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Patient-Specific 3D Printing of Mitral Para-valvular Leaks Derived from 3D Transesophageal Echocardiography: A Narrative Review

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Abstract

Paravalvular leak (PVL) of the mitral prosthetic valve is a significant postoperative complication that arises when there is incomplete sealing between the prosthetic valve and the native annular tissue. Depending on the severity, it may lead to heart failure symptoms, haemolysis, and increased morbidity. Therefore, precise anatomical assessment is necessary for the best possible care. Since three-dimensional transoesophageal echocardiography (3D TEE) offers comprehensive details about the defects, including their location, geometry, size, and spatial relationship to neighbouring cardiac structures, it has emerged as the ideal imaging method for evaluating mitral PVL.Recent developments in three-dimensional printing technology have enabled the transformation of 3D TEE imaging datasets into patient-specific physical models. These models provide a realistic representation of complex paravalvular anatomy, allowing clinicians to better understand defect morphology and plan interventions more effectively. The use of 3D-printed models has demonstrated particular value in pre-procedural planning for transcatheter paravalvular leak closure, facilitating device selection, procedural simulation, and anticipation of technical challenges. In addition, these models enhance multidisciplinary communication and support patient counselling.Despite its potential, the widespread adoption of 3D printing is still constrained by issues including cost, processing time, and a lack of established standards. This narrative review highlights the role of 3D TEE in imaging mitral PVL, outlines the workflow for converting imaging data into printable models, and discusses the clinical benefits, current limitations, and future directions of 3D printing in the management of mitral paravalvular leaks.

Keywords: *Device selection; Mitral paravalvular leak; 3D printing; 3D Transesophageal echocardiograph.*

1. Introduction

Mitral valve replacement, established for advanced mitral valve disease, Iis among the most well-established treatments globally. The medical field utilizes the replacement due to its effectiveness particularly in cases where valve repair is not feasible. The treatment involves the implantation of a prosthetic valve, and the improved outcome of the patient reflects the medical community's idea of the connection between surgical advances and prosthetic valve design. The excellent and clinical mitral valve replacement contains various medical factors, such as surgical techniques and prosthetic design, as well as potential complications, for instance, paravalvular leak (PVL). Clinicians observe numerous elements of this condition, for instance, regurgitant blood flow occurring between the prosthetic valve sewing ring and the native annulus rather than through the prosthetic valve itself. It has been observed that the reported incidence of PVL after mitral valve replacement ranges from 7% to 17% although only a

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smaller proportion of cases become clinically significant and require intervention (1). Moreover, clinically important paravalvular leaks may lead to symptoms such as heart failure, hemolytic anemia, or infective endocarditis and they are associated with increased morbidity and mortality.Accurate detection and characterization of mitral PVL, essential for appropriate clinical management, is among the most vital diagnostic assessments globally. Medical practitioners utilize echocardiography due to its primary role in the evaluation of prosthetic valve function and the identification of paravalvular regurgitation (2). The process involves an initial assessment via transthoracic echocardiography, and the limited diagnostic accuracy of this method reflects the acoustic shadowing caused by prosthetic valve materials. The superior and detailed Transesophageal echocardiography (TEE) provides various visualizations of cardiac structures, as well as the benefits of three-dimensional transesophageal echocardiography (3D TEE), for instance, the precise localization of leaks and the evaluation of their size, morphology, and relationship with adjacent structures (3).Three-dimensional (3D) printing technology has recently become an important tool in cardiovascular medicine. 3D printing converts imaging data in computed tomography, magnetic resonance imaging or 3D Echocardiography modalities into physical cardiac models for patient-specific anatomical model production (4). These models offer clinicians a physical representation of intricate cardiac structures, providing aid in pre-procedural planning, device selection and procedural simulation. As an emerging application of 3D TEE datasets, 3-dimension print technology has shown promising value with potential for both understanding the anatomy of paravalvular defects in greater detail and optimizing tailoring interventions in terms of strategy.As structural heart interventions continue to gain popularity, the combination of advanced imaging modalities and patient-specific modeling is receiving greater scrutiny. Models that can be 3D printed and which are derived from 3D transesophageal echocardiography (3D TEE) may improve procedural planning and operator confidence (5).As a result of this, the objective of paravalvular leaks review is to summarize the available evidence regarding patient-specific 3D printing of mitral paravalvular leaks on three-dimensional transesophageal echocardiography with emphasis on clinical usefulness.

2. Method

This was a narrative literature review study intended to ascertain the contributions of three-dimensional (3D) printing from three-dimensional transesophageal echocardiography (3D TEE) in the appraisal and treatment of mitral paravalvular leaks. A systematic literature search was electronically carried out via databases like PubMed, Scopus and Google Scholar to recognize studies related to 3D printing and imaging of structural heart disease. The keywords used in the search strategy were Mitral paravalvular[1] leak, 3D Transesophageal echocardiography,3D printing, Device selection. Studies between 2009-2025 were examined so that both the early stages developments as well as latest trends on 3D echo imaging and additive manufacturing technologies will be covered.Eligible studies included original articles, clinical studies, case reports and review articles describing the use of 3D TEE[2] imaging, 3D image reconstruction or 3D printed cardiac models for evaluation or procedural planning in mitral paravalvular leak and related structural heart conditions. Articles not related to 3D imaging or 3D printing applications in cardiovascular medicine were excluded.Relevant publications were identified by reviewing titles, abstracts and followed by full text assessment to determine their relevance. Information[3] from the selected studies were extracted and summarized, focusing on imaging techniques, model generation processes, clinical applications, and potential benefits of 3D programmed models for procedural planning and devices selection. The findings were synthesized qualitatively to provide an overview of the current applications, advantages, and limitations with combining 3DTEE with 3D printing technology in mitral paravalvular leak management (1,3,5)

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3. Discussion

The literature highlights the importance of 3D TEE in the evaluation paravalvular leaks especially mitral paravalvular leak. Spatial resolution is much higher than that obtained by 2D echocardiography enhancing[4] visualization of prosthetic valves and their surrounding cardiac structures thus better defining the position, shape and extent of these lateral leaks for optimal diagnosis and management (6).In addition to refine imaging techniques, the utility of 3D printing has become increasingly relevant enabling clinicians to better appreciate and plan complex[5] cardiovascular anatomy or pathology in patients. Recent advances have shown that it is possible to convert cardiac imaging data sets into 3D printed models that can facilitate improved understanding of structural abnormalities by both caregivers[6] and patients as well as preprocedural simulations for catheter-based interventions. (5)Several reports also show the usefulness of 3D printing models based on the cardiac CT data for procedural planning in structural heart disease. These models allow a detailed assessment of the paravalvular leak geometry and choosing the most suitable device type and size for percutaneous closure (7).

3.1.Mitral Paravalvular Leak

Recent studies have highlighted that PVL is a known complication following prosthetic valve implantation and if severe, it may manifest with symptoms such as heart failure or hemolysis. Therefore, precise localization and characterization of paravalvular defects are essential for preprocedural planning of transcatheter closure procedures. Modern imaging modalities have made[9] this increasingly possible. TEE provides direct assessment of the defect's size, location and its relationship to surrounding structures which may help in the planning of the appropriate transcatheter closure device type and size. Additionally, advances in 3D volumetric imaging now allow image data to be used for 3D printing to generate patient-specific models for procedural simulation and education. (8,9,10)

3.2.Comparison of Imaging Modalities: 2d Vs 3d Te

Research has highlighted the enhanced accuracy of three-dimensional transesophageal echocardiography (3D TEE) compared to two-dimensional echocardiography (2D) in evaluating paravalvular leakages (PVLs). Although 2D imaging can provide basic hemodynamic data regarding PVL, 2D imaging lacks accuracy when defining the shape of the defect and the circumference lengths of the paravalvular defects. Three-dimensional[7] TEE allows for en face visualization of the prosthetic heart valve, allowing the clinician to see exactly where the leakage occurs in reference to surrounding structures. Studies comparing the two imaging modalities have determined that 3D TEE will substantially increase the accuracy of diagnosing PVLs and provide additional concordance between physicians when evaluating[8] PVLs; however, this is most significant when evaluating complex or multiple PVLs. More recent studies (2023- 2025) have also shown that 3D TEE is superior to traditional modalities for guiding the procedural closure of transcatheter PVLs because it allows for the real-time evaluation of device position and residual regurgitation. Thus, 3D TEE represents an important improvement over conventional imaging method (10,11,12,13)

3.3.Role of 3d Printing In Structural Heart Disease

The 3D TEE provides detailed images although it is yet another view of a virtual heart. Researchers have explored the question of whether the addition of 3D printing is an added value to imaging.Comparative analyses indicate that physical models produced through[11] 3D printing provide a patient-specific physical presentation of the heart and are easier to comprehend[10] the complicated geometry of PVL. An imaging compels clinicians to visualize the anatomy by building it in the mind, whereas a physical model allows clinicians to see and feel the defect with their own hands, which improves the procedural planning (13,14).The research conducted with the aid of CT-based and 3D TEE-based models proves that 3D printing can assist the sizing and description of the defect correctly, more appropriate

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choice of closure devices, more real simulation of the process. However, models obtained by the use of CT tend to provide greater spatial, as compared to 3D TEE, which is best in real-time functional evaluation. The optimal option is reliant on the clinical case and available equipment (15,16).

3.4.Clinical Impact and Procedural Outcomes

There is an increasing amount of literature demonstrating that integrating three-dimensional imaging with three-dimensional printing can improve clinical outcomes when[15] managing paravalvular leaks (PVLs). Research has demonstrated that the use of three-dimensional imaging and printing can lead to Less time spent performing procedures, more accurate selection of devices, and Fewer cases with residual leaks. Additionally, using three- dimensional printed[12] models to simulate a procedure prior to performing it has enabled operators to anticipate possible issues and reduce complications during the procedure. This is especially important when managing a complex or irregularly shaped PVL due to the limitations[13] of traditional imaging techniques. While the benefits of using three-dimensional imaging and printing to manage PVLs are well documented, studies evaluating the efficacy of this method have primarily been small in size and/or observational in nature.(13,14,15) Therefore, there remains a need for large randomized controlled trials to confirm the clinical benefits of this technology[14].

4. Limitations And Challenges

There are numerous limitations to the widespread utilization of 3D printing for clinical applications. The factors that limit the capability of producing accurate models includes quality of imaging datasets, Availability of post-processing software designed to convert imaging data into useful 3d format, Access to 3D printing technology. The 3D printing process can also have a significant time requirement and cost associated with it, making this an impractical routine practice especially in resource-limited areas (11). The overall accuracy and reproducibility of 3D printed models may be limited by variation in the types and methods (materials and procedures) employed to manufacture the models. Another significant limitation to the application of 3D printed models is the lack of currently established standardized protocols for the acquisition of imaging data, the reconstruction of those images into a model, and the clinical application of that model (13). Because these processes differ from study to study, it becomes extremely difficult to compare results across various studies and develop general consensus for 3D printed models.

5. Future Directions

Future studies should find more accurate image processing systems and reduction in the period of producing them, and of artificial intelligence with 3D modeling technology. These advancements can help enhance how useful patient-specific cardiac models are in a healthcare setting. They may also help develop more personalized treatments for the patients that have structural heart disease[16]

Conclusion

Three-dimensional (3D) printing models made from three-dimensional transesophageal echocardiography (3D TEE) have emerged as a promising tool to improve the evaluation and management of mitral paravalvular leak (PVL). The use of advanced imaging and 3D modeling allows better visualization of prosthetic valve anatomy and paravalvular defects, aiding procedural planning and device selection in transcatheter PVL closure.

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