Use of a 3D Printer in the Prototyping of an Anatomical Model of the Human Heart with Morphophysiological Alterations

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Abstract

Background: **Three-dimensional (3D) printing has a wide range of applications, including medicine and medical education. It presents itself as an alternative to traditional teaching-learning methods of human morphophysiology.**

Objectives: **To report the initial experience in prototyping a 3D-printed anatomical model of the human heart with valvular heart disease, as well as its potential use in the active teaching-learning process in human morphophysiology.**

Methods: **This is an experimental, descriptive study developed in three distinct stages: 1) Selection of the morphofunctional structure for manufacturing the 3D part; 2) design and adaptation of the object in 3D computer-aided design (CAD) software; and 3) printing and application of the prototype. Models extracted from the Thingiverse website, simulating cardiac structures, were used.**

Results: **A cardiac prototype was 3D-printed to illustrate morphophysiological changes, including aortic stenosis and mitral insufficiency, modeled on the aortic and mitral valves, respectively.**

Conclusion: **The valve diseases represented in the prototype accurately reflect the pathological changes used as the basis for the study, providing a detailed and precise view of the anatomy, which shows significant potential for enhancing the teaching-learning approaches in morphophysiology and medical pathology.**

Keywords: **Three-Dimensional Printing; Proof of Concept Study; Medical Education; Anatomy.**

Introduction

Three-dimensional (3D) printing, also known as additive manufacturing, is a process within the concept of rapid prototyping that involves creating objects by depositing materials in layers until the desired 3D form is achieved. Rapid prototyping encompasses various technologies used to produce physical objects from data generated by computer-aided design (CAD) systems.[1,2]

3D printing finds application in a wide array of fields, including space science, technology, medicine, and medical education.[2] Within medical education, it has proven effective in enhancing the teaching-learning process of human anatomy, as it extends its utility to clinical case studies, surgical technique planning, and the creation of highly accurate anatomical prototypes.[3,4]

In this sense, the use of 3D printing for anatomical parts presents an alternative to traditional methods of teaching human morphophysiology, such as cadaver handling and dissection, and the use of two-dimensional images in textbooks and presentations, since it provides a detailed, precise, and relatively inexpensive means of representation, providing students with a faithful understanding of complex anatomical details.[4-7]

Medical education has been progressively integrating active teaching-learning methodologies and updating traditional approaches. Against this backdrop, this study aimed to evaluate the feasibility of prototyping an anatomical human heart with valvular heart disease using 3D digital printing and its potential for enhancing the active teaching-learning process in human morphophysiology.

Methods

This experimental, descriptive study aimed to report the initial experience of prototyping an anatomical model of the human heart with two morphophysiological changes using a 3D printer, with the purpose of creating a model for studying cardiac morphophysiology. The project was developed in three distinct stages: 1) Selection of the morphofunctional structure for manufacturing the 3D part; 2) design and adaptation of the object in 3D CAD software; and (3) printing and application of the prototype. Models extracted from the Thingiverse website, simulating cardiac structures, were used.

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Aortic stenosis and mitral insufficiency were the cardiac pathologies chosen for prototype adaptation, as they are prevalent valve diseases in Brazil,[8] and there were no 3D models available in the institution or in the Brazilian market depicting the reported morphophysiological changes.

To create this educational model, the authors searched for files suitable for 3D printing that depicted an anatomical human heart without morphophysiological changes. The Thingiverse open-source website was used to search and select available anatomical models. Next, a review of the literature was conducted on the mentioned pathologies using images from textbooks, medical teaching materials, and scientific articles to edit the aortic and mitral valves.

SolidWorks and MeshMixer software were used to model and adapt the aortic and mitral valves to represent aortic stenosis and mitral insufficiency, respectively. The Simplefly 3D and Cura 3D Ultimaker software were used to configure the design for printing. The prototype was created using a Creality 3D printer, model Ender-3, and 1.75mm white Polylactic Acid Filament (PLA).

Thingiverse files are available for free download at https://www.thingiverse.com/thing:3861544.

Results

A cardiac prototype was 3D-printed to illustrate morphophysiological changes, including aortic stenosis and mitral insufficiency, modeled on the aortic and mitral valves, respectively. The anatomical human heart prototype, sourced from Thingiverse, comprised six files representing various structures such as the atria, ventricles, heart valves (aortic, mitral, tricuspid, and pulmonary), papillary muscles, and cardiac arteries and veins. Using SolidWorks and MeshMixer software, only the aortic and mitral valves were modeled to demonstrate the pathological changes. These structures were printed separately and then assembled to depict the beginning of isovolumetric contraction in the cardiac cycle, where all valves should be closed.

Figure 1 shows the process of creating the aortic valve model.

Figure 2 represents the stages of construction of the mitral insufficiency specimen.

For teaching purposes, the selected model was enlarged by 30% during the configuration and printing process. However, the heart valves did not fit into the prototype after printing, thus requiring a 10% size reduction and reprinting of those components. The final objects were then sanded and painted with PVA (polyvinyl acetate) craft paint. The final prototype required 608 grams of PLA filament and 113 hours and 42 minutes of printing time.

The final prototype (Figure 3), as well as the morphophysiological changes, demonstrated an anatomical correlation with two-dimensional photorealistic images and photographs of pathological specimens found in medical literature. This prototype was presented during a 3D printing workshop for medical students, faculty, and staff at the institution. Participants acknowledged that the ability to interact with the 3D printed model enhanced their understanding of anatomical structures, their spatial orientation, and anatomical topography, thereby facilitating the identification of morphophysiological variations.

Discussion

3D printing allows personalized objects to be manufactured quickly, with high precision in relation to the actual part and low cost. It is useful to medical education through its printed replicas for better visualization and understanding of the human anatomy.[9] It presents itself as an alternative to traditional teaching-learning methods.

The final prototype created here allowed the visualization of complex anatomical details and a declared financial cost lower than plastic resin models found on the market. It is worth mentioning that plastic resin models do not allow customization in their morphology. Furthermore, the low depreciation and decharacterization of its anatomical morphophysiology over time stands out as a benefit, which is a limiting factor when using organic parts.

Similar results were obtained in the printing of a cardiac prototype with congenital pathologies, indicating that

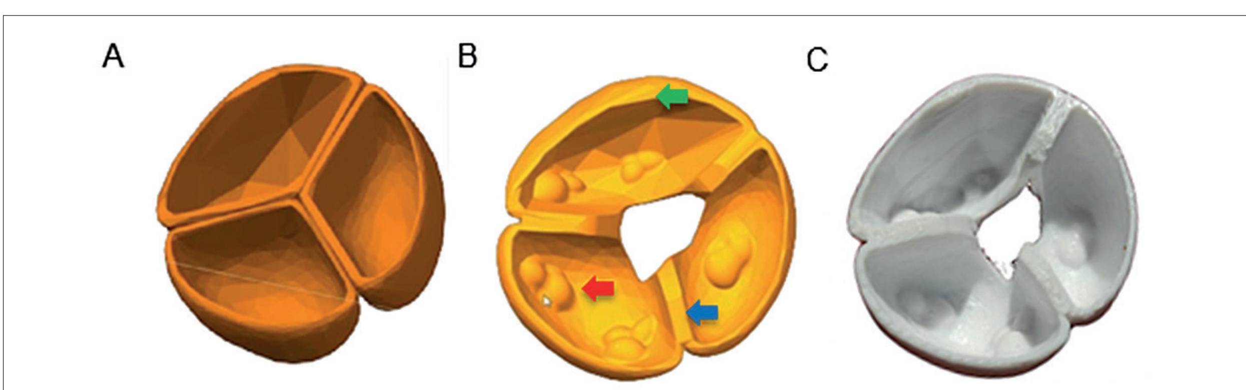

Figure 1 – *Representative model of Aortic Valve Stenosis. A: Anatomical model selected on Thingiverse; B: adjustments to portray aortic stenosis; in this model, nodular calcifications were added (red arrow), the cusps were thickened and distorted (green arrow), and the commissures were fused (blue arrow); C: final product after printing.*

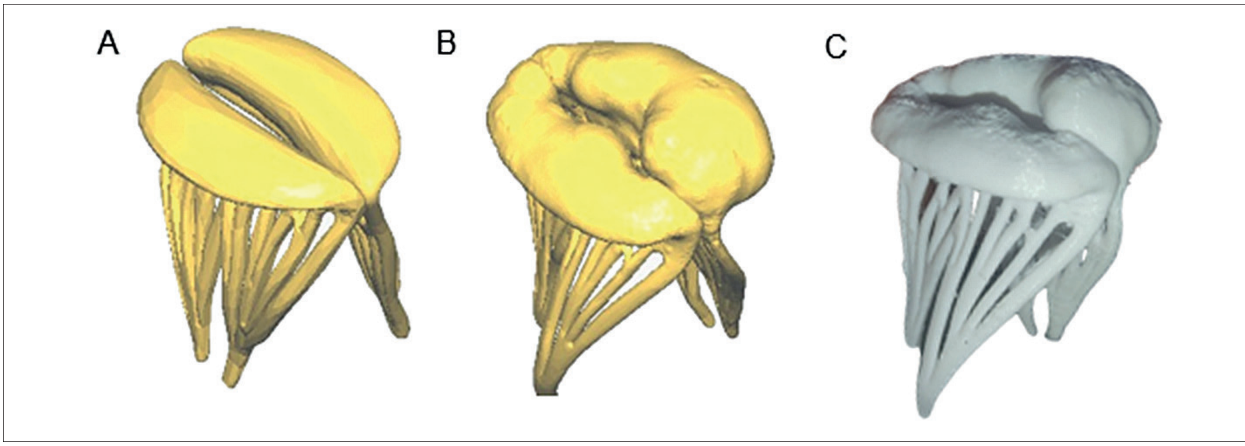

Figure 2 – *Representative model of Mitral Valve Insufficiency. A: Anatomical model selected on Thingiverse; B: adjustments to represent the mitral valve leaflets impairment; in this model the leaflets were thickened and displaced, preventing them from closing accordingly; C: final product after printing.*

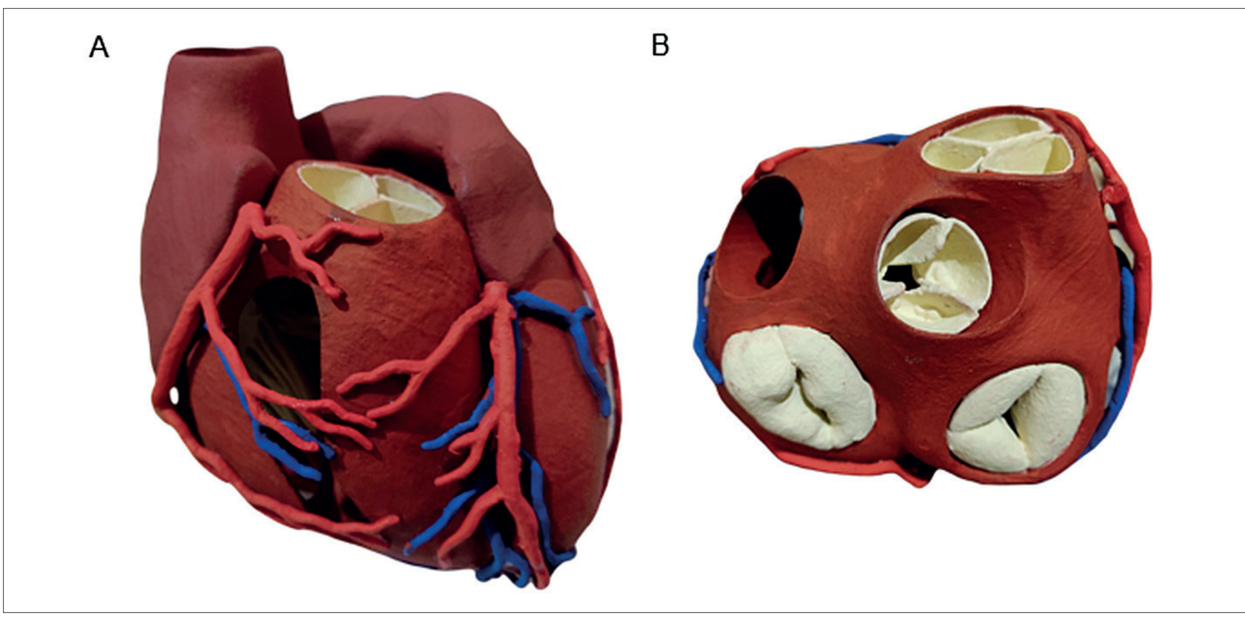

Figure 3 – *3D-printed anatomical human heart. A: Front view of the prototype after printing; B: heart valves.*

medical professionals do benefit from expanding their knowledge of heart disease by observing anatomy from various angles.[10] Another study showed advantages in learning through a sequence of models created to illustrate cardiac embryonic development. 3D printed parts, in addition to being cost-effective, aid in understanding the perspective and depth of the model, which is not possible with textbooks or images.[11]

Research with medical students demonstrated that using 3D structures during study reduced erroneous interpretations of pathological structures compared to using two-dimensional images. Additionally, there was a significant improvement in structural and anatomical conceptualization.[12] Thus, the use of 3D-printed cardiac models facilitates the understanding of complex structures, increasing learners' engagement and confidence in relation to the pathology being studied.

Conclusion

The valve diseases depicted in the prototype accurately reflect the pathological changes used in the study, providing a detailed and precise view of the anatomy. The use of colors further aids in distinguishing between different structures, enhancing the learning experience. Therefore, 3D-printed structures have significant potential in teaching morphophysiology and medical pathology, offering a relatively cost-effective alternative to anatomical models made of plastic resin.

Author Contributions

Conception and design of the research, acquisition of data, writing of the manuscript and critical revision of the manuscript for intellectual content: Freitas KG, Lana ALB, Ferreira VL, Quintão MAU; statistical analysis: Ferreira VL.

Potential Conflict of Interest

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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.

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