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Advancements in Three-Dimensional Printing Technology: Implications for Radiological Assessment and Management of Cardiovascular Diseases

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Abstract

Background: The advent of three-dimensional (3D) printing technology has markedly transformed medical practice, particularly in the field of cardiovascular diseases. 3D printed models facilitate better understanding and management of complex anatomical structures, enabling personalized treatment strategies.

Methods: This review synthesizes recent literature on the application of 3D printing in cardiovascular medicine, focusing on its utility in congenital heart disease (CHD) and other cardiovascular disorders. A comprehensive search was conducted across multiple databases to identify case reports, systematic reviews, and randomized controlled trials (RCTs) that highlight the efficacy of 3D printed models in preoperative planning, education, and clinical outcomes.

Results: The findings reveal that 3D printed models significantly enhance surgical planning and intraoperative navigation, particularly in CHD cases. Evidence from systematic reviews indicates improved educational outcomes for medical students and residents, as well as enhanced communication between healthcare providers and patients. However, the current literature is predominantly comprised of case studies and lacks extensive multicenter RCTs, limiting broader applicability.

Conclusion: 3D printing represents a burgeoning frontier in cardiovascular medicine, demonstrating substantial potential for improving surgical precision and patient outcomes. Future research should aim to address existing limitations, including cost-effectiveness and the development of dynamic models that accurately replicate physiological conditions. As technology advances, 3D printing could become integral to routine clinical practice in managing cardiovascular diseases.

Keywords: 3D Printing, Cardiovascular Diseases, Congenital Heart Disease, Surgical Planning, Medical Education.

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1. Introduction

Despite being an established technology, three-dimensional (3D) printing has seen significant advancements in the last decade, with a growing body of research highlighting its therapeutic efficacy across all domains. Patient-specific or customized 3D printed models precisely duplicate normal anatomical features and diseases, therefore functioning as a significant resource in medical applications, including orthopaedics, maxillofacial surgery, cardiovascular illness, and tumors [1-10]. Three-dimensional printed physical models provide valuable insights for pre-operative planning and simulation of intricate surgical procedures, teaching of medical students and residents, intraoperative navigation, and communication between physicians and patients [8-14].

In these applications, evidence of 3D printed models is mostly comprised of case reports and case series, but multi-centre studies and randomized controlled trials (RCTs) are being reported with increasing frequency in the literature [15-20]. 3D printed models enhance physicians' confidence in addressing various clinical scenarios by facilitating a better comprehension of the intricate spatial relationships between normal anatomy and diseases, which standard imaging techniques cannot effectively convey. As interest in 3D printing within the medical community increases, guidelines are emerging regarding its appropriate application in medical contexts, as endorsed by various organizations, including the Radiological Society of North America (RSNA) 3D Printing Special Interest Group and the newly established Society for Cardiovascular Magnetic Resonance (SCMR) 3D Working Group. Therefore, it is essential to comprehend the therapeutic significance of 3D printing and its possible constraints.

The review paper seeks to provide an overview of 3D printed models in medical applications, particularly emphasizing their significance in cardiovascular illness, since their clinical uses in orthopaedics and maxillofacial fields are well documented and validated in the literature [23-25]. This study discusses the use of 3D printed models in establishing ideal computed tomography (CT) scanning settings for cardiovascular disease and emphasizes future research areas.

2. Procedure for Generating 3D Segmentation Volume Data for 3D Printing

The first and crucial stage in generating a 3D printed model is to get high-quality imaging data, mostly volumetric pictures from computed tomography (CT) or magnetic resonance imaging (MRI), but ultrasound or invasive angiography images are also used in some studies for 3D printing [11-13]. Volume datasets first undergo a sequence of picture post-processing and segmentation procedures (either automated or semi-automatic) to eliminate extraneous or unnecessary structures while preserving the areas of interest for 3D printing. Semi-automatic or manual editing is often required to retain just the anatomical features intended for 3D printing.

The physical model may be fabricated using various materials, contingent upon many aspects, including clinical objectives and specifications, the availability of 3D printers and printing materials, and related expenses. Readers are directed to many review papers that provide a comprehensive overview of 3D printing methods and 3D printed models using various printing materials [11-14,26]. This section on bioprinting will address several materials used in the printing of cardiovascular tissues, focusing on their mechanical qualities and biocompatibility (Figure 1).

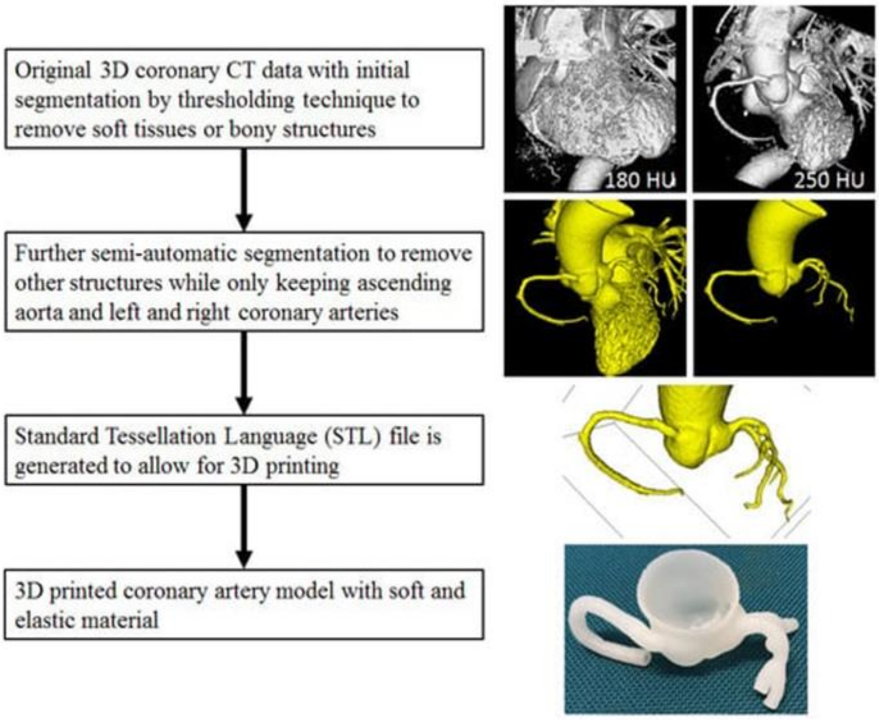

Figure 2. Procedure for producing a 3D printed model from the segmentation of original coronary CT volumetric data, culminating in the development of segmented data that only includes areas of interest (namely the coronary artery tree and ascending aorta in this instance) and an STL file for 3D printing.

3. Clinical Utilization of 3D Printing in Cardiovascular Disorders

3D printing has shown significant potential in several medical applications, contingent upon the location, nature, and severity of diseases. In the field of tumor detection and treatment, its use mostly focuses on pre-surgical planning and simulation or intraoperative navigation to direct surgical operations, therefore enhancing results and minimizing problems [14,27,28]. In the domain of cardiovascular disease, specifically congenital heart disease, the clinical utility of 3D printing emphasizes the education of medical students, junior doctors, and residents, enhances physician-patient communication, and bolsters the confidence of cardiologists and cardiac surgeons in managing intricate cardiac conditions [10-13,26]. 3D printing is advantageous for the development of medical devices in the management of aortic or valvular illnesses [26-32]. The following sections examine the therapeutic utility of 3D printing in each specialized domain, as informed by the existing research.

4. Three-Dimensional Printing in Congenital Heart Disease

3D printing offers an exceptional perspective on intricate anatomical features, significantly contributing to the treatment of patients with congenital heart disease (CHD). The diagnosis and treatment of congenital heart disease (CHD) need a thorough comprehension of the intricate spatial relationships between normal cardiac architecture and pathology, while 3D printing represents a disruptive technology that has shown the potential to revolutionize existing practices in CHD care.

Accurate pre-surgical planning for congenital heart disease (CHD) may be facilitated by the use of 3D printed models, as shown by recent systematic reviews, meta-analyses, and several other research [13,33-40]. In the systematic review by Lau and Sun, out of 24 eligible papers, 15 reported on the use of 3D printed models in the pre-operative planning of congenital heart disease therapy, detailing how these models facilitated surgical planning and the surgeons' perspectives on their efficacy [13]. 3D printed models were determined to aid surgeons in identifying the optimal surgical strategy, particularly in difficult congenital heart disease instances such double outlet right ventricle (DORV) [13]. Recent research [41] indicates that personalized therapy strategies and optimal surgical options may be developed using patient-specific 3D printed models.

A prevalent use of 3D printing in congenital heart disease (CHD) pertains to its utility in medical education. This is seen in 50% of the studies within the same systematic review [13]. Among these research, four randomized controlled trials (RCTs) compare 3D printed models with conventional teaching techniques in congenital heart disease (CHD) for medical students and residents [16-18,42]. Although the study by Wang et al. revealed no significant enhancement in the 3D printing group relative to the control group [42], the other three studies demonstrated that 3D printed models were beneficial in the instruction and comprehension of complex congenital heart disease scenarios compared to the control group utilizing conventional teaching methods [16-18]. This aligns with earlier research indicating the effectiveness of 3D printed models in educating healthcare professionals, patients, or families [43-45].

Less often documented domains demonstrating the therapeutic use of 3D printing in congenital heart disease (CHD) including communication between physicians and patients or their guardians, as well as preoperative simulation. Although there are few studies with qualitative findings, the majority of participants agreed that 3D printed models enhanced communication between doctors and patients, as well as among doctors. Significant satisfaction was seen with the use of 3D printed models during patient consultations with physicians [17,36,43]. This underscores the supplementary function of 3D printed models in enhancing doctor-patient communication.

Pre-surgical simulation is the primary objective of surgical planning, as it facilitates the execution of intricate surgical procedures, resulting in enhanced patient treatment results. This is particularly beneficial for novice surgeons or younger physicians to rehearse surgical simulation techniques on 3D printed models, therefore establishing intracardiac pathways [46].

5. Three-Dimensional Printing in Structural Heart Disease and Cardiac Interventions

3D printed models possess significant utility in structural heart disease, particularly in interventional cardiology, by simulating cardiac interventions to assess the feasibility of procedures, select suitable devices, predict outcomes related to the procedure, and monitor post-procedural device deployment. 3D printed models have significantly contributed to the planning of therapy for valvular illness and left atrial appendage closure [47-49]. A comprehensive evaluation of 29 papers about 3D printing in heart valve illness indicates that the predominant use of 3D printing is preoperative planning for valvular disease (63%), followed by surgical training (19%) and device testing and development (11%) [50].

Wang and colleagues conducted a comprehensive analysis of 43 papers examining the use of 3D printed models in adult cardiovascular diseases addressed with surgical or catheter-based interventions [51]. Out of 43 research, the majority (35/43, 81%) focused on the therapeutic uses of 3D printed models in adult cardiovascular illness, particularly facilitating cardiovascular surgery and transcatheter therapies. In many clinical contexts, 3D printing has been identified as a valuable resource for preoperative planning and simulation in two prevalent cardiac conditions: left atrial appendage occlusion (LAAO) and transcatheter aortic valve replacement (TAVR). Among the 296 patients in these 35 investigations, 50% received LAAO, whereas 17.6% got TAVR [51]. Three-dimensional printed models were used for the simulation and training of aortic valvular disorders for the remaining eight students, enhancing surgical trainees' comprehension of the condition.

A further use of 3D printing is in the enhancement of preoperative TAVR planning, as shown by recent research highlighting the utility of 3D printed models for evaluating paravalvular leak (PVL) [52]. Thorburn et al. developed five 3D printed models including the aortic root, coronary ostium, and left ventricular outflow tract derived from cardiac CT scans. The printed models were linked to a closed pressure system to measure PVL after TAVR implantation. The quantity of PVL assessed in 3D printed models was compared to that identified using echocardiography in patients who had TAVR treatment. Their investigation demonstrated a substantial association between the paravalvular leak volume in 3D printed models and postoperative echocardiographic measures in patients [52]. This work underscores the prospective use of using 3D printed models to anticipate paravalvular leaks in patients undergoing TAVR; however, more research is required to explore other factors, including the assessment of various valve sizes and the positioning of the devices after implantation.

Haghiashtiani et al. enhanced the 3D printed aorta model by including an array of internal sensors into the aortic root, demonstrating the potential of dynamic features in the 3D printed models [53].

The use of 3D printed models in coronary artery disease (CAD) primarily serves to facilitate the management of intricate coronary abnormalities, as shown by case reports in the literature [54-57]. These single case studies demonstrated the efficacy of 3D printed coronary models in simulating interventional coronary procedures and in planning and guiding treatment strategies for complicated coronary disease. Another use of 3D printed coronary artery models is to enhance comprehension of cardiac abnormalities. In this investigation, Lee et al. chose eight patients, with one normal coronary artery and seven affected arteries exhibiting various coronary abnormalities [58]. Eight patient-specific coronary models were developed and presented to nine cardiovascular researchers and eight clinicians (comprising two cardiac surgeons and six cardiologists) to solicit their comments on the use of 3D printed models. Both groups reported that 3D printed models improved comprehension of coronary architecture and diseases, however the clinically experienced group said that 3D printed models are more beneficial than CT scans alone. This study indicated that 3D printed coronary models are beneficial in enhancing patient-physician communication by elucidating conditions to patients, facilitating preoperative planning for cardiac surgeons, and improving decision-making through multidisciplinary team collaboration by illustrating the diagnostic anatomy to clinicians.

A nascent research domain is using 3D printed coronary models to explore optimum coronary CT scanning techniques for the imaging of calcified plaques and the coronary lumen during coronary stenting. Recent investigations by Sun and colleagues have documented their experience with favorable outcomes attained with individualized coronary models [59-63]. High-resolution CT imaging enhances the visibility and evaluation of coronary lumen stenosis resulting from calcified plaques, hence corroborating prior results on the influence of spatial resolution on the diagnostic assessment of calcified coronary plaques [60]. Coronary CT angiography is extensively utilized for diagnosing CAD; however, its clinical utility in coronary stenting is contentious due to beam hardening artifacts produced by coronary stents, which adversely impact the precise evaluation of the coronary lumen, particularly in assessing in-stent restenosis. The research done by Sun and Jansen [63] used 3D printed coronary artery models using six distinct stent sizes to mimic coronary stenting. Scans performed on a state-of-the-art 192-slice CT scanner revealed that images rebuilt using a sharp kernel method significantly enhanced the visibility of the stent and stented lumen in comparison to those reconstructed using a conventional kernel technique. Thin slab maximum-intensity projection (MIP) pictures facilitated superior visibility of the stented lumen compared to thick slab MIP images. Three-dimensional volume rendering pictures provide distinct perspectives of the stent's position relative to the coronary architecture, as seen in Figure 9. These first observations, along with others, indicate the potential use of 3D printed coronary or cardiac models for examining optimum CT procedures; nevertheless, more research is required to substantiate these conclusions [59,62,63].

6. Constraints and Prospective Research Avenues

The aforementioned fields provide promising outcomes of 3D printing in cardiovascular applications; nonetheless, certain obstacles persist that impede its extensive use in clinical practice. There is a deficiency of prospective and multi-centre research, with randomized controlled trials (RCTs) limited to the use of 3D printing in congenital heart disease (CHD) for medical education. In contrast, case reports or case series constitute the majority (66%) of applications in other domains, as shown by a recent review article on 3D printing in CHD [64]. The inclusion of a larger sample size and potential longitudinal studies on mid to long-term outcomes is essential to validate the clinical efficacy of 3D printing, specifically regarding its impact on patient management and the significance of treatment outcome improvements when integrating 3D printing into practice. The elevated expenses represent a significant concern that must be resolved prior to the integration of 3D printing into standard clinical practice. As the costs of 3D printers and printing materials decrease, 3D printing will emerge as a viable method for both patients and physicians.

Despite the excellent precision and quality of 3D printed models, even using multicolored materials, the majority of existing models remain static, unable to exhibit realistic qualities akin to actual tissues. The generation of realistic and dynamic models is therapeutically significant for cardiovascular illness, since the simulation of hemodynamic blood flow in these three-dimensional cardiovascular models is essential for establishing an environment that accurately replicates actual physiological conditions. Recent research has established the dynamic mechanical characteristics of 3D printing materials in relation to coronary artery disease and coronary stents [65-67]. 3D printed bioresorbable stents fabricated from polymer materials like polylactic acid (PLA) or polycaprolactone (PCL) have excellent compatibility with blood and cells, making them suitable for the production of coronary stents for the treatment of coronary artery disease [68]. Guerra et al. fabricated 3D printed composite stents with PLA and PCL materials. They demonstrated that both PLA and PCL exhibit biocompatibility, with the PLA stent showing an average cell proliferation of 8.28% and PCL 12.46% after three days [67]. Nonetheless, each material had limitations: PLA exhibits a high modulus (signifying great elasticity and an outstanding recoil ratio) but has inadequate qualities for implantation, while PCL has a low modulus (indicating high stiffness and optimal radial expansion), hence limiting its suitability for stenting applications. Consequently, composite PCL/PLA stents were advocated since they enhance performance by mitigating the limits inherent to each material.

Despite considerable efforts by researchers to utilize 3D bioprinting technologies for the fabrication of hearts, blood vessels, heart valves, and cardiovascular constructs [64-71], the primary technological challenges in bioprinting involve the development of appropriate biomaterials (bioinks) that possess adequate mechanical strength and biocompatibility to align with the biological characteristics of native organs [72]. Bioprinting cardiovascular organs or cells is more complex since the bioprinted cells or stem cells must sustain proliferation and differentiation within a live extracellular milieu. Although existing bioprinters provide satisfactory resolution, enhancements are required to achieve high-precision printing of tiny vessels.

7. Synopsis

3D printing undoubtedly represents a rapidly expanding technology over recent decades, with a rising number of studies accessible across several medical sectors. The use of 3D printing in cardiovascular illness represents a significant advancement in medicine, considering the global prevalence of cardiovascular conditions and their accompanying morbidity and death rates. Customized 3D printed models transform the existing methodologies for planning and treating patients with various cardiovascular conditions, including congenital heart disease and acquired coronary, valvular, aortic, and pulmonary artery illnesses. These realistic physical models augment clinicians' comprehension of intricate pathological scenarios concerning adjacent structures and bolster their confidence in executing challenging procedures, thereby facilitating improved patient management with reduced surgical or procedural complications. 3D bioprinting is demonstrating a substantial influence on the advancement of 3D printing technology, shown by first outcomes in the fabrication of biocompatible cardiovascular tissues and structures. This article offers a summary of the therapeutic uses of 3D printing in several domains. Anticipating additional enhancements in 3D printing technology and developments in printing materials, we hope to see more encouraging outcomes in the literature and to witness the advantages of this approach for patient care and clinical practice.

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التطورات في تكنولوجيا الطباعة ثلاثية الأبعاد: آثارها على التقييم الإشعاعي وإدارة أمراض القلب والأوعية الدموية

الملخص

الخلفية:

أحدثت تكنولوجيا الطباعة ثلاثية الأبعاد تحولًا ملحوظًا في الممارسة الطبية، خاصة في مجال أمراض القلب والأوعية الدموية. تسهم النماذج المطبوعة ثلاثية الأبعاد في فهم وإدارة البُنى التشريحية المعقدة بشكل أفضل، مما يتيح استراتيجيات علاجية مخصصة.

المنهجية:

تجمع هذه المراجعة بين الأدبيات الحديثة حول تطبيق الطباعة ثلاثية الأبعاد في طب القلب والأوعية الدموية، مع التركيز على فائدتها في علاج أمراض القلب الخلقية وغيرها من الاضطرابات القلبية الوعائية. تم إجراء بحث شامل في قواعد بيانات متعددة لتحديد التقارير الحالتية والمراجعات المنهجية والتجارب العشوائية المُنضبطة (RCTs) التي تسلط الضوء على فعالية النماذج ثلاثية الأبعاد في التخطيط قبل الجراحة والتعليم والنتائج السريرية.

النتائج:

تشير النتائج إلى أن النماذج ثلاثية الأبعاد تُحسن بشكل كبير من التخطيط الجراحي والملاحة أثناء العمليات الجراحية، خاصة في حالات أمراض

القلب الخلقية. تُظهر الأدلة المستمدة من المراجعات المنهجية تحسنًا في النتائج التعليمية للطلاب والمقيمين في الطب، بالإضافة إلى تعزيز التواصل بين مقدمي الرعاية الصحية والمرضى. ومع ذلك، فإن الأدبيات الحالية تتكون في الغالب من تقارير حالات وتفتقر إلى التجارب العشوائية متعددة المراكز، مما يحد من إمكانية تطبيقها على نطاق أوسع.

الاستنتاج:
تمثل الطباعة ثلاثية الأبعاد مجالًا ناشئًا في طب القلب والأوعية الدموية، مما يظهر إمكانيات كبيرة لتحسين دقة الجراحة ونتائج المرضى. ينبغي أن تركز الأبحاث المستقبلية على معالجة القيود الحالية، بما في ذلك تحليل الفعالية من حيث التكلفة وتطوير نماذج ديناميكية تحاكي الظروف الفسيولوجية بدقة. مع تقدم التكنولوجيا، يمكن أن تصبح الطباعة ثلاثية الأبعاد جزءًا أساسيًا من الممارسة السريرية الروتينية في إدارة أمراض القلب والأوعية الدموية.

الكلمات المفتاحية:

الطباعة ثلاثية الأبعاد، أمراض القلب والأوعية الدموية، أمراض القلب الخلقية، التخطيط الجراحي، التعليم الطبي.