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Transformative applications of 3D printing in cardiac surgery: Implants, simulation, and personalized models

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ABSTRACT

Three-dimensional (3D) printing has become a transformative technology in cardiac surgery, advancing personalized care and surgical precision. By generating patient-specific anatomical models from imaging data, it provides detailed insights into cardiovascular structures that conventional imaging, such as CT and echocardiography, cannot fully capture. Procedures like transcatheter aortic valve replacement (TAVR) and left atrial appendage occlusion (LAAO) benefit significantly from these models by facilitating preoperative simulations that optimize device selection and minimize surgical risks. In addition to static models, dynamic 3D models have expanded the utility of this technology. With mock circulatory systems replicating blood flow and valve dynamics, these models provide a functional simulation environment, improving the accuracy of surgical planning and device testing. These developments mark a shift toward functional models that bridge the gap between imaging and clinical outcomes. However, the adoption of 3D printing faces challenges, including high production costs, regulatory hurdles, and the need for specialized expertise to design and operate advanced systems. Additionally, the time-consuming nature of printing and post-processing limits its applicability in urgent cases. Further research is needed to develop models that better replicate real-time cardiovascular conditions. Looking ahead, the integration of AI and robotics with 3D printing offers substantial potential. AI automates model generation, reducing time and human error, while robotic systems guided by 3D models enable more precise, minimally invasive interventions. As these technologies evolve, they will further enhance personalized cardiac care, improving surgical outcomes and patient safety. In conclusion, with ongoing innovation, 3D printing is set to become an essential tool in cardiac surgery, driving advancements in planning, education, and patient care.

KEYWORDS

Cardiovascular system; Echocardiography; Atrial appendage; 3D printing; Anatomical models

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Introduction

Three-dimensional (3D) printing, initially developed for orthopaedic and maxillofacial applications, has expanded into various medical fields, including cardiology. Introduced over 30 years ago, the technology was first used to produce surgical guides and implants. As advancements progressed, 3D printing enabled the creation of patient-specific anatomical models, offering new opportunities to visualize complex structures, improve surgical planning, and enhance education [1]. Cardiovascular interventions particularly benefit from this shift due to the heart's complex anatomy, which traditional imaging techniques cannot fully capture. In cardiology, 3D printing offers unique advantages over conventional diagnostic tools such as CT and echocardiography. While these tools provide detailed images, they lack the tactile feedback and spatial depth necessary for complex surgical planning. By creating patient-specific models, 3D printing facilitates better visualization of pathologies and anatomical relationships, leading to clearer preoperative strategies and improved outcomes [2]. These models are especially valuable in managing congenital heart disease (CHD), valvular disorders, and aortic aneurysms, where accurate anatomical representation aids in selecting appropriate interventions.

Recent studies highlight the successful application of 3D printing in cardiac surgeries, such as transcatheter aortic valve replacement (TAVR) and left atrial appendage occlusion (LAAO). These models assist in simulating surgeries, predicting complications, and improving patient-specific decision-making. Dynamic models capable of hemodynamic testing further expand 3D printing's potential beyond static anatomical models [3].

Despite its promise, the adoption of 3D printing faces challenges. Producing precise, functional models is time-consuming and costly, limiting accessibility. Additionally, static models do not replicate the physiological conditions required for real-time surgical environments. A key research gap lies in developing dynamic, functional models that simulate blood flow and valve dynamics [4]. Addressing this limitation could significantly improve personalized cardiovascular care. This review explores the transformative role of 3D printing in cardiac surgery, focusing on its use in implant development, personalized models, and emerging technologies. It highlights achievements, challenges, and future directions, providing insights into how 3D printing can revolutionize cardiac care [5].

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Current Applications of 3D Printing in Cardiac Surgery

Preoperative planning and simulation

Preoperative planning is one of the most impactful applications of 3D printing in cardiac surgery. By converting imaging data from CT, MRI, or echocardiography into physical models, surgeons can visualize complex cardiovascular structures with unprecedented clarity. These patient-specific models allow clinicians to explore anatomical relationships, test surgical approaches, and predict potential complications before entering the operating room [6] .

In particular, TAVR and LAAO have benefited from the use of 3D printing. TAVR procedures, which replace the aortic valve through minimally invasive techniques, rely heavily on precise preoperative assessments. 3D models assist in visualizing the patient's valve anatomy, helping to select the correct prosthesis size and ensuring optimal device fit to reduce complications like paravalvular leaks or coronary artery obstruction. Similarly, for LAAO, patient-specific 3D models enable the simulation of device deployment, ensuring proper placement to prevent stroke while minimizing procedural risks [7] .

These models also play a crucial role in intraoperative guidance. Surgeons use the models to orient themselves in real time, particularly in minimally invasive procedures where anatomical landmarks are less visible. Additionally, the tactile nature of 3D models improves surgeon-patient communication, facilitating discussions about treatment options and fostering patient trust. Through these applications, 3D printing not only enhances surgical precision but also reduces operative times and improves patient outcomes, making it an invaluable tool for complex cardiovascular interventions [8].

Implants and device manufacturing

3D printing has revolutionized the development of personalized implants and cardiovascular devices. Traditional manufacturing methods produce standardized implants, which can lead to suboptimal fit and increased postoperative complications. In contrast, 3D printing allows for the creation of patient-specific devices, such as customized stents and heart valves, tailored to fit individual anatomies [9].

For example, biocompatible heart valves manufactured with flexible materials like TangoPlus closely replicate the mechanical behavior of native valves, improving durability and functionality. Personalized stents designed with precise anatomical measurements ensure better vascular support, minimizing the risk of restenosis or device migration. Moreover, 3D printing shortens the design-to-production cycle, allowing for rapid prototyping and testing of new device designs, which accelerates innovation and improves patient care outcomes [10].

The use of additive manufacturing also reduces production costs by minimizing waste and enabling quick adjustments to device specifications. This makes it possible to produce small batches of personalized devices, that address the needs of patients with rare or complex conditions. As a result, 3D printing is helping healthcare providers deliver more precise, effective, and patient-centered cardiovascular treatments [11] .

Medical training and education

The integration of 3D printing into medical education has significantly enhanced the training of surgeons and other healthcare professionals. Traditional teaching methods, relying on 2D images and cadavers, often fail to convey the complexities of cardiovascular anatomy. In contrast, 3D-printed models provide tactile, life-like representations of heart structures, improving spatial understanding and manual skills among trainees [12]. Simulation training using 3D models allows medical professionals to practice complex procedures such as valve replacements or congenital defect repairs in a risk-free environment. These models help trainees develop the technical competence and confidence needed for real-world surgical scenarios. Hospitals and universities are increasingly adopting 3D printing for simulation labs and preoperative training, contributing to better patient safety by reducing surgical errors and shortening procedural times [13] . Beyond training, 3D models are also valuable for doctor-patient communication. By visually explaining disease conditions and treatment plans, clinicians can improve patient understanding, leading to better adherence and treatment outcomes. This dual benefit of enhanced education and improved communication makes 3D printing a powerful tool in modern cardiology [14]. Table 1 shows the different types of 3D printing techniques used in cardiology.

Table 1. Types of 3D printing techniques used in cardiac surgery.

3D Printing Technique	Description	Materials Used	Advantages	Limitations	Applications in Cardiac Surgery
Stereolithography (SLA)	Uses a laser to cure liquid resin layer by layer into a solid object.	Photopolymer resins	High resolution, smooth surface finish, ideal for fine details.	Fragile materials, requires post-curing, limited to small models.	Precise anatomical models for surgical planning.
Selective Laser Sintering (SLS)	Fuses powder material using a laser to build objects layer by layer.	Polymers, metals	Strong, durable parts, no need for support structures.	Rough surface finish, expensive machinery.	Durable, functional implants like custom stents and heart valves.

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PolyJet Printing	Sprays multiple liquid photopolymer materials simultaneously, cured with UV light.	Flexible and rigid photopolymers	Multi-material printing with high detail and color accuracy.	Fragile materials, limited to small models.	Models mimicking heart valves and tissues with various textures.
Fused Deposition Modeling (FDM)	Extrudes thermoplastic filament through a heated nozzle to build layers.	PLA, ABS, PEEK, other thermoplastics	Cost-effective, easy to use, good for educational models.	Lower resolution, less detailed, weaker in mechanical properties.	Simple anatomical models for medical education and training.
Electron Beam Melting (EBM)	Uses an electron beam to melt metal powder layer by layer in a vacuum.	Titanium, cobalt-chrome	Produces strong, biocompatible metal parts, ideal for implants.	High cost, limited material choices, slow process.	Manufacturing of biocompatible heart valve components.
Digital Light Processing (DLP)	Similar to SLA but uses a digital projector to cure resin layers faster.	Photopolymers	Faster than SLA, high detail, good surface finish.	Limited material choices, requires post-processing.	Patient-specific anatomical models for procedural rehearsals.
Binder Jetting	Deposits a binding agent onto powder material to create parts.	Sand, metal, and polymer powders	Large build volume, cost-effective for complex shapes.	Lower strength, requires post-processing.	Prototypes of surgical devices for testing and validation.
Multi-Jet Fusion (MJF)	Uses a fusing agent and detailing agent with powder material for fine details.	Polyamides	High strength, accurate parts, minimal waste.	Requires cooling time, limited material availability.	Custom surgical instruments and prototypes.
Bio-printing	Prints layers of bio-inks containing living cells to create tissue-like structures.	Hydrogels, living cells	Potential for creating functional tissues, customized organ models.	Limited by current technology, challenges with cell viability.	Research into heart tissue models and artificial cardiac tissues.

Technological Advances and Challenges

Advances in printing materials and techniques

Significant advancements in printing materials and techniques have expanded the applications of 3D printing in cardiac surgery. The introduction of flexible materials, such as TangoPlus and Visijet CE-NT, allows for the creation of models that closely mimic the mechanical properties of cardiovascular tissues. These materials enhance the ability to develop dynamic heart models that replicate tissue elasticity, which is essential for simulating physiological conditions like blood flow and valve movement [15].

Multi-material printing, enabled by polyjet printing technologies, allows the integration of different materials with varying hardness and color into a single model. This capability provides detailed representations of complex structures, such as calcified lesions and valve abnormalities. These dynamic models can simulate cardiac function, such as valve opening and closing, improving preoperative assessments and planning. Additionally, stereolithography (SLA) printers, known for their high resolution, enable the production of intricate heart models with smooth surfaces, aiding in precise surgical simulations and device testing [16] .

Future Directions

Dynamic 3D models and simulated environments

The development of dynamic 3D models marks a significant advancement in cardiac surgery, providing more than just anatomical representations. These models simulate real-time physiological behavior, such as pulsatile blood flow and valve

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dynamics, offering a more accurate environment for preoperative planning and device testing. Coupled with mock circulatory systems, these models allow clinicians to replicate complex conditions, enhancing surgical strategies for procedures like valve replacements and transcatheter interventions [17].

The integration of materials like TangoPlus has improved elasticity, allowing heart valves and vessels to mimic native tissue movement. This level of realism enables testing of device behavior under near-physiological conditions, ensuring better predictions of surgical outcomes. By improving the accuracy of preoperative planning, dynamic models help clinicians minimize complications and reduce operative time. The future development of such models will bridge the gap between imaging data and clinical outcomes, enhancing the precision of complex cardiac interventions [18].

Integration with AI and robotics in cardiac surgery

The convergence of AI technologies and robotics with 3D printing is transforming cardiac surgery, enhancing precision and efficiency. AI-driven segmentation tools streamline the creation of patient-specific 3D models by automating the extraction of anatomical structures from imaging data. This reduces both human error and processing time, ensuring the production of more accurate models for surgical planning [19]. Surgical robotics, integrated with AI-enhanced models, enable real-time guidance during procedures. Systems like the Da Vinci Surgical System can utilize preoperative 3D models to plan incision paths, improving precision and reducing intraoperative risks. Machine learning algorithms further refine surgical outcomes by analyzing large datasets, predicting potential complications, and personalizing surgical strategies. As AI continues to evolve, it will enhance the utility of 3D printing by enabling predictive modeling of patient-specific outcomes, further advancing personalized medicine. The combined power of AI, robotics, and 3D printing will revolutionize the way complex cardiovascular surgeries are planned and executed [20]. Table 2 explains the comparison between conventional implants and 3D-printed implants used in cardiac surgery.

Table 1. Comparison of Conventional vs. 3D-Printed Implants in Cardiac Surgery.

Parameter	Conventional Implants	3D-Printed Implants
Manufacturing Process	Mass-produced using casting, molding, and machining.	Additive manufacturing using CAD models and layered printing.
Customization	Limited customization with standard sizes and shapes.	Highly customizable to fit patient-specific anatomy.
Production Time	Longer lead times due to tooling and molding.	Shorter lead times with rapid prototyping.
Cost	High costs for custom implants due to retooling.	Initial setup can be expensive, but cost per unit decreases with volume and customization.
Fit and Comfort	May result in suboptimal fit leading to discomfort or complications.	Precise fit to individual patient's anatomy, improving comfort and clinical outcomes.
Material Selection	Limited to metals and polymers used in conventional processes.	Diverse materials including biocompatible polymers, metals, and composites.
Risk of Complications	Higher risks of complications such as migration or rejection.	Lower risks of migration and better biocompatibility due to precise design.
Durability	Reliable but with potential wear and tear over time.	Comparable or enhanced durability with materials mimicking native tissues.
Design-to-Production Time	Lengthy process requiring multiple manufacturing stages.	Rapid design-to-production with fewer intermediate steps.
Patient-Specific Adjustments	Requires extensive preoperative assessment and modifications.	Adjustments are incorporated during design, reducing intraoperative changes.
Device Innovation	Limited flexibility for iterative designs.	Allows for rapid prototyping and iterative improvements.
Waste and Environmental Impact	Higher waste due to excess material in machining.	Minimal waste as only required material is used in printing.
Regulatory Approval	Well-established regulatory pathways.	Emerging regulatory frameworks; longer approval times expected.
Examples of Use	Standard heart valves, generic stents, pacemaker components.	Customized stents, patient-specific valves, and anatomical models for testing.
Availability	Widely available due to established production lines.	Limited availability; requires specialized 3D printing facilities.

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Conclusions

The integration of 3D printing into cardiac surgery offers numerous benefits, significantly advancing personalized medicine and surgical precision. Patient-specific models have proven invaluable for visualizing complex cardiovascular anatomy, enabling physicians to simulate interventions and optimize preoperative planning. Procedures such as TAVR and LAAO benefit greatly from these models, as they allow precise decision-making and reduce intraoperative risks. Furthermore, dynamic models capable of mimicking physiological conditions enhance device testing and improve predictions of surgical outcomes.

Despite these advancements, several challenges limit the widespread adoption of 3D printing in clinical practice. High production costs, regulatory hurdles, and the need for specialized expertise to operate advanced printing systems pose significant barriers. Additionally, the lengthy time required for model production and post-processing can delay surgical procedures, limiting the technology's application in urgent cases. The absence of fully dynamic models that accurately replicate in vivo conditions remains another limitation, underlining the need for further research into mock circulatory systems and advanced materials that better simulate real-time cardiovascular behaviour. Looking ahead, the convergence of AI and robotics with 3D printing presents a transformative opportunity. AI can automate the segmentation of imaging data, improving both the accuracy and speed of model preparation while minimizing errors. Robotic surgery systems integrated with 3D models provide real-time guidance, enabling precise, minimally invasive procedures with reduced risk of complications. As AI evolves, predictive algorithms will further refine personalized surgical strategies, enhancing outcomes and advancing patient care.

In conclusion, 3D printing is poised to revolutionize cardiac surgery, offering substantial benefits in planning, device development, and education. However, addressing current limitations such as production delays, high costs, and regulatory challenges will be crucial to achieving seamless clinical integration. With continued innovation, 3D printing will undoubtedly play a pivotal role in shaping the future of patient-centered cardiovascular care.

Disclosure statement

No potential conflict of interest was reported by the authors.

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