been developed in parallel, yet their convergence within bioprinted constructs offers a synergistic approach capable of restoring function in tissues damaged by injury, aging, or genetic defects.Bioprinting facilitates spatial control over stem cell placement and microenvironmental cues, enabling more effective differentiation and tissue organization than conventional injection-based methods. Moreover, genetically engineered stem cells such as induced pluripotent stem cells (iPSCs) corrected using CRISPR-Cas9 can be embedded into constructs that carry both reparative and curative potential. For instance, a study demonstrated the bioprinting of neural tissues using iPSCs edited to correct Parkinson's-related mutations, leading to dopaminergic neuron restoration in murine models [4]. Gene-bioprinting hybrids are also being explored for treating monogenic disorders such as cystic fibrosis or muscular dystrophy. Bioprinted epithelial sheets or muscle patches loaded with CRISPR-corrected cells have shown promising in vitro and preclinical results [5]. Additionally, dynamic hydrogels that allow for the in situ release of gene therapy vectors are being designed to enable staged gene delivery post-implantation, enhancing the longevity and integration of the construct [6]. However, the risks of off-target gene effects, immune reactions to viral vectors, and regulatory uncertainty still constrain the clinical deployment of these strategies. Comprehensive longitudinal studies, rigorous biosafety protocols, and ethical oversight mechanisms are necessary to ensure that this integration proceeds responsibly. Future applications may include biofabricated constructs that not only replace damaged organs but actively regenerate them in vivo through programmed gene expression and controlled cell proliferation, heralding a new era of smart regenerative implants.

15.3 Bioprinting in Space

15.3.1 Space Medicine Applications

The unique environment of space presents both a challenge and an opportunity for tissue engineering. Microgravity alters fluid dynamics, cell morphology, and tissue assembly, all of which are critical parameters in bioprinting. In the past few years, experiments aboard the International Space Station (ISS) have confirmed that bioprinting in microgravity facilitates the formation of thicker and more structurally complex tissues than on Earth due to the absence of gravitational collapse [7]. NASA and ESA, in collaboration with bioprinting companies such as 3D Bioprinting Solutions, have successfully printed cartilage, skin, and rudimentary vascularized tissues in orbit [8]. These achievements pave the way for on-demand fabrication of tissue grafts, organoids, and diagnostic models during deep space missions, where terrestrial medical evacuation is impossible. Moreover, space bioprinting is not limited to astronaut health. The microgravity environment serves as a unique bioreactor for developing high-fidelity organoids and disease models, offering insights into aging, musculoskeletal degeneration, and radiation-induced tissue damage conditions that are accelerated in space [9]. These models could be leveraged for Earth-based therapeutic discovery and validation. Looking forward, future missions to the Moon or Mars may include autonomous bioprinting laboratories capable of producing skin grafts, bone constructs, or even whole organs using astronaut-derived cells. The development of closed-loop biomanufacturing systems, cryopreserved cell banks, and compact bioreactors will be key enablers of this vision. Space bioprinting exemplifies the ultimate frontier in biomanufacturing where biology, engineering, and space science converge to support human life beyond Earth.

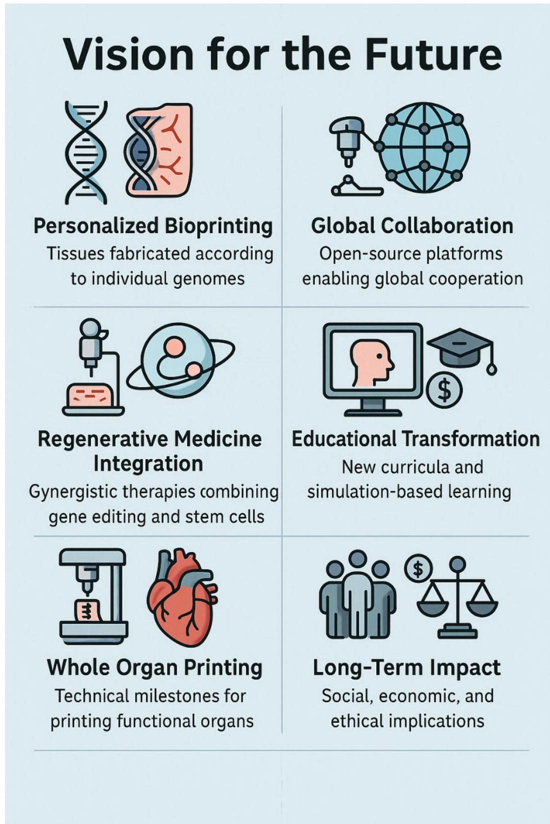

Figure 15.1: Vision for the Future of 3D Bioprinting

15.4 Whole Organ Printing

15.4.1 Full Organ Fabrication Prospects

The fabrication of fully functional, transplantable organs remains one of the most ambitious goals of 3D bioprinting. While partial tissues such as skin, cartilage, and corneal layers have reached clinical trials, the leap to whole organ bioprinting necessitates a confluence of breakthroughs across biomaterials, cellular integration, vascularization, and regulatory science.

At the core of whole organ printing lies the challenge of vascular complexity. Organs like kidneys and livers require a dense and hierarchical vasculature to ensure oxygen and nutrient diffusion. Several research groups have successfully demonstrated perfusable networks using sacrificial bioinks or coaxial nozzle systems, enabling short-term function in bioprinted constructs [10]. Additionally, decellularized organ scaffolds are being combined with bioprinting to provide natural extracellular matrix (ECM) topography while embedding functional cells layer by layer [11]. Organ-specific cell sourcing also plays a critical role. Advanced differentiation protocols are being used to generate hepatocytes, nephrons, or cardiac myocytes from iPSCs, while recent studies focus on coaxial and multimaterial printing to place parenchymal, stromal, and immune cells in spatially defined architectures [12]. Furthermore, machine learning algorithms have started to guide complex g-code generation for organ-scale prints, optimizing print path, droplet size, and cell density in real-time.

Despite these technological strides, challenges remain in tissue maturation, innervation, and immune tolerance. Printed organs must not only mimic anatomical structures but also integrate seamlessly post-transplantation. For example, a bioprinted heart must beat synchronously and establish electromechanical coupling with host tissue an extremely high bar to meet. Ethical and logistical considerations will also define the future of whole organ printing. The need for standardized quality assurance, biobanking infrastructure, and international harmonization of regulatory frameworks cannot be overstated. Nevertheless, the trajectory is promising: research initiatives such as the Wyss Institute's Heart Bioprinting Project and the NIH-funded Lung Bioprinting Consortium are actively bridging the bench-to-bedside gap [13]. If realized, whole organ printing could eliminate transplant waitlists, end organ trafficking, and dramatically extend healthy human lifespan.

15.5 Global Collaboration

15.5.1 Open-Source Bioprinting Platforms

In an era where the democratization of science is increasingly prioritized, open-source approaches to bioprinting are gaining traction. These platforms encourage international collaboration, knowledge sharing, and low-cost technological access especially critical for research institutions and clinics in low-resource settings. Several initiatives have already begun to break down the exclusivity of proprietary systems. For instance, the Open Source Bioprinter Project (OSBP) and BioBots community have published detailed schematics, software code, and instructional resources to help users build and operate low-cost bioprinters with standard materials [14]. These efforts have inspired community-driven improvements in print head design, firmware efficiency, and even biocompatible hardware alternatives. GitHub repositories and preprint platforms such as bioRxiv have become venues for rapid dissemination of protocols for bioink formulation, cell culture maintenance, and scaffold design. Furthermore, crowdsourced bioprinting challenges hosted by platforms like Foldit and Eterna encourage algorithmic contributions from citizen scientists to enhance print pattern prediction and biomolecular folding.

However, open-source bioprinting is not without concerns. Issues related to data standardization, intellectual property (IP), biosafety, and quality control must be addressed. There is also the risk of dual-use research if tools are misused for unethical or non-therapeutic purposes. Thus, governance models must be co-developed alongside open technologies to ensure responsible innovation. In the long term, establishing international bioprinting consortia akin to the Human Genome Project or COVID-19 ACT Accelerator could foster coordinated global progress. These consortia could align regulatory bodies, standardize data sharing formats, support underfunded laboratories, and ensure equitable access to life-saving bioprinting technologies. Open science, when supported by robust ethical frameworks, can accelerate bioprinting’s impact across geographies, socioeconomic strata, and clinical disciplines.

15.6 Educational Transformation

15.6.1 Bioprinting in Medical Training

As bioprinting enters clinical practice, medical and biomedical curricula must evolve accordingly. The inclusion of bioprinting in education is not merely supplementary—it is imperative to prepare the next generation of surgeons, researchers, and bioengineers for a rapidly changing therapeutic landscape. Simulation-based training using bioprinted models has already shown promise in fields such as neurosurgery, cardiovascular repair, and dental prosthodontics. These models can replicate patient-specific anatomies derived from imaging data, offering tactile, high-fidelity surgical rehearsal tools without ethical concerns associated with cadaveric dissection [15]. Unlike plastic-based simulations, bioprinted tissues can mimic the mechanical properties and histological features of real tissue, enhancing the accuracy of skill acquisition. Moreover, bioprinting enables curriculum personalization. For instance, students can engage in designing and printing disease-specific models that demonstrate pathophysiological changes in vascular diseases, cancers, or congenital malformations. Integrating bioprinting with augmented and virtual reality systems further enriches the learning environment, creating immersive digital twin simulations of organ systems. Institutions such as Harvard, Stanford, and the Indian Institute of Technology have begun offering interdisciplinary courses combining regenerative biology, CAD modeling, materials science, and clinical translation, laying the foundation for comprehensive bioprinting education [16]. Interprofessional education where engineers, doctors, and regulators co-learn is also being adopted to reflect the collaborative nature of bioprinting development. However, widespread adoption faces barriers such as cost of equipment, lack of trained faculty, and limited availability of standardized teaching protocols. Partnerships with bioprinting firms, grant-funded curriculum development, and online MOOCs are emerging solutions to scale bioprinting education globally. Ultimately, bioprinting will not only shape how medicine is practiced but how it is taught bridging knowledge gaps across biological, computational, and ethical domains.

15.7 Long-Term Impact

15.7.1 Social, Economic, and Ethical Projections

The long-term societal impact of 3D bioprinting will extend far beyond the laboratory or surgical theater. As the technology matures, it will challenge conventional norms in economics, bioethics, employment, and human identity. Economically, bioprinting may reduce the burden on healthcare systems by preventing end-stage diseases through early regenerative intervention. The cost of organ transplants, immunosuppressive regimens, and long hospitalizations could be significantly lowered. Conversely, access inequality may worsen if bioprinting services are monopolized or remain confined to high-income countries. Strategic public-private partnerships and tiered pricing models will be needed to ensure equitable access [17]. Socially, bioprinting raises questions about what it means to be human. As tissues, organs, and perhaps even parts of the nervous system are bioprinted, the line between biological and synthetic may blur. Would an individual with multiple bioprinted parts still be biologically "natural"? These questions intersect with philosophical, legal, and theological domains, requiring interdisciplinary discourse and policy foresight. Ethically, debates will intensify around enhancement vs. therapy. Bioprinting may eventually allow for organs that outperform their natural counterparts lungs with greater oxygen exchange capacity, or hearts resistant to ischemia. Regulatory frameworks must preemptively distinguish between acceptable clinical application and controversial bioenhancement, a distinction that may be culturally relative [18].

Environmental sustainability also deserves attention. The lifecycle analysis of bioprinting materials, energy consumption, and waste disposal must be integrated into future designs. Biodegradable scaffolds, green biomanufacturing, and closed-loop systems will be necessary to ensure a sustainable future. In sum, 3D bioprinting holds transformative potential but its long-term impact will be shaped by how society chooses to govern, disseminate, and integrate it across ethical, economic, and cultural dimensions.

Table 15.1: Future Prospects in Personalized Medicine

Key Area	Description	Examples	Potential Implications	References
Advancements in Bioprinting Technology	The evolution of bioprinting technologies that enable faster, more precise, and scalable production of bioprinted tissues and organs.	Introduction of high-resolution printers, advanced bioinks, and multi-material bioprinting for complex tissue structures.	Increased speed, precision, and affordability of bioprinted tissues and organs, accelerating their use in clinical practice.	19
	Use of AI and Machine Learning	Integration of AI and machine learning in bioprinting to optimize designs, predict tissue growth, and improve production efficiency.	AI-driven systems to design patient-specific tissues and organs, predicting their behavior and success rates based on data.	20
Personalized Medicine	The future of bioprinting in creating patient-specific treatments and therapies based on genetic, molecular, and physiological data.	Bioprinted tissues, organs, and drug delivery systems tailored to the genetic makeup and disease profile of individual patients.	Custom solutions for patients, leading to improved treatment outcomes, reduced side effects, and faster recovery.	21
	Tailored Drug Delivery Systems	Bioprinting of customized drug delivery systems based on a patient's specific needs, ensuring precise and efficient	Development of 3D printed oral films, gels, and implants that release drugs at the right time, dose, and site.	22

		medication release.		
Tissue Regeneration and Repair	Bioprinting of tissues and organs to repair or replace damaged or diseased organs, advancing regenerative medicine.	Printing of complex tissues such as skin, cartilage, bone, and vascular tissues for use in reconstructive surgery.	Potential to reduce organ transplant waiting lists and provide alternative treatments for degenerative diseases.	23
	Printing Vascularized Tissues	The challenge and solution of creating bioprinted tissues with functional blood vessels for better integration in the body.	Printing of vascularized tissues, such as liver and kidney tissues, that can survive long-term post-implantation.	
Synthetic and Bio-Inspired Materials	The use of advanced biomaterials that mimic natural tissue properties to support the growth and functionality of bioprinted tissues.	Use of bioinks derived from collagen, alginate, and other natural polymers to improve tissue integration and functionality.	Advances in biomaterials that make bioprinted tissues more lifelike, durable, and functional, enhancing their application in clinical settings.	24
Regenerative Medicine	The potential of 3D bioprinting to repair or regenerate damaged tissues and organs through the printing of functional tissues for therapeutic use.	Bioprinted skin grafts for burn victims, cartilage for osteoarthritis treatment, and custom bone implants for fractures.	Expanding the boundaries of regenerative medicine, reducing reliance on organ donors and improving quality of life for patients with chronic conditions.	25

Ethical Considerations in Bioprinting 2.0	New ethical dilemmas arising from the ability to create fully functional tissues, organs, and genetically modified organisms.	Discussions on the ethics of creating bioengineered organs for human transplantation or modifying genetic material using bioprinting.	The need for new ethical frameworks to address concerns around organ commodification, genetic privacy, and the limits of human intervention.	26
	Access to Technology	Addressing the disparities in access to cutting-edge bioprinting technologies, particularly for underserved populations.	Ensuring that advances in bioprinting benefit all populations, not just the wealthy, and addressing global healthcare inequalities.	
Regulation and Standardization	The development of comprehensive regulatory frameworks for the safe and effective application of bioprinted tissues and organs.	Establishing clear global regulations for bioprinted medical devices, organs, and pharmaceuticals to ensure safety and efficacy.	The need for international collaboration in creating standards that ensure the safe use of bioprinted products.	27
Cost and Scalability	The economic challenges of scaling up bioprinting technologies for widespread clinical use while maintaining affordability.	Developing cost-effective methods for mass production of bioprinted tissues and organs.	Bioprinted organs could become more affordable and accessible to the general public, revolutionizing healthcare delivery.	28
Integration with Other Technologies	How bioprinting will integrate with other	Combining bioprinting with gene editing to	The convergence of multiple advanced	29

	cutting-edge technologies like CRISPR, nanotechnology, and robotics to create transformative medical solutions.	produce genetically tailored tissues or with robotics for automated organ printing.	technologies could result in breakthroughs that address complex medical challenges.	
Global Healthcare Impact	The transformative potential of bioprinting in revolutionizing global healthcare systems, especially in developing countries.	Providing on-demand, affordable bioprinted prosthetics, implants, and organ transplants in low-resource settings.	Bioprinting could help bridge healthcare gaps and improve access to essential medical treatments in underserved regions.	30

Table 15.1 outlines the vision for Bioprinting 2.0 and its transformative impact on personalized medicine, tissue regeneration, and global healthcare. Bioprinting 2.0 encompasses advancements in technology, such as high-resolution printers, AI integration, and personalized medicine, allowing for the precise creation of patient-specific tissues, organs, and drug delivery systems. Innovations in tissue regeneration, including vascularized tissues for organ transplants, and the use of bio-inspired materials further enhance clinical applications. Regenerative medicine benefits from 3D bioprinting by enabling tissue repair and organ replacement, while ethical concerns arise regarding the creation of genetically modified organisms and access to technology. To address these, clear regulations and cost-effective scalability must be developed to ensure bioprinting is accessible globally, especially in underserved regions. As bioprinting integrates with other technologies like CRISPR and nanotechnology, its potential to revolutionize healthcare systems, reduce reliance on organ donors, and provide personalized treatments grows, offering new hope for improved patient outcomes.

CONCLUSION

Chapter 15 envisions a bold and transformative future for 3D bioprinting, positioning it as a cornerstone technology in precision medicine, regenerative therapies, space healthcare, and biomedical education. Personalized bioprinting driven by genomic data will enable highly tailored tissue constructs, improving therapeutic outcomes and reducing rejection risks. The integration of gene editing and stem cell therapy within bioprinted scaffolds is set to revolutionize treatment for chronic and genetic conditions. In parallel, bioprinting in microgravity environments is unlocking novel possibilities for tissue fabrication during space missions and enhancing biomedical research on Earth. The chapter also highlights progress toward whole organ printing an ambitious goal that, if realized, could eliminate transplant waitlists and reshape the field of organ replacement. Open-source bioprinting initiatives are democratizing access, fostering global collaboration, and accelerating innovation across geographies. In medical education, bioprinted models are redefining surgical training and interdisciplinary learning. However, the long-term impact of bioprinting extends into complex ethical, social, and economic domains raising questions about enhancement, access equity, sustainability, and human identity. The chapter underscores that while the technological roadmap is promising, its success depends on proactive governance, equitable distribution, and societal readiness to embrace this paradigm shift in human health and biomedical capability.

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