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Echocardiography and 3D printing: cardiac models for the education of dog owners

Ecocardiografia e impressão 3D: modelos cardíacos para a educação de tutores de cães

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Highlights

Is possible to develop 3D cardiac models that help understand the echocardiography.
3D printed models improved owner's understanding of echocardiographic examination.
This study generated 3D digital models where it is possible to download.
3D cardiac model can help veterinaries in communicating with the owners.

Abstract

Three-dimensional (3D) printing is a new method for creating human and veterinary anatomical models, which makes the education of students and professionals in the health area more complete, in addition to helping the patients themselves understand. In the area of cardiology, this technique can efficiently help the assessment of cardiac alterations for the patient during medical consultations, tying a feeling of involvement with the medical team. Likewise, it is possible to use 3D printing to understand the echocardiographic technique, where conceptual knowledge of the anatomy of the heart and the ability to translate a two-dimensional ultrasound image into a 3D idea is required. This research aimed to develop printable 3D cardiac models, to demonstrate cardiac sections used in echocardiography and use them to teach dog owners, evaluating their suitability as a tool for a better understanding of the echocardiographic exam. The 3D cardiac models were validated by dog owners through an evaluation questionnaire prepared on a Likert scale, after monitoring the echocardiographic examination with an explanation by the echocardiographer using the printed models. A total of 30 dog owners participated in the study. In all seven questions of the questionnaire, the vast majority of positive responses were observed, with partial or total agreement by the participants. These results showed that the use of 3D printed models is effective in improving the understanding of the echocardiographic examination and is

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feasible in the daily workflow.
Key words: 3D printing. Anatomical heart. Echocardiography. Three-dimensional model. Veterinary medicine.

Resumo

A manufatura aditiva ou impressão 3D é um novo método para a criação de modelos anatômicos humanos e veterinários, que torna a educação de alunos e profissionais da área da saúde mais completa, além de auxiliar o entendimento dos próprios pacientes. Na área da cardiologia, esta técnica pode auxiliar de maneira eficiente a avaliação das alterações cardíacas para o paciente durante as consultas médicas, atrelando um sentimento de envolvimento com a equipe médica. Da mesma maneira, é possível utilizar a impressão 3D para o entendimento da técnica ecocardiográfica, onde é necessário conhecimento conceitual da anatomia do coração e a capacidade de traduzir uma imagem de ultrassonografia bidimensional em uma ideia tridimensional. Este artigo teve como objetivo desenvolver modelos cardíacos 3D imprimíveis, com o intuito de demonstrar cortes cardíacos utilizados na ecocardiografia e utilizá-los para ensinar os tutores de cães, avaliando sua adequação como ferramenta para melhor compreensão do exame ecocardiográfico. Imagens em DICOM de um exame de tomografia computadorizada de uma cadela foi adquirida para criação, edição e impressão dos diferentes modelos em 3D, que representam os cortes ecocardiográficos. Os modelos cardíacos em 3D foram validados por tutores de cães por meio de um questionário de avaliação elaborado em uma escala Likert, após acompanhamento do exame ecocardiográfico com uma explicação pelo ecocardiografista utilizando os modelos impressos. Um total de 30 tutores de cães participaram do estudo. Em todas as sete perguntas do questionário, foram observadas em sua grande maioria respostas positivas, sendo elas com concordância parcial ou total dos participantes. Até o momento não foram encontrados na literatura estudos com modelos de coração desenvolvidos para a educação clínica dos tutores de cães. Os resultados revelam que o uso dos modelos impressos em 3D é eficaz para melhorar a compreensão do exame ecocardiográfico e é viável no fluxo de trabalho diário.
Palavras-chave: Coração anatômico. Ecocardiografia. Modelo tridimensional. Medicina veterinária. Impressão 3D.

Introduction

In recent years, additive manufacturing or three-dimensional (3D) printing has become a new method for creating human and veterinary anatomical models (Liaw & Guvendiren, 2017; Wilhite & Wölfel, 2019), that generated opportunities to improve education, although its use for this purpose has only just begun to be explored. Anatomical models support students and professionals understand the three-dimensionality of structures through visual inspection and direct manipulation of normal or pathological human and animal models (Pawlina & Drake, 2013).

3D models can convey complex anatomical arrangements and describe changes caused by disease. They can be instructional to teach professionals and improve patients' understanding of the disorder (Vukicevic et al., 2017). They can become tools to clarify procedures for patients during medical consultations, a practice that improves patient satisfaction and ties a sense of involvement with the medical team (Biglino et al., 2015).

Understanding the echocardiographic technique requires conceptual knowledge of the anatomy of the heart and the ability to translate 3D anatomical spatial orientation into a two-dimensional grayscale ultrasound image (Moscova et al., 2015). Unfortunately, virtual models cannot offer what physical objects provide with their tactile qualities. These are the reasons why 3D printed anatomical models have been increasingly used in cardiology training.

Owners usually do not have enough technical training and knowledge to understand the echocardiographic examination of their dogs. The equivalent occurs with biomodels of humans, where it has already been shown by some studies that 3D printed hearts are effective in improving the understanding of heart disease for patients themselves and their families (Awori et al., 2021). 3D-printed cardiac models with echocardiographic cross-sections in the examination of canine patients have already been used in veterinary medicine and have been shown to have benefits for students in teaching echocardiographic anatomy, involving them and offering technology in the learning process (Borgeat et al., 2022).

Until then, these models were not used to demonstrate echocardiographic cross-sections and use them for teaching dog owners. Thus, the objective of this study was to evaluate the suitability of 3D-printed hearts as a tool for a better understanding of the echocardiographic examination, improving communication between the veterinary cardiologist and the owners of their patients.

Materials and Methods

A computed tomography (CT) scan of a six-year-old female Beagle dog, in good general health, weighing 10.5 kg, with an echocardiographic examination showing parameters within the normal range, was selected to generate the 3D cardiac model. Intravascular contrast was used in these CT examinations to outline cardiac structures and the great vessels. The images in DICOM (Digital Imaging and Communications in Medicine) format were imported into Materialise's Interactive Medical Image Control System (Mimics) (Leuven, Belgium), and segmented to remove non-cardiac structures (Figure 1). Segmentation methods like automatic, semiautomatic, and hand segmentation were used to create a 3D digital cardiac segmentation. The created file was converted into STL (StereoLithography) format and edited to correct any imperfections and flaws in the geometry in the program MeshMixer 3.0 (Autodesk® Inc.), by a veterinary cardiologist (author ATG) (Figure 2).

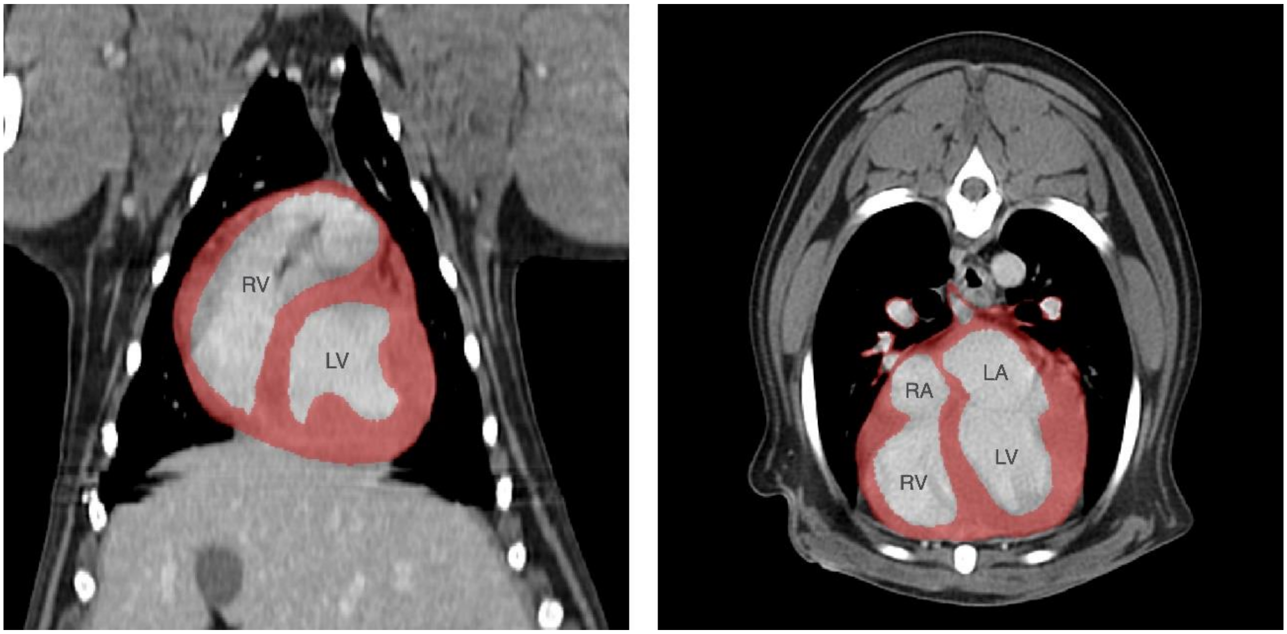

Figure 1. Segmentation of the heart from cardiac computed tomography (CT) of a six-year-old female Beagle dog. The cropping of the mask is in red, restricting the region of interest to the myocardium, excluding the blood volume. The anatomical representation is then transformed into a StereoLithography (STL) format. LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

Three models of hearts were reproduced in 3D printing at a 1:1 scale, representing four specific echocardiographic views, one of which shows two transverse echocardiographic views, and the other two models show the two longitudinal views. The echocardiographic cross-sections represented in the two 3D print heart models are the left parasternal long-axis 4-chamber view (Figure 2C) and the left parasternal long-axis 5-chamber view (Figure 2D). The echocardiographic cross-sections represented in another one of the 3D print model hearts are the right parasternal short-axis view at the level of the papillary muscles and the right parasternal short-axis view at the level of the left atrium and aortic root (Figure 2E and 2F, respectively). The atrioventricular valves could not be defined by the CT exam, and, for this reason, they were created similar to the anatomical structure in the MeshMixer 3.0 program.

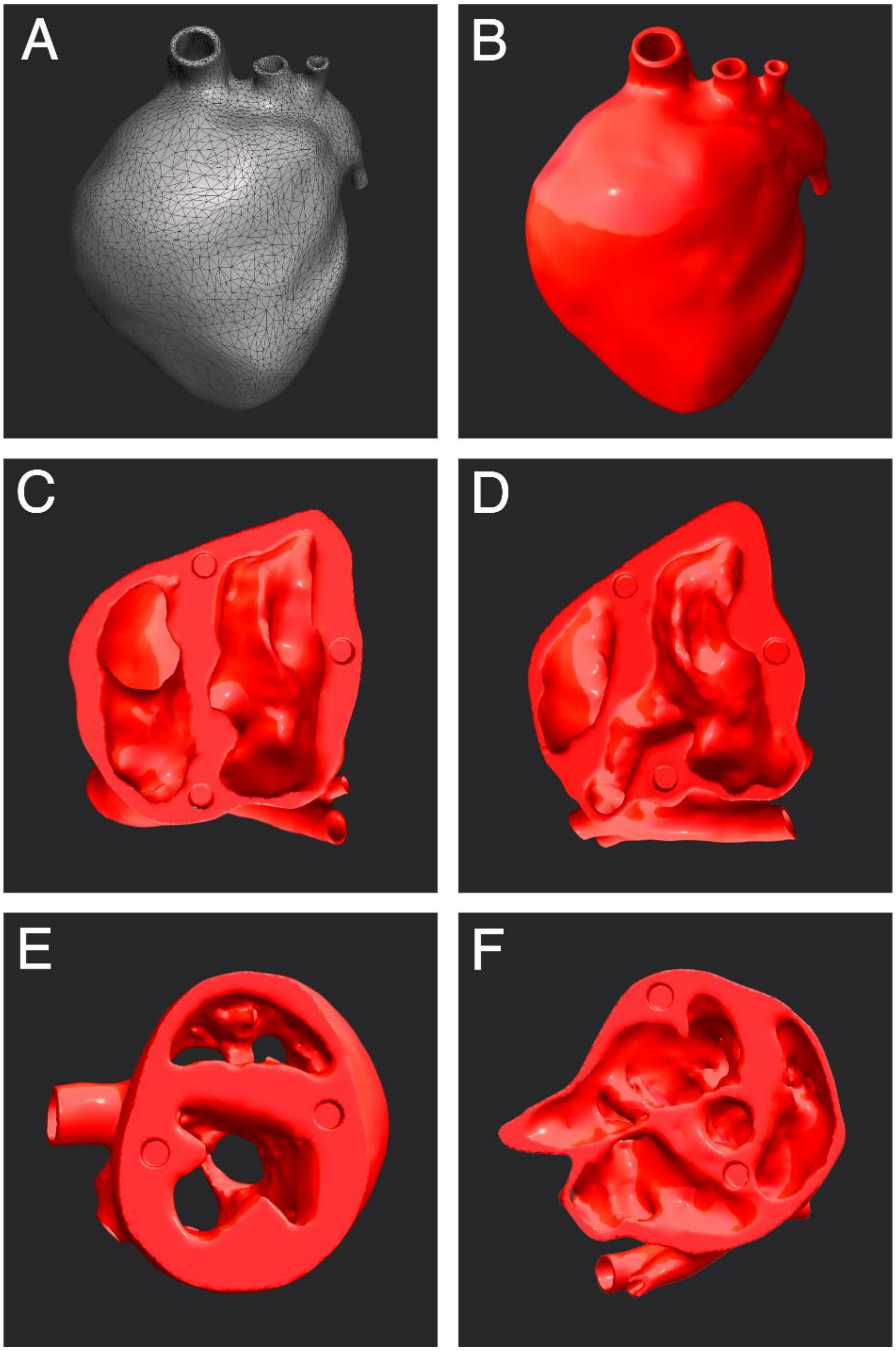

Figure 2. Generation of a three-dimensional (3D) digital model. The manipulation of the StereoLithography (STL) format with the aid of computer-aided design software. Fixing holes in the geometry and cleaning the surface through wrapping and smoothing. A – The 3D digital model of the heart without the echocardiographic cross-sections, showing the 3D mesh surface as a collection of triangles or facets. B – The 3D digital model of the heart without the echocardiographic cross-sections. C – Left parasternal long-axis 4-chamber view. D – Left parasternal long-axis 5-chamber view. E – Right parasternal short-axis view at the level of the papillary muscles. F – Right parasternal short-axis view at the level of the left atrium and aortic root.

The geometry of the three heart models was processed by Ultimaker Cura software, version 4.12.1 (Ultimaker BV, Netherlands) and sent to the 3D printer (BLU-3 V2, Two Trees, China), with material extrusion printing technology, printed in polylactic acid (PLA) (Slim 3D). The atrioventricular valves were printed in thermoplastic polyurethane (TPU). The printing parameters used for each type of material are described in Table 1. The valves were glued with ethyl-cyanoacrylate to the PLA-printed hearts in the exact location and the magnets in the fixing hole were made in each piece.

Table 1
The printing parameters used for the three heart models with polylactic acid (PLA) and the atrioventricular valves with thermoplastic polyurethane (TPU)

Parameters	Polylactic acid (PLA)	Thermoplastic polyurethane (TPU)
Layer height	0.12 mm	0.2 mm
Top and bottom layers	3	3
Wall line count	3	3
Infill density	10%	20%
Nozzle temperature	200˚C	220˚C
Build plate temperature	60°C	75°C
Print speed	50 mm/s	15 mm/s
Support overhang angle	60˚	60˚
Retraction distance	6.5 mm	0

Dog owners were recruited during clinical consultations with a cardiologist and, after the consent, the echocardiographer explained the echocardiographic examination to them using the printed cardiac models (Figure 3). Participants had the entire duration of the exam to view and handle the models.

A questionnaire with seven questions on a Likert scale was given to the participants after the completion of the echocardiographic exam with the models, to assess their understanding of the exam and the functioning of the heart, and possible existing disease. The seven questions are described in Table 2.

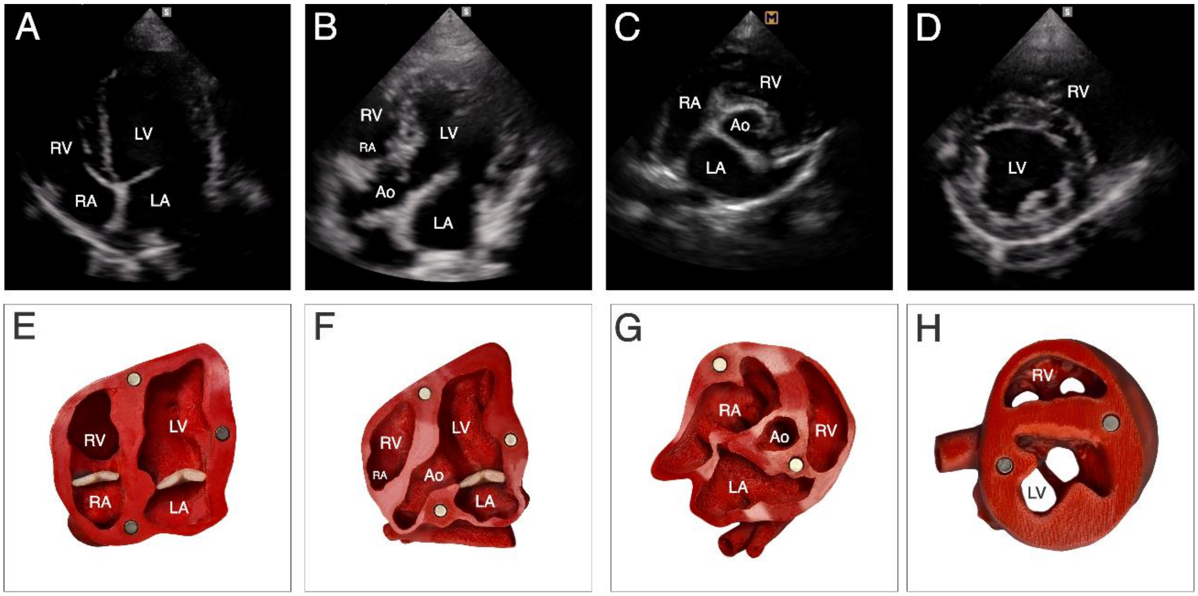

Figure 3. The echocardiographic cross-section images (A to D) and their respective photographs of three-dimensional (3D) cardiac print models (E to H). Models represent four echocardiographic views: left parasternal long-axis 4-chamber (A and E), left paraesternal long-axis 5-chamber (B and F), right parasternal short-axis at the aortic root (C and G), and right parasternal short-axis at the papillary muscles (D and H). Ao, aorta; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

It was chosen to define concise and direct questions, as the scope of this study was limited to initial impressions of understanding by people who did not have technical knowledge of the subject. In addition, the objective of the study was to assess the feasibility of using models in a busy service flow. Thus, the questions were limited and simple to support feasibility. Likert scale ranged from 1 to 5: 1 = strongly disagree, 2 = partially disagree, 3 = indifferent, 4 = partially agree, and 5 = strongly agree. Finally, the participants also could fill a free-text comment for the subjective feedback, where they could give their opinion, and evaluate the usefulness of the 3D models for communication, education, and their general satisfaction with the models, with the questionnaire being anonymous. The answers to the questions were compiled for statistical analysis. Cronbach's alpha was used to evaluate the internal consistency of the Likert scale questions. Statistical analyses were performed using IBM® SPSS® Statistics, version 28.0.1.1 (IBM Corp., Armonk, NY).

Results and Discussion

A total of 30 participants were recruited. The quantity of each questionnaire answered by the Likert scale, considering a negative, neutral and positive result, is described in Table 2. The descriptive analysis of question answers is demonstrated in Table 3. Cronbach's alpha ($\alpha=0.862$) showed high internal consistency of the Likert scale questions and research confidence (Landis & Koch, 1977).

Table 2
Responses to the seven questionnaire questions on dog owners' experiences of using the three-dimensional (3D) printed heart models during the echocardiographic exam. The Likert scale used was considered negative (scale 1 and 2), neutral (scale 0), and positive (scale 4 and 5)

	Responses (n = 30)		
	Negative (1 and 2)	Neutral (3)	Positive (4 and 5)
1 - The manipulation of the 3D model helped to understand the anatomy of the heart.	0	0	30
2 - The 3D model made me better understand my pet's heart and disease (if any).	0	1	29
3 - The use of the 3D model made me understand the echocardiographic exam better.	0	0	30
4 - I prefer to follow the exam of my pet using the 3D model.	0	1	29
5 - I am more satisfied with the service because I can better understand the exam.	0	0	30
6 - I understood better the importance of the exam for the diagnosis of my pet.	0	2	28
7 - I recommend the 3D model for understanding other diseases and exams.	0	0	30

Likert scale ranged from 1 to 5: 1 = strongly disagree, 2 = partially disagree, 3 = indifferent, 4 = partially agree, and 5 = strongly agree.

Table 3
Descriptive analysis of responses to the seven questionnaire questions about owners' experience of using three-dimensional (3D) printed heart models. Likert scale ranged from 1 to 5, where: 1 = strongly disagree, 2 = partially disagree, 3 = indifferent, 4 = partially agree, and 5 = strongly agree

	Questions						
	1	2	3	4	5	6	7
Average	4.97	4.83	4.97	4.80	4.93	4.73	4.87
Median (IQ 25%-75%)	5 (5-5)	5 (5-5)	5 (5-5)	5 (5-5)	5 (5-5)	5 (5-5)	5 (5-5)
Mode	5	5	5	5	5	5	5
Standard deviation	0.183	0.461	0.183	0.484	0.254	0.583	0.346
Minimum	4	3	4	3	4	3	4
Maximum	5	5	5	5	5	5	5

IQ: interquartile.

A percentage of 96.7% (n=29) of the participants strongly agreed and 3.3% (n=1) partially agreed that the 3D model helped understand the heart's anatomy. Eighty-six percent (n=26) and 10% (n=3) of the participants strongly agreed or partially agree that the 3D printed heart made them understand their dog's heart and disease, although only 3.3% (n=1) said it was indifferent. Similar responses were also found when asked about the preference to follow the exam using the 3D model. Almost 100% of dog owners strongly agreed (96.7%, n=29) that using the 3D model made them better understand the echocardiographic exam. When asked about better satisfaction with the service because they better understood the exam, 93.3% (n=28) of participants strongly agreed and 6.7% (n=2) partially agree. In the question about "better understanding, the importance of the exam for the diagnosis with the use of the 3D printed cardiac model", 80% (n=24) of the tutors totally agreed, 13.3% (n=4) partially agreed and 6, 7% (n=2) of tutors classified it as indifferent. Finally, participants strongly (86.7% and n=26) and partially (13.3% and n=4) agreed and recommend the 3D model for understanding other diseases and exams. These overall participants' feedback is summarized in Figure 4.

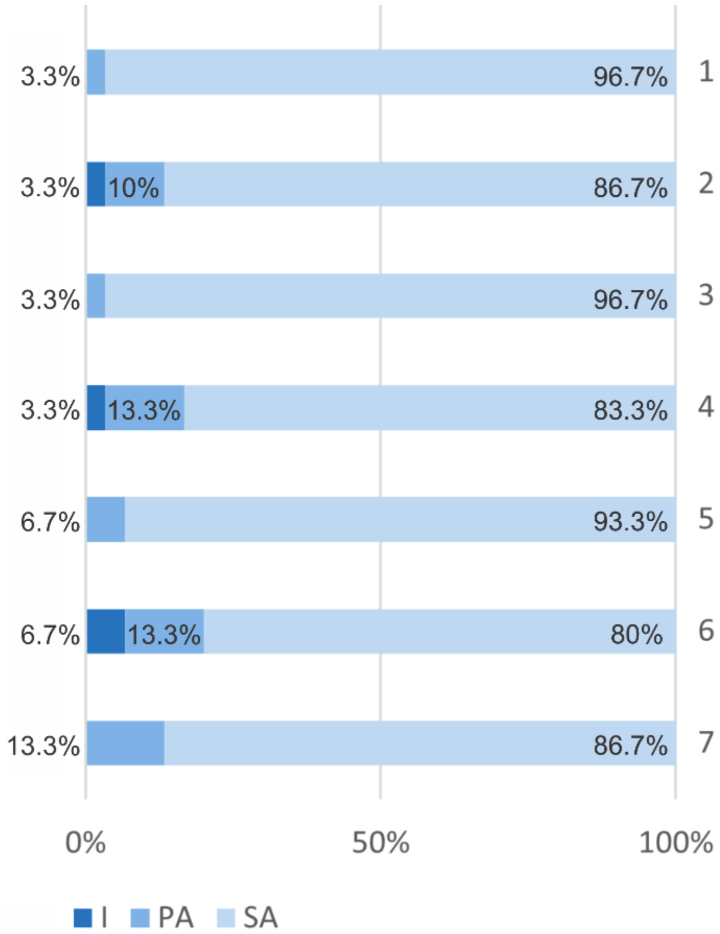

Figure 4. Graph exemplifying the percentage of the seven questionnaire responses (questions are in Table 2) using the five Likert scale, performed with 30 dog owners during the echocardiographic examination using the three-dimensional (3D) printed cardiac models. Likert scale ranged from 1 to 5 (1 = strongly disagree, 2 = partially disagree, 3 = indifferent (I), 4 = partially agree (PA), and 5 = strongly agree (SA).

Free-text comments were made by 16/30 (53.3%) participants, and they generally commented that the models helped them to understand the cardiac structure more clearly, improving their understanding of the echocardiographic images. Owners' comments included statements about compliments on the initiative and use of technology and saying that because they are not from the health area, they better understood the exam.

In this study, it was shown that it is possible to develop 3D printed cardiac models from CT images of dogs that help pet owners understand the echocardiographic examination. Data from this study suggest that the use of 3D-printed models may be helpful for this group of people to understand cardiac anatomy in a clinical context, and users of the models strongly believed that they should be used more frequently. In the clinical routine of medicine and veterinary medicine, echocardiography, magnetic resonance imaging (MRI), and CT exams are used for cardiac evaluation, and their images are difficult to understand both for students and patients and patient owners. The images provided by these complementary exams are difficult to understand, as knowledge and an assessment are required in a single two-dimensional plane. The advantage of 3D printed models is that they provide a real 3D spatial relationship that helps to understand their complexity after viewing conventional images (Valverde, 2017; Anwar et al., 2018; Borgeat et al., 2022; Valverde et al., 2022).

There is only one study using 3D printed cardiac models in veterinary medicine with undergraduate students (Borgeat et al., 2022). This study showed that students score higher on a test after using 3D cardiac models and advocates introducing teaching anatomy using 3D printed models in veterinary undergraduate courses. In medicine, there are publications with the use of these models for teaching patients and their families, which show enhanced patient-perceived understanding of cardiac disease (Awori et al., 2021). Similar research in veterinary medicine with the teaching of pet owners using 3D printed hearts are not available. Thus, this study is the first to show the use of 3D-printed cardiac models for teaching dog owners.

What makes the models more interesting for patient owners is the authenticity of the models: they are of a real dog, not a standard didactic model that would be ideal for theory. Many participants are surprised to learn that the model is the size and shape of a real heart, and they make comparisons with their pet's heart. Thus, the use of new devices and technology can help trigger situational interest. The impact of the use of 3D-printed models on the engagement of both students and using it to explain to the patient has already been evidenced (Biglino et al., 2015; Borgeat et al., 2022), demonstrating that the involvement of people has positive effects on the results of learning and improves their experience and satisfaction (George et al., 2008).

Regarding the feasibility of incorporating such models into the flow of cardiology exams, this study showed that 3D instruction does not impose a significant increase in time during patient care. Previous medical studies show that the use of 3D printed cardiac models in the clinic led to an average increase of 5 minutes per consultation, not perceived as problematic by physicians (Biglino et al., 2015; Awori et al., 2021). In addition, even with these small increases in time during the exam, there can be significant time-saving gains in thinking about the entirety of the care, by decreasing anxiety and increasing understanding for dog owners.

The teaching potential of 3D models does not just lie in the immediate pedagogical problems it can solve but plays on the broad visual knowledge it can create, readily available around the world. Having shown the associated benefits in terms of generation time and cost and, mainly, the potential to improve the understanding demonstrated by 3D digital models, it is suggested that further studies be carried out with an analysis of this modality and its cost-benefit of including 3D modeling in clinical practice.

This study generated 3D digital models that can contribute to a virtual database of cardiac specimens. A link is provided to the reader in this article, where it is possible to download the STL files used in this research. Cardiac specimen files are not widely available online (Kiraly et al., 2019), but we believe that it would be interesting if all future research using 3D models could make them available to any practitioner, teacher, or student so that they have the opportunity to print and use them for didactic purposes.

Using technology that is constantly evolving, it is possible to improve 3D models acquired by CT and MRI. A limitation of this 3D technique occurs with the heart, where a static model of a dynamic organ is made, making it difficult to understand its hemodynamic functioning (Gosnell et al., 2016). In this study, CT was used, but future work will likely have 3D echocardiography as an ally for more accurate renderings, improving understanding and communication about the heart, its function, and diseases.

As a limitation, this present study used a reasonable number of participants but, despite this, the results were adequate and reliable conclusions were possible. The educational background of the participants was not evaluated and, therefore, it was not possible to assess whether a higher level of education would make anatomical and physiological explanations about the heart more accessible.

Conclusions

The use of 3D printed cardiac models for client clinical education (dog owners) appears to be useful and proved to be effective in improving the understanding of the echocardiographic examination without significantly impacting clinical workflow and would be interesting to use them again. The printing of 3D cardiac models is a low-cost process that, being widespread, can help many veterinary professionals in communicating with the owners of their patients.

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