Using Three-Dimensional Printing in Surgical Mitral Valve Repairs

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Central Illustration: Using three-dimensional printing in surgical mitral valve repairs

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Abstract

Mitral regurgitation is an important cause of morbidity and mortality, and surgical mitral valve repair continues to be the treatment of choice when feasible. We use three-dimensional echocardiography associated with three-dimensional printing to create surgical models that allow trainees to practice or improve surgical techniques in order to improve the outcomes of surgical repairs, contributing to more advanced medical training.

Keywords

Three-Dimensional Printing;Echocardiography; Mitral Valve Insufficiency; Thoracic Surgery; Mitral Valve Annuloplasty

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Introduction

Mitral regurgitation is an important cause of morbidity and mortality, progressively leading to a decline in cardiac function, enlargement of the left cavities, and development of pulmonary arterial hypertension, being a prevalent cause of heart failure with a major social and public health impact.[1] Its causes include congenital, inflammatory, infectious, degenerative factors, secondary functional changes such as ventricular dilation, dysfunction and displacement of the papillary muscles, and, less commonly, increased atrial volume.[2]

As shown in several studies, mitral repair has numerous benefits when it comes to valve replacement in terms of prognosis, early and late mortality, morbidity, and durability, being considered the gold standard treatment for mitral regurgitation.[3,4] However, this approach is technically challenging, compromising outcome predictability and often resulting in increased surgery duration, increased extracorporeal circulation time, and significant residual mitral insufficiency, which may lead to the need for valve replacement with implantation of prosthesis.[3-5]

Valvular dysfunction does not occur symmetrically. It may involve isolated segments or affect the valve more comprehensively (Figure 1). Echocardiography can identify numerous parameters that help determine the mechanism of dysfunction. The method determines anatomical details such as the segments involved, measurements of the leaflets and their ratios, shape and dimensions of the mitral annulus, involvement of the subvalvular apparatus, distance between the papillary muscles and the valve tissue or adjacent structures involved, as well as the degree of regurgitation. The mechanism and anatomical information will be key to determining the possibility of surgical repair and the surgical technique to be used. Degenerative valve disease with mitral prolapse is the most commonly found dysfunction, and its surgical repair outcome is known to be beneficial when feasible. Three large groups can be differentiated . The degree of involvement of the leaflets can be divided into two groups: grades 1 and 2, known as fibroelastic degeneration (FED), being the mildest form with involvement of few valve segments and less excess tissue, mainly from the posterior leaflet, with a greater possibility of performing a successful repair; and grades 3 and 4, known as Barlow's syndrome (BS), a multi-segmental condition consisting of a myxomatous infiltration with greater involvement of both leaflets, showing a marked alteration, with significant deformation of the valve complex, restricting its repair to highly specialized centers with extensive experience. Therefore, valve replacement is the treatment of choice in most cases. The frustum form (FF), or Barlow frustum, would be grade 3 and refers to an intermediate change whose approach must be evaluated on a case-by-case basis. Analyzing the most affected leaflet is of great importance for the final outcome. Surgery on the posterior leaflet, especially when the involvement is located at the level of scallop P2, is considered simpler, with better success rates. Injuries to scallops P1 and P3 and commissural lesions are technically more difficult, but still have a good possibility of repair. Involvement of the anterior leaflet requires more challenging techniques and must be performed by experienced surgeons. The most currently used techniques in repairs include triangular or quadrangular resection of the involved segment, patch placement, cleft closure, chord transfer, the use of neochords, and annuloplasty with ring placement.[6-10]

Divergent results can be observed in repairs performed on valves with similar involvement, which may be related to the surgeon's degree of proficiency, the patient's own factors, or an inadequate preoperative assessment.[11] Currently, echocardiography, especially with three-dimensional evaluation, allows a better analysis of the valve anatomy with more precise measurements and a good visualization of the mechanism involved. However, these data are often not adequately presented to the surgeon, resulting in a poorly planned procedure.

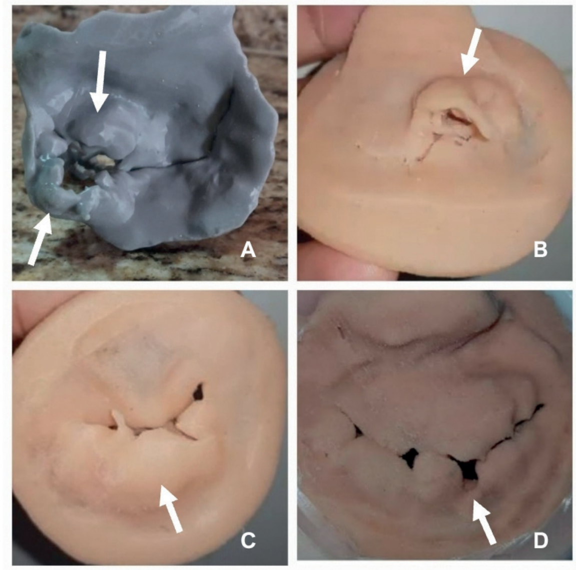

Figure 1 – *Printed models showing different forms of mitral disease with prolapse and flail affecting the lateral commissure and A1/P1 (A), anterior leaflet flail at the level of A2/A3 (B), prolapse with flail of P2 (C), and Barlow's syndrome with posterior cleft (D).*

New technologies allow the printing of realistic models from images obtained from 3D TEE with scale accuracy proven in studies, enabling physical measurements and allowing prior visualization of the operating field. From the three-dimensional image acquired in DICOM format, a three-dimensional model is obtained, which is converted into a file that can be printed on different materials with different physical characteristics and resistances using a three-dimensional printer. Furthermore, molds can be printed using materials that mimic the resistance of the valve tissue. A simulated surgery can then be performed pre-operatively with the same dimensions and characteristics that would be found during the actual procedure.[12-16]

This study aims to allow more effective planning for mitral valve repair surgeries by creating models that mimic the patient's anatomy. These models are useful when deciding on the surgical treatment and verifying and testing pre-operatively the best surgical approach to be adopted.

It is intended to make cardiac images more tangible and may allow greater predictability of the surgical outcome without harming the patient. Another potential effect is to train a greater number of professionals to perform these techniques, reducing the learning curve and allowing the development of new approaches or alternative techniques in a controlled and close-to-real environment, impacting medical training.

Methods

The study involves the creation of three-dimensional models through 3D printing, which are then submitted to a cardiac surgeon specialized in surgical mitral valve repair, who will assess whether it is possible to perform the usual surgical techniques on the printed models to simulate an actual surgical procedure.

Advanced models were created, which include mitral annulus, leaflets, papillary muscles, and tendon chordae of different mitral diseases, using silicone with resistance characteristics similar to those of the human valve tissue. These models were based on images obtained by three-dimensional transesophageal echocardiographic examinations. The diseases were selected considering varying degrees of surgical difficulty and the need to use different surgical techniques.

The exams were performed using a Phillips Epic Cvx device with an X8 esophageal probe. The images were submitted to the QStation software to evaluate valve measurements using a semi-automatic method and, subsequently, the images were exported to an open-source software (3DSlicer) to create three-dimensional models (Figure 2) and recorded in stl (stereolithography) format. Then, the file was exported to a three-dimensional printer (Flashforge Inventor) for printing a mold which must be printed in a soluble filament (PVA) and then filled with specific silicone (Ecoflex), thus generating a model with elastic characteristics that supports simulated surgery (Figure 3).

To aid the applicability of the surgical technique, ring models for annuloplasty were constructed by three-dimensional printing using elastic material from computer models generated using measurements and shapes of annuloplasty rings already available on the market.

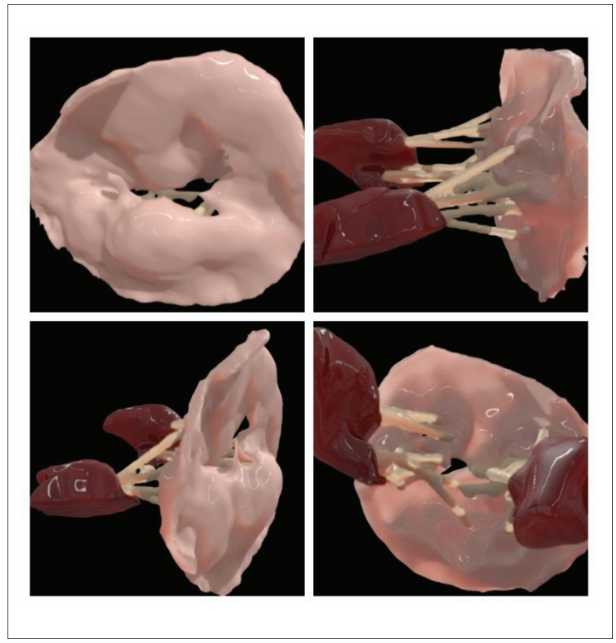

Figure 2 – *Virtual three-dimensional model.*

Results

Advanced valve models were created featuring diseases involving the anterior leaflet, the posterior leaflet in its three scallops, and Barlow's syndrome with diffuse involvement. The chordae are 1.5 mm thick, which is the smallest thickness accepted for the methods used, to allow their integrity after the manufacturing process. A silicone dye was used to facilitate visualization during handling and to allow more accurate placement.

Specimens created were measured using a caliper. The measurements were compared with those obtained from the three-dimensional transesophageal echocardiogram using an automated software (Philips MVQ) with a good correlation between the measurements (Figure 4).

From the printed models, it was possible to apply different techniques using regular surgical material and common surgical threads (Figure 5). Techniques such as annuloplasty, triangular and quadrangular resection, and neochord implantation were performed with good correlation with tissue resistance, texture, and behavior when compared to the actual patient when assessed by a cardiac surgeon specialized in mitral valve repair (Figure 6).

Conclusion

Although this is an experimental work with limited scope, we tried to demonstrate that it is possible to use three-dimensional echocardiography associated with three-dimensional printing for the planning and training of surgical mitral valve repairs. Currently, a large number of surgeons in Brazil perform few surgical repairs, which impacts their ability to perform more advanced techniques, leading to unnecessary valve replacement in some cases. Investments and more research in this field could induce a more advanced medical training program, which could lead to more qualified surgeons and train new ones. In addition, it is also possible to develop new techniques, such as minimally invasive surgery and robotics, without negative impacts on patients. Therefore, we could improve surgical repair statistics with impacts on the general population.

Author Contributions

Conception and design of the research, acquisition of data, analysis and interpretation of the data and writing of the manuscript: Visconti RB; critical revision of the manuscript for intellectual content: Visconti RB, Belem LHJ, Cornélio MCL, Nogueira ACS, Weitzel LH.

Potential Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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Study Association

This study is not associated with any thesis or dissertation work.

Ethics Approval and Consent to Participate

This article does not contain any studies with human participants or animals performed by any of the authors.

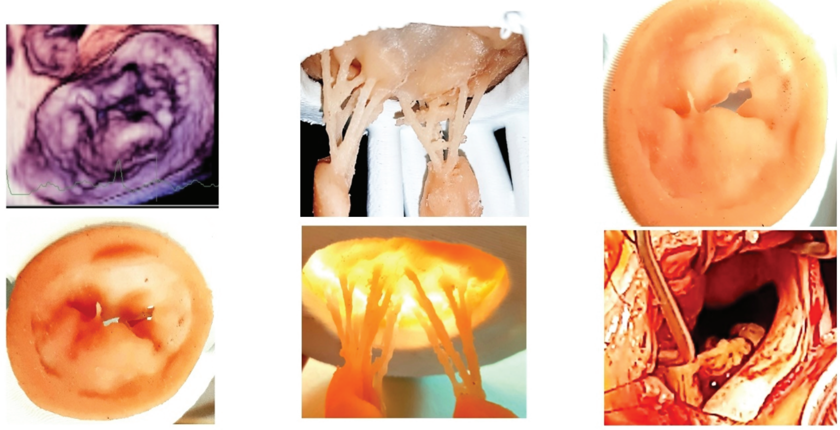

Figure 3 – *Image on the upper left corner obtained by three-dimensional echocardiography. Advanced three-dimensional model printed in silicone containing leaflets, subvalvular apparatus, and papillary muscles. Picture of the surgical specimen on the lower right corner.*

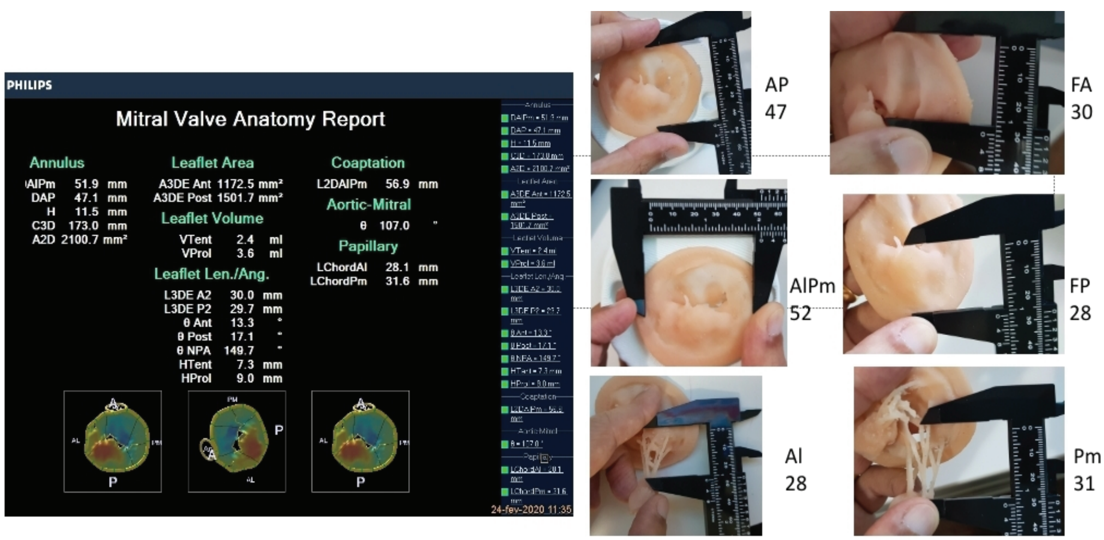

Figure 4 – *Comparison between mitral valve measurements obtained using specific software (Philips MVQ) and measurements found on the printed model. AP: anteroposterior diameter, AlPm: laterolateral diameter, FA: anterior leaflet, FP: posterior leaflet, Al: chordae of the anterolateral papillary muscle, Pm: chordae of the posteromedial papillary muscle.*

Figure 5 – *Before and after simulated surgery on a printed specimen.*

Figure 6 – *Surgical techniques applied to printed model.*

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