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Three-dimensional canine heart rendering protocol using Materialise Mimics software

Protocolo de renderização tridimensional de coração canino utilizando o software Materialise Mimics

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Highlights

It is possible to standardize the 3D rendering of dog cardiac biomodels.
A protocol is important to ensure repeatability in biomodel production.
3D canine heart biomodels improve veterinary anatomy teaching.
Biomodels can be used in educational institutions that lack new teaching materials.

Abstract

Additive manufacturing is a production principle that can potentially transform the two-dimensional teaching process from CT to three-dimensional images, increasing student interest and tactile appreciation. Anatomy taught in universities, traditionally using cadavers, has undergone changes in recent years in search of active methodologies capable of implementing technological solutions in teaching and reducing the use of cadaveric anatomical specimens that need care and incur high maintenance costs. One of the most complex structures is the heart, a contractile pump that propels oxygenated blood to the entire body through the cardiovascular system. Given the scarcity of research that creates cardiac biomodels with a protocol, the aim of this study was to use a protocol reproducible in other cardiac models applying Materialise Mimics software to select regions of interest and 3D rendering. A Beagle heart specimen was printed in resin using the photopolymerization 3D printing methodology to exemplify the use of the proposed protocol.

Key words: 3D printing. Anatomical heart. Three-dimensional model. Teaching.

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Resumo

A manufatura aditiva é um princípio de fabricação que tem o potencial de transformar o processo de ensino bidimensional a partir de imagens de tomografia computadorizada em tridimensional aumentando o interesse dos estudantes e o apreço tátil do ensino. O ensino de anatomia, tradicionalmente feito utilizando cadáveres, tem passado por renovações nos últimos anos como forma de encontrar metodologias ativas capazes de implementar soluções tecnológicas no ensino e reduzir a utilização de peças anatômicas cadavéricas que necessitam de cuidado e possuem alto custo para sua manutenção. Por sua vez, uma das estruturas mais complexas do estudo é o coração, uma bomba contrátil e propulsora que impulsiona o sangue oxigenado para toda a extensão de um indivíduo através do sistema cardiovascular. Ao observar a escassez de pesquisas que realizem a fabricação de biomodelos cardíacos por meio de um protocolo, o objetivo deste trabalho foi utilizar um protocolo de base capaz de ser reprodutível em outros modelos cardíacos utilizando o software Materialise Mimics como base para a seleção das regiões de interesse e renderização 3D. Ao final, foi impresso um espécime de coração canino da raça beagle em resina a partir da metodologia de fotopolimerização em cuba de impressão 3D para exemplificar a utilização do protocolo proposto.
Palavras-chave: Impressão 3D. Coração anatômico. Modelo tridimensional. Ensino.

Introduction

Anatomy is traditionally studied using textbooks with a description of the characteristics of a particular tissue, organ or system (Borgeat et al., 2022; Suñol et al., 2019). The main resources are handling of cadaveric parts and atlases containing images of macroscopic anatomical structures (Yammine & Violato, 2015; Patra et al., 2023).

Although teaching strategies using technology have emerged in recent decades, teachers still face significant difficulty in preparing anatomy classes and finding a more practical way to teach with didactic resources different from those currently in use (Garcia et al., 2018; Wang et al., 2017).

Three-dimensional (3D) rendering driven by technologies such as additive manufacturing (AM) means that the use of 3D biomodels is becoming a reality in many educational centers worldwide (Bhagat et al., 2015; Pawlina & Drake, 2013).

Teaching anatomy is an essential part of veterinary medicine because it introduces students to the main concepts that will be reviewed in their curriculum (Lima et al., 2019; Wilhite & Wölfel, 2019). For radiological and surgical practice, knowledge of anatomical accidents and complex structures is fundamental (Li et al., 2018; Mogali et al., 2018).

The heart is a contractile-propellant pump and one of the most complex anatomical structures in an animal's body (Singh, 2019). This is because the study of its chambers and vessels aligns with the need for detailed knowledge of the physiological processes and an understanding of the possible diseases that can affect the organ (Nelson, 2015).

Studying the cardiac anatomy of domestic animals is still restricted to the cadaveric specimens available at universities and training centers (Wilhite & Wölfel, 2019), which reduces the student's chance of learning anything beyond traditional structures and makes learning less productive in terms of understanding anatomical variations and macroscopic diseases (Valverde et al., 2022).

Diagnostic imaging includes echocardiography, x-ray, and computed tomography (CT), the last requiring the use of intravascular contrast techniques to reveal morphology (Salmi et al., 2013).

Knowledge about three-dimensional rendering from a CT DICOM file is not standardized, precluding repeatability by multi-users of the technology. The initial problem is that there is no specific process for generating a 3D mesh capable of a detailed illustration of the anatomical structures of a canine heart.

The key issue addressed here is how to render a simple 3D digital model of a canine heart.

Based on this problem, a model was developed considering the scientific literature and prioritizing the non-correction of the biomodel after its rendering.

As such, the aim of this study was to postulate a protocol for the generation of a 3D digital biomodel of a canine heart to teach anatomy, using Materialise Mimics software (Mimics, Leuven, Belgium).

Materials and Methods

Experimental design

A CT scan with intravenous contrast of a Beagle was used to delineate the cranial and caudal vena cavae, aortic artery, pulmonary trunk, and pulmonary veins.

First iteration: importing the file into the software

The dog's DICOM file was imported using the traditional method. After DICOM was selected, the first iteration was based on choosing the best data series that had been captured.

A total of 23 data series were imported, consisting of mediastinum and lung images with and without contrast.

The contrast-free mediastinum and lung images were more opaque, hindering a detailed observation of the morphology (Figure 1). On the other hand, the contrast mediastinum and lung images, known as CE (Contrast Enhanced), exhibited better image definition, and without changing brightness or contrast in the software, macrostructures such as cardiac chambers and the path of the great vessels were identifiable.

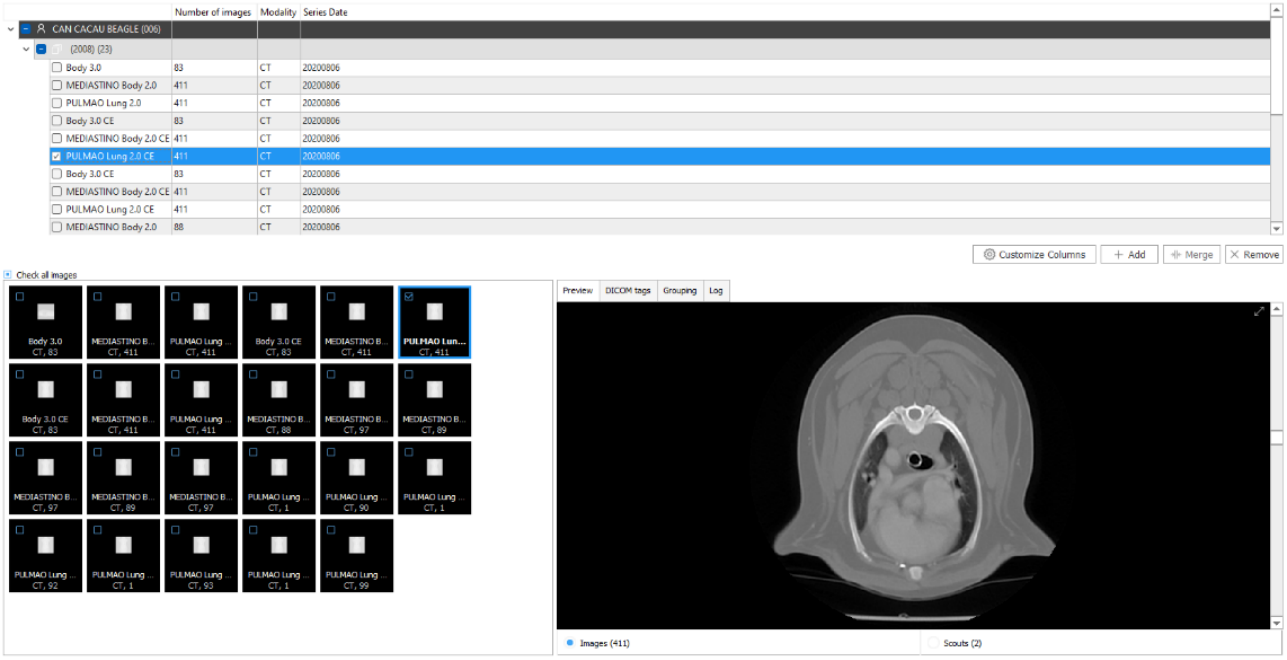

Figure 1. Screenshot of the data series import page in the Mimics software showing the image selection area for importing the DICOM files, where the series with the largest number of images was selected after the contrast was enhanced.

Furthermore, the choice of data series with a greater number of images was essential to obtain good final quality in the following stages. While some data series contained 83 images, the series selected contained 411 cross-sectional images. Thus, we chose the data series with the largest number of images to ensure better definition in the two-dimensional model obtained for the selection of the regions of interest.

Some datasets with images captured in the craniocaudal and dorsoventral senses were disregarded due to their poor quality.

Finally, the dataset selected had the highest number of captured images and contrast to improve 2D observation.

Second iteration: study area delimitation

The imported image had a minimum and maximum software-preset grayscale of -1024 and 4677, respectively. The ideal scale for the model to facilitate observation was between -259 and 588.

Mimics' native CT Heart tool was used to create the 3D mesh. The minimum and maximum density indices (178 and 339 HU, respectively) were selected. At this time a cut can be made with an interpolation function of the mask layers, selecting a cut of hundreds of images that will then be automatically transposed to all the others.

The region was selected to isolate the heart from other structures with a density similar to that of the heart muscle.

It should be noted that when isolating the region of interest, in this case the heart, the process must be performed 3 times, that is, for the three possible cuts to be observed in the software. By only isolating in the axial view, it was possible to change the future 3D mask in the right and left X-axes, and dorsal and ventral Z-axes. In sagittal visualization, the dorsal and ventral Z-axis, and cranial and caudal Y-axis could be changed, and the cranial and caudal Y and right and left X axes in the coronal view.

The CT heart function has a section of advanced tools that can manually identify the chambers of the heart, aortic artery, pulmonary artery and other structures of interest, called seed points in the software.

The tool identified all these structures, helping Mimics select only those of interest.

The seed points were placed in the following locations: left atrium (LA), left ventricle (LV), right atrium (RA), right ventricle (RV), aorta (ascending and descending) and pulmonary artery (ascending, right branch and left branch) (Figure 2).

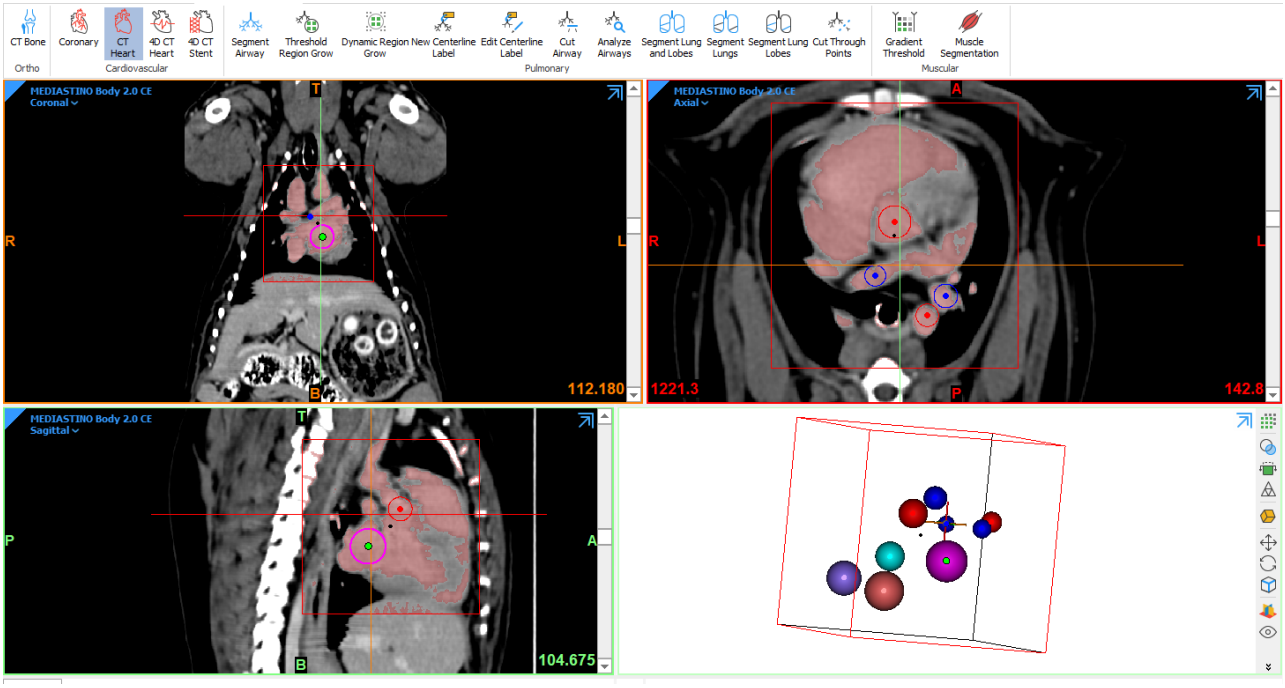

Figure 2. Seed points for automatic blood pool selection. Mimics capture showing the choice of seed points with the CT Heart tool. The color of the dots in 3D indicates the selected area. Pink: Right atrium; Orange: Right ventricle; Cyan: Left atrium; Purple: Left ventricle; Red: Aortic artery; Blue: Pulmonary trunk.

Masks were then calculated for each of the selected parts, making it possible to observe all the different-colored structures. The "mask 3D preview" function, found in the top right corner of the three-dimensional observation quadrant, confirmed that all structures were consistent with those selected.

It is important to note that this selection method is also known as blood pool (Figure 3), as reported by Farooqi (2016). It selects all regions with the presence of blood. However, when creating a 3D object, the heart will contain regions that are still hollow because the heart muscle was not selected.

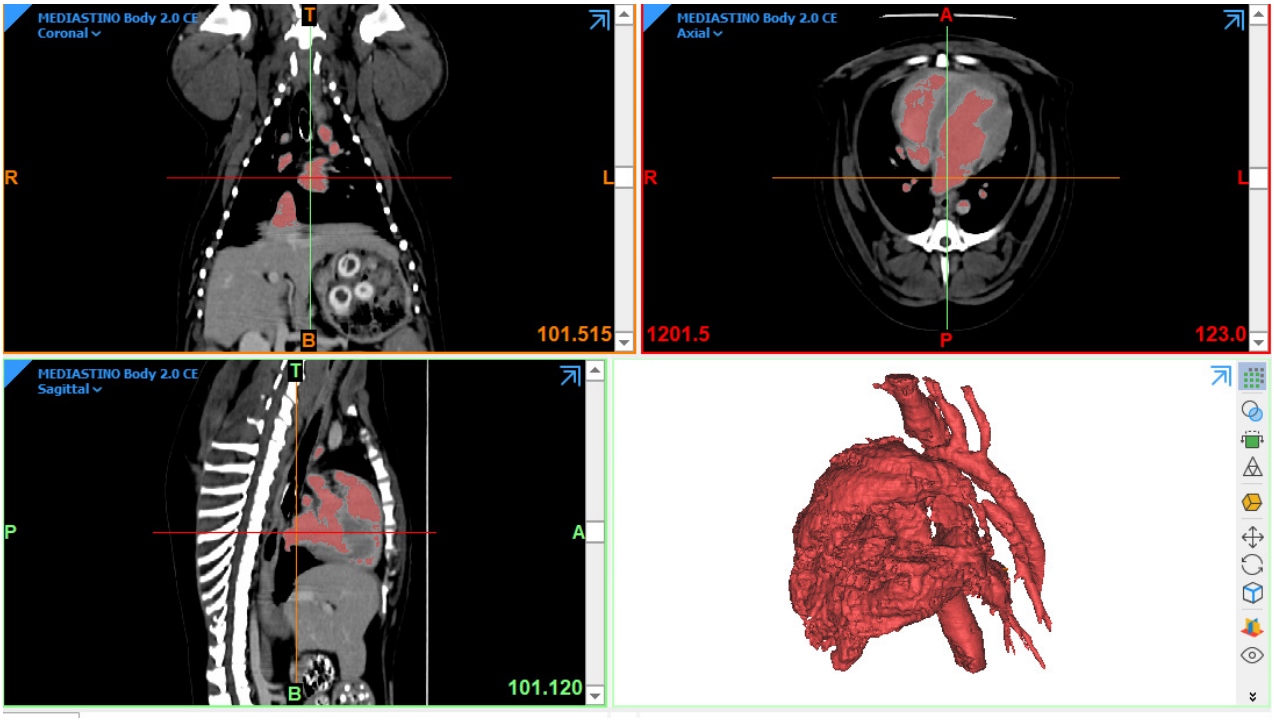

Figure 3. Blood pool selected in three cuts and three-dimensionally. As a result of using the software's CT Heart tool, the blood pool can be seen in the three-dimensional observation quadrant.

Cardiac muscle selection

To solve the problem of hollow muscle structures, a more comprehensive selection of the heart was proposed, focusing on selecting the heart muscle and extracting the previously selected morphologies by means of a Boolean function. A minimum and maximum of 57 and 252 HU were selected, thereby capturing the entire cardiac morphology and adjacent structures such as the liver and ribs. The selection tool delimited the area of the heart to facilitate editing what had been selected and to remove structures that were undesirable for the study.

To that end, the pseudocolor display function called "full spectrum" was activated. Next, a new mask was created with a minimum and maximum density of 70 and 459 HU, respectively. The same isolation process was carried out so that only the heart remained, but the heart muscle was selected in a different color.

In two-dimensional views, it was possible to separate the blood pool and the new mask by color. Thus, both masks were selected and subtraction was performed with the help of the Boolean Operations tool (Figure 4), thereby creating a new mask.

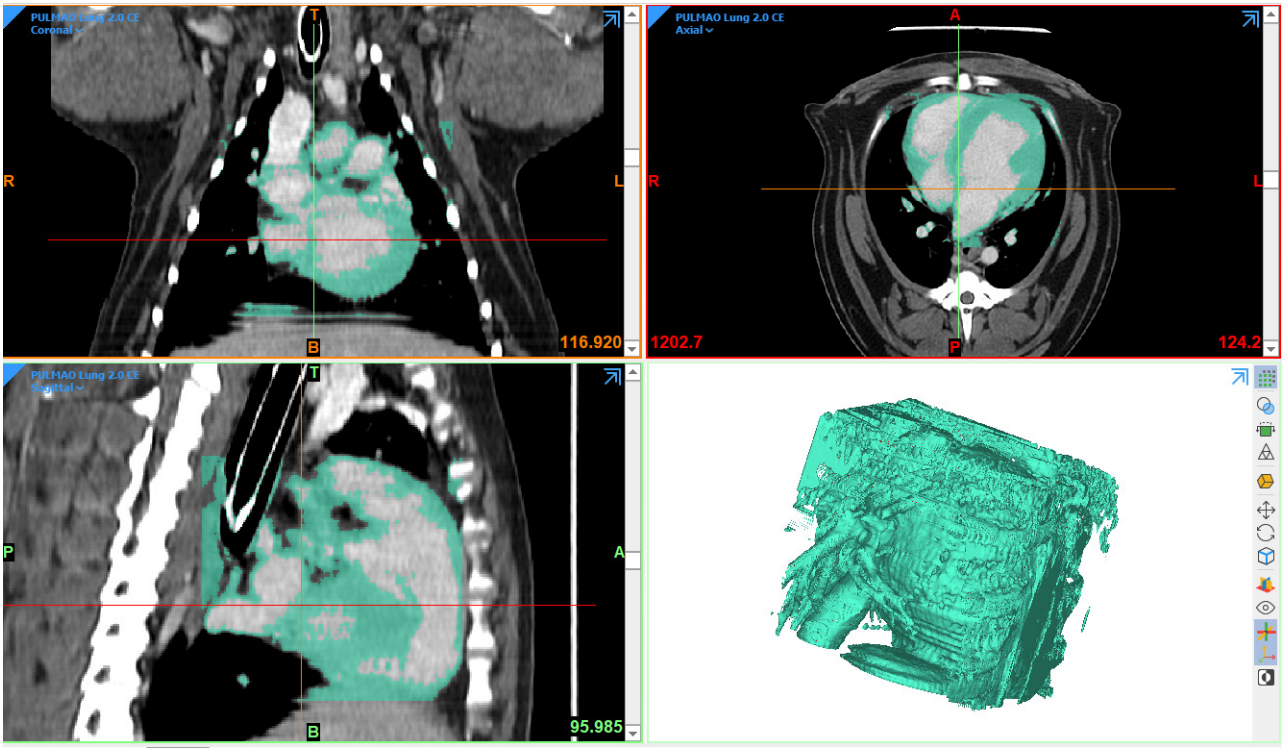

Figure 4. Selection of the heart muscle to perform the Boolean separation of the model. Only the heart muscle was selected to obtain the anatomical shape of the heart.

The Mask 3D Preview tool showed that the quality of the new mask was not ideal, since it exhibited adjacent structures that polluted visualization, such as ribs, the cranial portion of the liver, and vessels whose density is very similar to that of the heart.

For removal, the "Edit Masks" tool was used to crop or create new areas directly in the 3D Preview for extrapolation to the two-dimensional images. This produced a better quality model, enabling accurate observation of important anatomical structures such as the aortic artery, vena cavae and pulmonary trunk (Figure 5).

Due to the roughness of the final 3D model in the rendering software, for esthetic reasons and to correct possible flaws in the structural mesh, the model was used in 3D CAD software (Autodesk Meshmixer) to smooth the mesh and correct errors inherent to the process, such as inverted triangles (Figure 6).

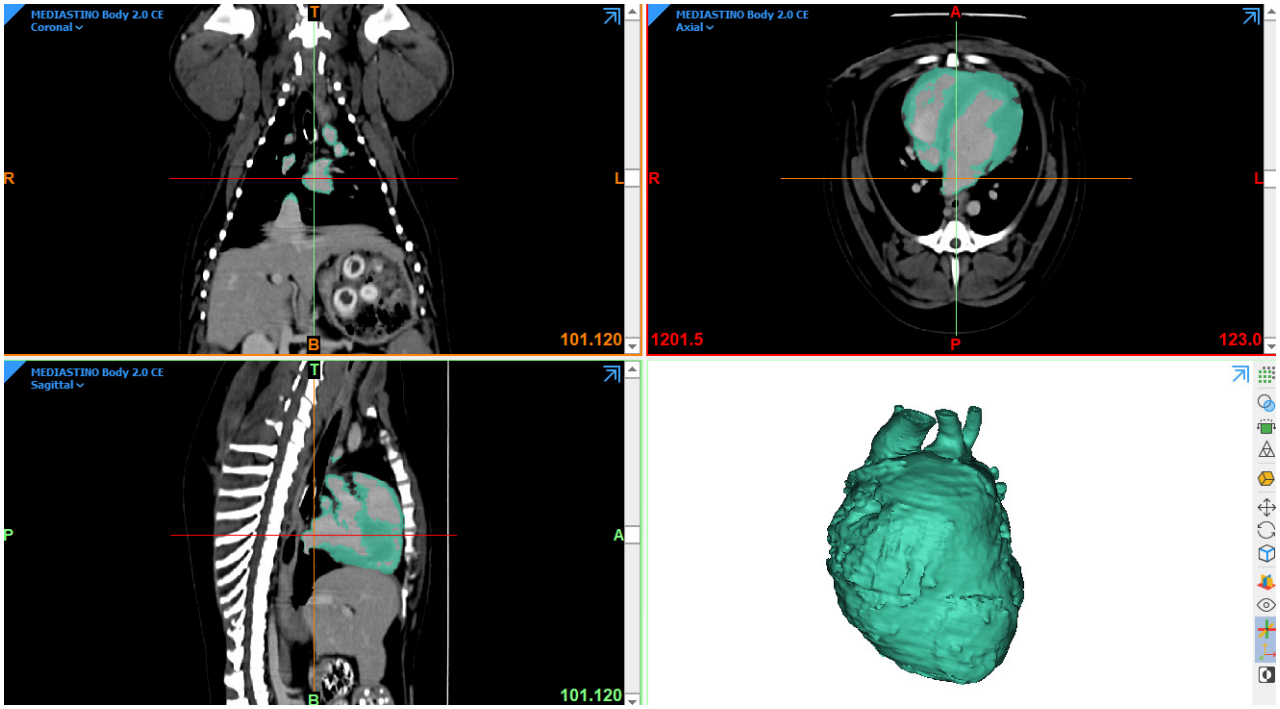

Figure 5. Final biomodel after being edited. After the Boolean separation between the mask with only the heart muscle and the blood pool, the operation resulted in a model that allows observation of the external structure and internal chambers through which the blood circulates.

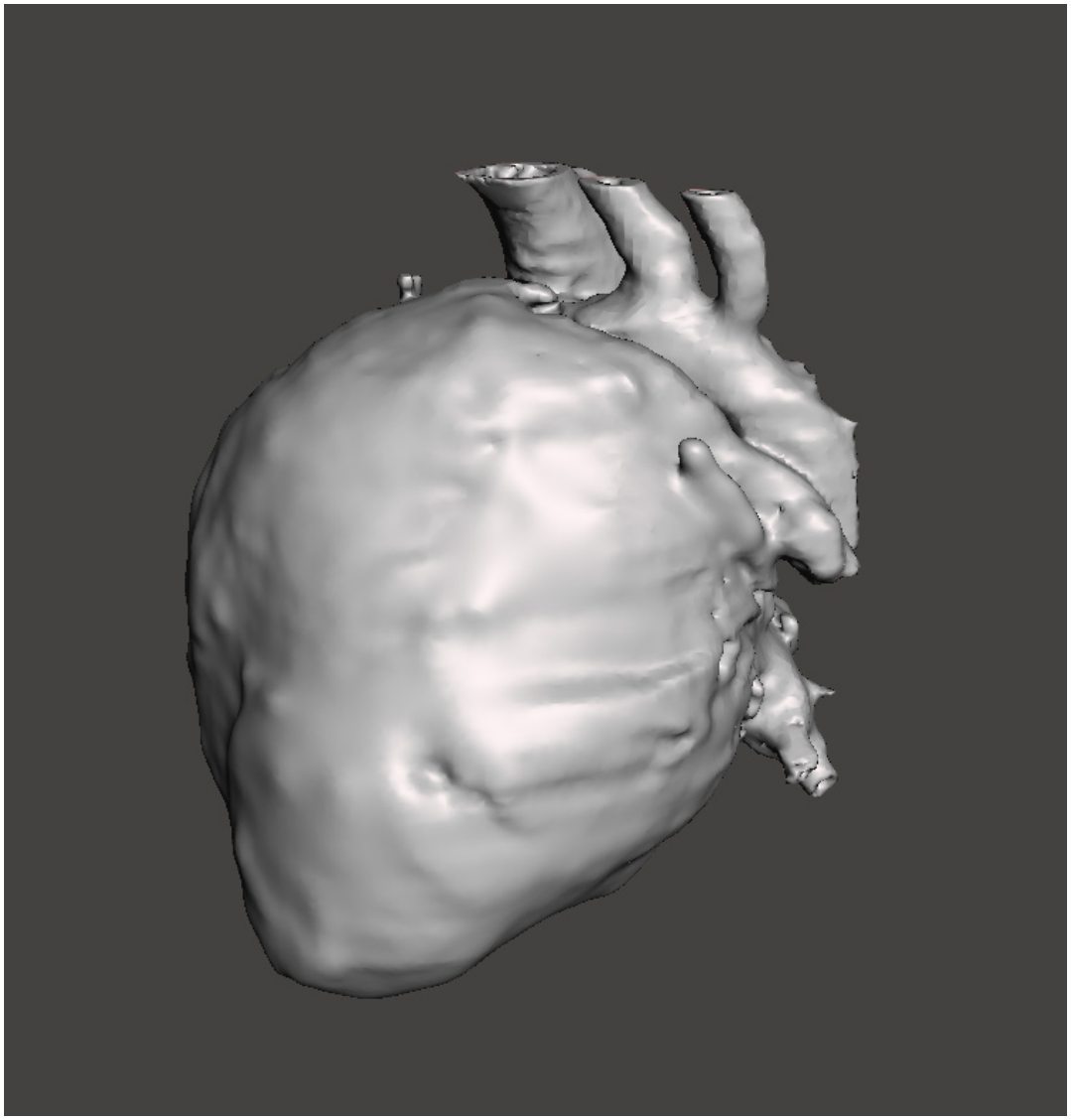

Figure 6. Biomodel imported into CAD software for mesh smoothing before 3D printing. Only smoothing operations were carried out so that the outer wall would be smoother at the time of printing, without compromising the structures to be observed.

Process planning

To perform the printout, the exported model in STL was imported into CHITUBOX software version 2.1.0 where the manufacturing process was planned (Figure 7).

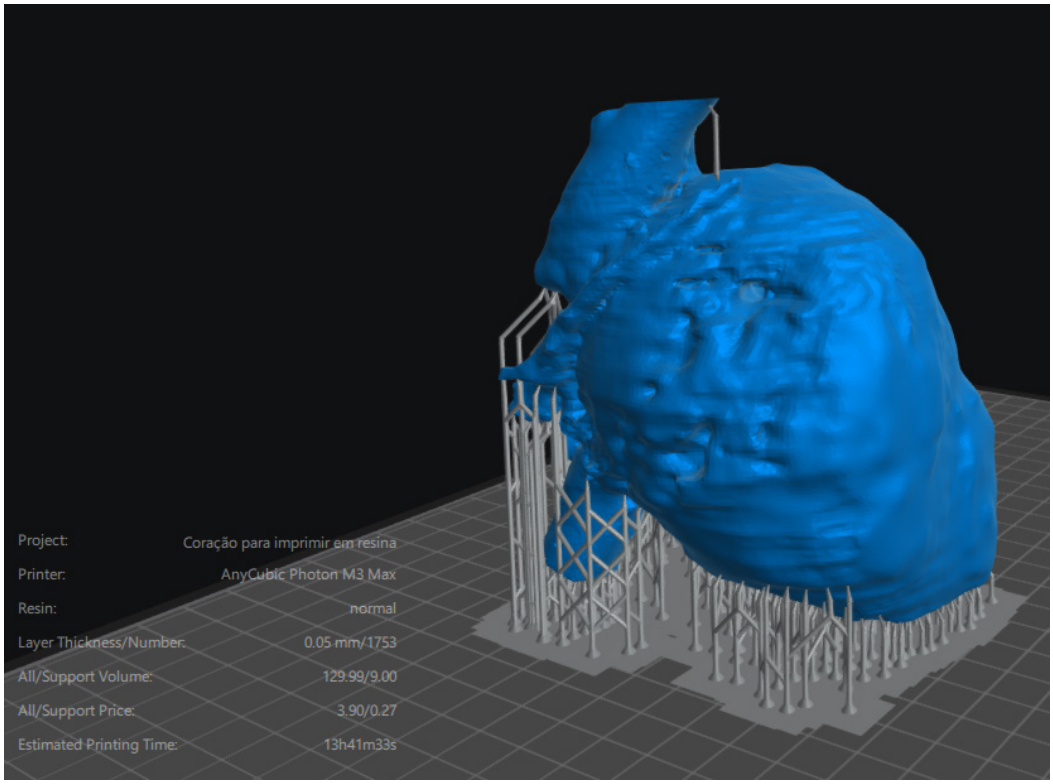

Figure 7. Final biomodel shape in the process planning software. Support structures were created to prevent deformation in areas without a base and to make it easier to adhere to the construction platform.

The printing parameters used are shown in Table 1.

Table 1
Manufacturing parameters of the cardiac biomodel in photopolymerization 3D printing

Item	Value
Resin density	1,100 g/mL
Resolution	6480 x 3600 px
Layer Height	0.050 mm
Bottom layers	9
Exposure time	3.200 s
Delay when turning off UV	2.500 s
Lower lifting speed	60.00 + 180.00 mm/min
Lifting speed	45.00 + 180.00 mm/min
Lower retraction speed	180.00 + 60.00 mm/min
Retraction speed	180 + 45.00 mm/min
Retraction Distance	6.00 + 6.00 mm

Printing of the biomodel

The biomodel was printed in 13 hours, 41 minutes and 33 seconds, on an AnyCubic Photon M3 Max printer using photopolymerization 3D printing with a light beige Anycubic Standard resin.

After printing, the biomodel was submitted to two post-processing stages. First, it was bathed in isopropyl alcohol for 5 minutes to remove excess liquid resin from the surface, and then placed in a UV Curing chamber for 20 minutes to complete solidification.

Results and Discussion

Due to the complexity of the details and the fact that the technique produces better quality printed models, printing the cardiac biomodel of a Beagle from this protocol using the photopolymerization technique (Figure 8) was effective in maintaining the large structures of the heart and fabricating it entirely without having to slice or print it into two halves, as demonstrated in (Giannico et al., 2023).

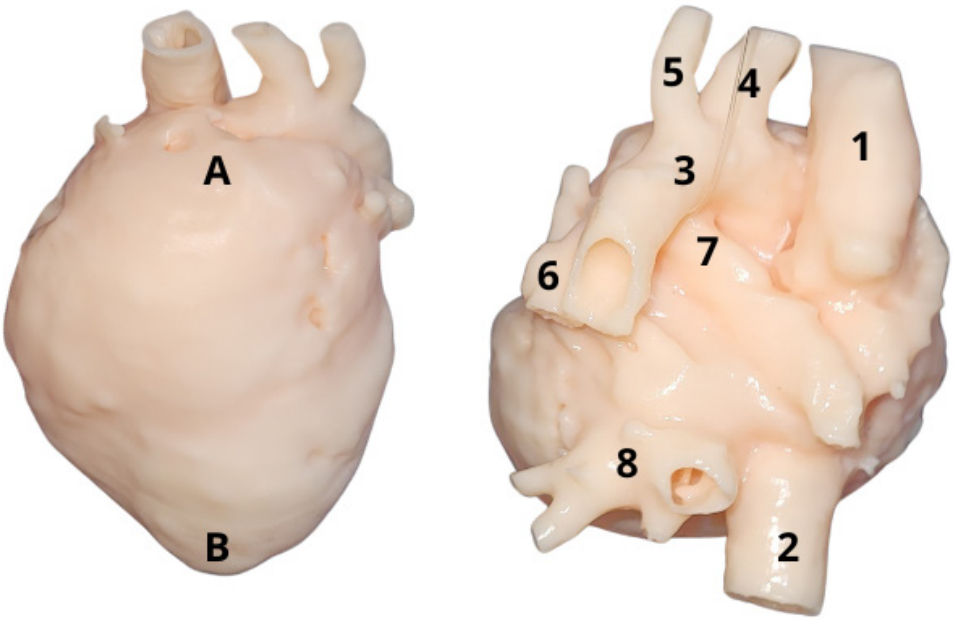

Figure 8. Heart printed in resin using the photopolymerization technique, indicating the main anatomical structures. The letter indicates the structures: A – Base, B – Apex; 1 – Cranial vena cava, 2 – Caudal vena cava, 3 – Aorta, 4 - Right subclavian artery, 5 – Left subclavian artery, 6 – Left pulmonary artery, 7 – Right pulmonary artery, 8 – Pulmonary veins.

During the development of the project, some difficulties were encountered that may be a hindrance for those with little experience in modeling and 3D printing (Table 2). One is related to the DICOM file. In some sets of images, phantoms may make it difficult to observe the entire organ. The lack of contrast does not prevent the model from being manufactured, but makes it difficult to select the regions of interest and increases production time.

Another difficulty was finding a pattern of masks from the software to identify structures that are difficult to detect, such as the atria. To solve this problem, several different-colored masks were created to facilitate visualization of darker and lighter structures.

Before producing an anatomical model such as the entire heart, it is important to note the size of the printing table, which, depending on the printer, does not support the size of the organ, as well as the number of support structures that are created to produce an error-free model.

This heart is used in undergraduate anatomy classes to allow students to macroscopically examine it. As observed by Petersson et al. (2009), studying anatomy without cadavers but using 3D anatomical parts may be a functional and intuitive alternative to continue using the senses, primarily tactile, and consolidate learning about the size of the organ and characteristics that can vary anatomically between individuals.

Manufacturing time was relatively fast given that the heart would still undergo mandatory post-processing linked to the methodology. Undergraduate professors would be able to prepare their course material a few days before the class.

Another important benefit is the ability of the printed biomodel to be patient-specific, in this case a Beagle. In cases of advanced anatomy teaching, CT heart scans of macroscopically important pathologies, such as aortic and pulmonary stenosis, persistent ductus arteriosus, and malformation in the septa that separate the cardiac chambers, can be studied without the need for dissection.

In this respect, the cost of producing a biomodel specific to a CT scan is more closely related to the time spent to produce it than the printing equipment required. One of the factors that can change manufacturing is the rendering time of the 3D mesh from DICOM. This step may vary depending on the software, computer settings and, most importantly, the user's experience with 2D medical images.

Table 2
Main difficulties and respective resolutions during biomodel development

Resolution of problems encountered during biomodel development	
Difficulties	Resolution
Set of images with several phantoms and no contrast.	Choose a dataset with the highest capture resolution and that was preferably captured during contrast infusion.
Difficulty in identifying the beginning and end of the main morphological structures (atria, ventricles, aorta, etc.).	In the CT Heart tool, identify as many seed points as possible so that the software understands the beginning and end of each region.
Dark regions or regions that are difficult to identify due to the brightness or contrast of the software.	Create new masks with different colors that highlight darker regions. Yellow and blue masks provide greater clarity in structures that are difficult to identify.
Many adjacent structures when rendering the three-dimensional model.	Some structures such as ribs, spine and liver may appear because they have a Hounsfield scale similar to that of the apex of the heart. To that end, it is possible to use manual selection tools in the segment → Multiple Slice Edit tab and disregard what is not of interest to the project.
Very rough surface when finishing the 3D rendering of the file.	Export the STL and import it into CAD software to smooth the mesh and make it easier to print.
Several jagged triangles in the mesh and open spaces inside the heart, which is not possible to access without cutting the model.	Use software that automatically corrects mesh errors related to irregular triangles. Cutting the model to edit the mesh can alter the anatomy and triangle distribution, creating an altered anatomy instead of a realistic model.

Conclusions

Research in health sciences technology and teaching has increased in recent years. There are clear benefits to manufacturing 3D printed biomodels for anatomy teaching, especially for preparing more personalized classes and using active teaching methodologies that incorporate theoretical and practical knowledge into everyday situations.

This study is the continuation of a series of research projects on the manufacture of cardiac models for health education, using a small protocol to construct a biomodel.

The literature lacks protocols to produce anatomical biomodels, a fact that is not common in areas that have been using AM manufacturing for more than 20 years and have well-established protocols for producing parts and components.

Future research is needed to evaluate teachers' and students' perceptions concerning biomdel use in the classroom and for specific anatomy practices.

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