Review Article

Advancements and Applications of Three-dimensional Printing Technology in Surgery

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Abstract

Three-dimensional (3D) printing technology has revolutionized surgical practices, offering precise solutions for planning, education, and patient care. Surgeons now wield tangible, patient-specific 3D models derived from imaging data, allowing for meticulous presurgical planning. These models enhance surgical precision, reduce operative times, and minimize complications, ultimately improving patient outcomes. The technology also serves as a powerful educational tool, providing hands-on learning experiences for medical professionals and clearer communication with patients and their families. Despite its advantages, challenges such as model accuracy and material selection exist. Ongoing advancements, including bioactive materials and artificial intelligence integration, promise to further enhance 3D printing's impact. The future of 3D printing in surgery holds potential for regenerative medicine, increased global accessibility, and collaboration through telemedicine. Interdisciplinary collaboration between medical and engineering fields is crucial for responsible and innovative use of this technology.

Keywords: Anatomical models, surgical innovation, surgical planning, technology, three-dimensional printing

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Introduction of Three-dimensional Printing in Surgery

Various modifications have been seen in the medical field through the use of three-dimensional (3D) printing technology. It has helped for the advancement in surgical planning and medical education.[1] This technology has benefited medical science by increasing surgical outcomes and also for the improvement of patient care.[2] This cutting-edge technology also known as additive manufacturing is used to transform digital designs into 3D real structures with unmatched accuracy. Originally confined to engineering and manufacturing prototyping, 3D printing has now made its impact in diverse industries such as aerospace, automotive, fashion, and healthcare.[3]

Revolutionary changes have come in surgery after the introduction of 3D printing technology.[4] It allows surgeons to step into the operating room wielding a tangible map of the complex terrain they are about to navigate. Each intricate structure, unique to the patient, stands ready for inspection, allowing for meticulous presurgical planning, that is, as intricate as it is effective.[5]

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Benefits of Three-dimensional Printing in Surgical Planning

Commercially introduced 3D printing in 1980 is now experiencing significant advancements with diverse applications, including intricate structures manufacturing, the fabrication of engine components for the aviation industry, surgical planning, and modern surgical practices. Explaining the procedures to patients and their families has become easier due to 3D-printed models. 3D printing converts two-dimensional imaging data, such as computed tomography (CT) scans and magnetic resonance imaging scans, into 3D models, greatly helping the surgeon to visualize complex anatomical structures. As a result, surgeons are now able to understand the spatial relationships and anticipate potential challenges actually before entering the operating room.[6,7] Gillaspie *et al*.[8] performed the

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imaging and 3D printing for the tumor induction therapy. They also created 3D models demonstrating anatomical features and physiological activity from the CT and positron emission tomography data.

The 3D-printed models are now boosting the confidence of surgeons as they are now refining their strategies and approaches before the actual operation. It has also increased the success rate of surgeries by reducing the potential for complications during the procedure. Each 3D-printed model accurately reflects an individual patient's anatomy, embodying the essence of personalized medicine. This high level of customization ensures that surgical plans are precisely tailored to each patient, taking into account their unique anatomical characteristics and specific needs. Equipped with the insights derived from 3D-printed models, surgeons are better prepared to conduct their procedures with accuracy and efficiency.[9,10]

The anxiety of surgery can melt away under the magic of 3D-printed planning. Quicker procedures and lower complication rates translate to less stress and faster journeys back to the peacefulness of a normal life. 3D-printed models also bridge the gap in communication between the surgeon, the patient's family, and other medical professionals. They serve as powerful visual aids, enabling surgeons to convey their surgical strategies with remarkable clarity, and helping families and health-care teams better understand the intricacies of the planned procedure.[11,12]

Numerous studies have described the pros and cons of the use of 3D printing in surgery. Martelli *et al*.[13] investigated the 20 domains for qualitative research to understand the advantages and disadvantages of 3D printing in surgical applications. Fused deposition modeling and selective laser sintering were commonly used printer types. Results from this study showed exceptional accuracy in creating guides and templates for preoperative planning.

Hoang *et al*.[14] conducted a systematic review identifying two main purposes of 3D printing. The first was for the creation of anatomical models that were useful in preoperative planning, simulation training, and surgical guides and to aid in identifying areas of resection. The second was for education based on patient-specific anatomy and as a substitute for dissection.

Another systematic review conducted by Tack *et al*.[12] identified 227 papers detailing the 3D printing application in surgery. Forty-five percent of studies in this systematic review showed that orthopedic surgery (knee, hip, shoulder, and hand) predominantly uses 3D printing applications compared to other surgical specialists.

Numerous studies have mentioned reduced operating room time, supporting this claim with numbers and statistics. In the study by Ballard *et al*.,[15] seven studies using 3D-printed anatomic models in surgical care demonstrated a mean time saving of 62 min per case, resulting in cost savings of $3720 per case. In addition, 25 studies of 3D-printed surgical guides demonstrated a mean time saving of 23 min per case, equating to cost savings of $1488 per case. The study also reported mean operating room time saved in various other types of surgeries: 85 min in endovascular aortic surgery,[16] 37 min in interventional cardiology procedures,[17] and 9 min in cardiothoracic surgery.[18]

Enhancing Surgical Education with Three-dimensional Printing

Beyond surgical planning, the integration of 3D printing technology has introduced innovative dimensions to medical education. Complex anatomical structures that were once confined to textbooks or digital screens can now be physically replicated, fostering a tangible learning experience that greatly benefits aspiring medical professionals.[19] Medical students and practicing surgeons alike can engage in hands-on learning using 3D-printed models, thereby bridging the gap between theoretical knowledge and practical application. This experiential learning enhances skill acquisition and fosters a deeper understanding of intricate surgical procedures.[20]

The technology enables the creation of intricate, patient-specific surgical scenarios, allowing trainees to navigate complex cases in a controlled environment. This dynamic educational approach cultivates critical thinking, decision-making skills, and adaptability in the face of surgical challenges.[21]

Jones *et al*.[22] conducted a survey involving 51 medical students and surgeons, revealing that an overwhelming 96% expressed a desire for models that could assist in explaining diseases to patients. In a study by Naftulin *et al*.,[23] patients and neurosurgeons were surveyed after interacting with 19 personalized 3D-printed brain and cranial specimens. Among the surveyed surgeons, 64% believed that the personalized brain specimens would be beneficial, while 53% of patients found them to be helpful or extremely helpful. The consensus among the authors of these studies indicated that 3D printing was perceived as a disruptive technology expected to see increased utilization in patient education, surgical planning, and enhancing the education of surgeons.

Challenges and Limitations

3D printing technology has made significant advancements in surgical planning, but it also comes with various challenges and limitations.

The study conducted by Shahrubudin *et al*.[24] delineated the challenges faced by biomedical industries utilizing 3D printing technology in their manufacturing processes. This research successfully pinpointed 12 primary challenges associated with the integration of additive manufacturing into the production of biomedical products. These challenges encompass concerns related to binder selection, suboptimal mechanical properties, diminished dimensional accuracy, pronounced powder agglomeration, nozzle size and distribution, restricted material options, considerations regarding texture and color, material longevity, the need for customized fit and design, layer height optimization, and the potential occurrence of build failures. Furthermore, the study also identified six additional hurdles in managing the manufacturing process of biomedical products through 3D printing technology, including the imperative need for staff reeducation, pricing strategies, the scarcity of comprehensive guidelines, cyber security vulnerabilities, marketing strategies, and issues surrounding patents and copyright protection.

Ensuring the accuracy and reliability of 3D-printed models is a critical concern. Variability in printing materials, technologies, and processes can potentially lead to discrepancies between the physical models and the patient's actual anatomy. Garcia *et al*.[25] note that the vast majority of printed models are made with hard materials, with only a few exhibiting some flexibility and elasticity. While hard materials are adequate for achieving anatomical fidelity, replicating models with tissue characteristics that closely resemble human pathological specimens has proven challenging. A meta-analysis of 158 studies from 2005 to 2015 highlighted several advantages of 3D printing, such as improved preoperative planning and time savings in the operating room. However, it also emphasized that accuracy was not satisfactory in 34 studies. Measurements using skull and mandibular models revealed incorrect or completely missing anatomy. In addition, deformations in 3D-printed dental surgical guides were reported. Such inaccuracies in 3D printing applications can lead to inappropriate treatments that could harm patients.[26] Given the well-known propensity of microorganisms to persist on inanimate surfaces, it is imperative to maintain a constant regimen of cleanliness and sterilization for the printer to eliminate any potential risk of material contamination, especially when utilizing the printer for transplantation purposes.[27]

Various types of 3D printers serve specific purposes, and it is crucial to understand your intended applications and material requirements before acquiring a 3D printer. Failure to do so may require the use of multiple types of printers within the institution, resulting in increased complexity and costs.[28]

Recent breakthroughs in 3D printing are addressing current limitations and expanding its potential. Continuous Liquid Interface Production by Carbon offers faster, higher-quality prints.[29] Material innovations include four-dimensional printing, which allows objects to change shape over time, and new metal alloys enhancing strength and durability.[30] Large-scale 3D printing is advancing with companies such as ICON and Apis Cor constructing buildings efficiently, while hybrid manufacturing systems combine 3D printing with traditional methods for complex parts.[31]

Bioprinting is advancing with the development of functional tissue and organ printing, including bioprinters capable of producing skin grafts.[32] Advances in resolution and precision are seen in multi-axis 3D printing and nanoprinting techniques. Sustainability efforts focus on recycled materials and biodegradable polymers. These innovations promise to overcome existing limitations and unlock new applications across industries.

Various materials are utilized in 3D printing, each with its own set of constraints and limitations. Different materials used in 3D printing and their limitations are listed in Table 1.[32]

Case Studies and Clinical Applications

Numerous real-world case studies demonstrate the pivotal role of 3D printing in optimizing surgical outcomes. From complex cardiac surgeries to intricate orthopedic interventions, these examples underscore the technology's impact on surgical precision and patient safety. In-depth case analyses reveal how 3D printing can mitigate risks, enhance procedural success, and contribute to postoperative patient satisfaction.[5]

In the realm of orthopedic oncology, 3D-printed models play a pivotal role by enabling direct visualization through the creation of bone and tumor models. Orthopedic surgery stands out as the primary field actively utilizing 3D printing due to its focus on hard tissues such as bones and joints, which align well with 3D printing capabilities. This technology is instrumental in crafting various orthopedic implants, including customized hip and knee replacements, and in aiding surgeons with precise guidance for intricate procedures.[33]

The United States has taken the lead in leveraging 3D printing for surgical planning across diverse medical specialties. In critical fields such as those involving brain surgeries, custom-made 3D printed models engaging the particular needs of the patients have increased the accuracy of planning and implementation of these tricky craniofacial surgeries by leaps and bounds.[34]

The latest released data from the United States on surgical outcomes emphasized the keen impact of 3D printing. Cardiac surgeons have effectively utilized 3D-printed models to simulate and refine complex procedures, resulting in improved patient outcomes. Moreover, intricate pediatric surgeries have been meticulously planned with the assistance of 3D-printed models, leading to shorter hospital stays and enhanced recovery rates.[35]

Technological Advances and Innovations

The field of 3D printing is rapidly evolving, with continuous innovations in materials and techniques.[33] From biocompatible materials to enhanced printing resolutions, these advancements continually elevate the capabilities of 3D printing in surgery. The combination of 3D printing and virtual reality (VR) technologies holds immense promise. Combining 3D-printed anatomical models with immersive VR environments offers an unprecedented platform for surgical training, planning, and collaboration.[36]

The integration of 3D printing technology into surgical planning and education has ushered in a new era of precision, comprehension, and experiential learning. This study delved

Table 1: Materials used in three-dimensional printing, limitations, and common laboratory/field of use

Material type	Limitations	Common laboratory/field of use
PLA	Limited heat resistance, not suitable for high-temperature applications	Prototyping, educational laboratories, hobbyist 3D printing
ABS	Prone to warping, emits fumes during printing, and requires good ventilation	Industrial design, automotive, aerospace, and engineering laboratories
PETG	Not as stiff as some other materials, may be prone to stringing	Medical device prototyping, food-safe applications, consumer goods
Nylon	Requires careful drying, susceptible to moisture absorption	Custom tooling, functional prototypes, aerospace research
TPU	Lower print speed may require specialized equipment	Flexible parts in robotics, wearable technology, and footwear research
Metal (e.g., aluminum and titanium)	High cost, often requires postprocessing for smooth surfaces	Aerospace engineering, automotive industry, and advanced manufacturing laboratories
Wood-based filaments	Limited strength and durability, can be prone to clogging	Art and design schools, decorative applications, architectural models
Carbon fiber	Abrasive to nozzles, may require hardened components in the printer	Aerospace, automotive, and high-performance sports equipment development

PLA: Polylactic acid, ABS: Acrylonitrile butadiene styrene, PETG: Polyethylene terephthalate glycol, TPU: Thermoplastic polyurethane, 3D: Three-dimensional

further into the multifaceted dimensions of 3D printing's applications, benefits, challenges, and prospects in the realm of surgery.[37] In the United States, continuous research and development in 3D printing materials and techniques have accelerated the integration of this technology into surgical practice. Biocompatible materials have gained prominence, ensuring that printed implants seamlessly integrate with the patient's body. The United States has witnessed a convergence of 3D printing and VR technologies, creating immersive surgical planning environments. Surgeons can now interact with 3D-printed models in VR, allowing for a comprehensive exploration of anatomical structures and the practice of intricate procedures [Table 2].[38-46] Table 2 shows 3D printing advancements in the USA: Cleveland Clinic develops customizable prosthetics, patient-specific training models, and controlled drug delivery systems. Birmingham creates new surgical techniques for cardiovascular conditions. Harvard has 3D-printed microsurgery robots. MIT produces realistic surgical training simulations. Stanford develops precise surgical guides. Mayo Clinic performed a complete facial reconstruction using 3D printing. Wake Forest transplanted a 3D-printed ear in 2022.[40-46]

Ethical and Regulatory Considerations

The utilization of 3D models in surgical planning necessitates rigorous ethical considerations, particularly regarding patient consent and privacy. Patients should be fully informed about the use of their medical data for 3D printing and must grant explicit consent for its application in their care. Safeguarding patient privacy, both in terms of data security and confidentiality, becomes paramount when dealing with sensitive medical information. Adherence to established medical standards and regulatory guidelines is essential in ensuring the safety and efficacy of 3D printing in surgery. Medical devices and implants produced through 3D printing must meet rigorous quality and safety standards, akin to traditional medical devices, to guarantee patient well-being and health-care provider liability.[46]

Regulatory bodies worldwide are facing challenges in addressing the complexities of 3D bioprinting technology and its associated potential risks. There remains uncertainty regarding how to effectively manage and regulate this evolving technology. In the United States, the Federal Drug Administration (FDA) currently lacks specific regulations about biological, cellular, or tissue-based products integrated into 3D printing processes. The FDA's Technical Considerations for Additive Manufactured Devices from 2016 exclude these products, recognizing that they may require different regulatory pathways and additional considerations in manufacturing processes.

Similarly, Australia's Therapeutic Goods Administration (TGA) is in a phase of evolution to keep pace with rapidly advancing combination technologies. Presently, there is a lack of tailored regulation or guidance worldwide for 3D-printed products. However, within Australia, the existing Therapeutic Goods Act of 1989 allows for some flexibility. The TGA is exploring whether this current legislation can effectively accommodate the evaluation of innovative therapies, including those involving 3D printing, without necessitating entirely new laws.[47,48]

Future Directions and Potential

The potential applications of 3D printing in surgery are far from exhausted. Future directions may involve the development of bioactive materials for 3D-printed implants, the integration of artificial intelligence (AI) for automated surgical planning, and the expansion of 3D printing into regenerative medicine, among others. Exploring these untapped potentials holds promise for groundbreaking advancements in patient care. The utilization of patient-specific 3D models of the mitral valve could significantly impact our capacity to identify suitable candidates for structural heart therapy. It also allows us to foresee potential

Table 2: Three-dimensional printing technology advances at the different institutes in the USA

Institution	3D printing technology advances
Cleveland Clinic	Developing 3D-printed prosthetics and implants that are more customizable and comfortable for patients
	Using 3D printing to create patient-specific training models of patient's organs and tumors to help surgeons plan complex procedures
	Developing 3D-printed drug delivery systems that can release medication at a controlled rate
Birmingham	Researchers are using 3D printing to develop new surgical techniques for treating complex cardiovascular conditions
Harvard University	Harvard scientists have developed 3D-printed robots that can perform microsurgery on the eye and brain
MIT	MIT researchers have developed a 3D printing process that can be used to create realistic simulations of human tissues and organs for surgical training
Stanford University	Developing 3D-printed surgical guides that can be used to perform complex procedures with greater accuracy and precision
Mayo Clinic Hospital	Surgeons at the Mayo Clinic in Minnesota have performed a complete facial reconstruction of a 32-year-old male using 3D printing
Wake Forest Institute for Regenerative Medicine	In 2022, a team of surgeons successfully transplanted a 3D-printed ear into a 20-year-old woman

MIT: Massachusetts Institute of Technology, 3D: Three-dimensional

procedural complications and has the potential to refine and enhance the plethora of intracardiac devices rapidly emerging for therapeutic purposes. However, before initiating 3D printing, it is crucial to account for the material characteristics of both healthy and diseased native cardiac structures, if available. This consideration is essential for approximating a similar static performance in the printed models.[4]

Creating functional vascular networks within 3D-printed organs remains a formidable challenge. Future innovations in vascularization techniques, such as 3D printing with bioactive factors or microfluidic channels, may address this limitation, making it possible to fabricate larger and more intricate organs. 3D bioprinting has the potential to usher in an era of personalized medicine, where we can create patient-specific tissues and organs for transplantation. This shift could significantly reduce rejection rates and improve patient outcomes.[44] The evolution of 3D printing in surgery is anticipated to be marked by increased affordability, accessibility, and customization. 3D printing will likely become an integral part of routine surgical procedures, with advancements in materials and techniques further enhancing its utility. In addition, merging 3D printing with telemedicine and remote surgery may redefine the geographical boundaries of surgical expertise.[49] The future of 3D printing in surgery extends beyond the confines of conventional practice. From drug testing to the creation of complex organs, this technology is poised to redefine health care, offering innovative solutions to age-old challenges and opening doors to unprecedented possibilities in medicine, pharmaceuticals, and cosmetics.[50,51]

Emerging trends and recent developments indicate promising avenues for growth. Here are some enhanced insights into future directions:

Bioactive materials

The development of bioactive materials compatible with 3D printing holds immense promise. These materials have the potential to create implants that not only perfectly fit to patient's body but also seamlessly engage with it, enabling quicker healing and lowering the chances of rejection.[52]

Artificial intelligence integration

3D printing process integration in the AI world enhances automation and precision in surgical planning. AI algorithms can assist in optimizing surgical strategies and predicting outcomes, further reducing the potential for complications.[53]

Regenerative medicine

3D printing's synergy with regenerative medicine offers an exciting frontier. The ability to print patient-specific tissues and organs for transplantation could revolutionize health care, potentially eliminating long waiting lists and improving patient outcomes.[54,55]

Global accessibility

Efforts to make 3D printing more affordable and accessible will likely democratize its use. This may enable surgeons worldwide to harness its power, benefiting patients in underserved regions, and expanding the reach of advanced surgical procedures.[56]

Telemedicine and remote surgery

Merging 3D printing with telemedicine and remote surgery could redefine geographical boundaries in surgical expertise. Surgeons may collaborate across continents, performing complex procedures with the aid of 3D-printed models and real-time guidance.[57]

Collaboration between Medical and Engineering Fields

Successful implementation of 3D printing in surgery hinges on robust interdisciplinary collaboration between the medical and engineering fields. Surgeons, researchers, and engineers must collaborate closely to align technology with clinical needs, ensuring that 3D-printed solutions are both effective and safe.[58] Doctors, as end-users, provide invaluable insights into the practical utility of 3D-printed models and devices. Researchers drive innovation by exploring novel applications and materials, while engineers bring technical expertise to refine printing techniques and ensure compliance with medical standards. The convergence of these disciplines fosters holistic solutions.[59]

Here are some specific examples of successful collaborations between the medical and engineering fields in 3D printing:

- The Cleveland Clinic and Case Western Reserve University are collaborating to develop new 3D-printed implants and surgical guides for a variety of medical procedures[60]
- The University of Birmingham and the Birmingham Women's Hospital are collaborating to develop 3D-printed scaffolds for tissue engineering applications[61]
- Harvard University and the Massachusetts General Hospital are collaborating to develop 3D-printed robots that can perform surgery.[62]

Conclusion

3D printing technology in surgery is a catalyst for transformative innovation, poised to redefine the landscape of health care. Its continuous evolution promises improved surgical precision, enhanced patient outcomes, and streamlined medical education. However, ethical considerations, regulatory compliance, and interdisciplinary collaboration are paramount for its responsible utilization.

The future of 3D printing in surgery remains promising, with ongoing developments in bioactive materials, AI integration, and regenerative medicine. Increasing affordability, accessibility, and customization will make 3D printing an integral component of routine surgical procedures, benefiting patients and the medical community alike.

In essence, 3D printing is not merely a tool but a driving force propelling the future of surgery toward unprecedented heights. Embracing its potential assures a future where surgical practices are more precise, efficient, and patient-centered, with 3D printing leading the way.

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