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Three-dimensional printed models of the heart represent an opportunity for inclusive learning

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Abstract

3-dimensional (3D) printed models of anatomic structures offer an alternative to studying manufactured, "idealised" models or cadaveric specimens. The utility of 3D printed models of the heart for clinical veterinary students learning echocardiographic anatomy is unreported. This study aimed to assess the feasibility and utility of 3D printed models of the canine heart as a supplementary teaching aid in final year vet students. We hypothesized that using 3D printed cardiac models would improve test scores and feedback when compared to a control group.

Students (n=31) were randomised to use either a video guide to echocardiographic anatomy alongside 3D printed models (3DM), or video only (VO). Prior to a self-directed learning session, students answered eight extended matching questions as a baseline knowledge assessment. They then undertook the learning session and provided feedback (Likert scores/free text). Students repeated the test within 1-3 days. Changes in test scores and feedback were compared between 3DM and VO groups, and between students track an non-track rotation students.

The 3DM group had increased test scores in the non-track sub-group. Track students' test scores in the VO group increased, but not in the 3DM group. Students in the 3DM group had a higher completion rate and more left free-text feedback. Feedback from 3DM was almost universally positive, and students believed more strongly that these should be used for future veterinary anatomy teaching.

In conclusion, these pilot data suggest that 3D printed canine cardiac models feasible to produce and represent an inclusive learning opportunity, promoting student engagement.

Introduction

Contextualising a knowledge of anatomy with clinical imaging techniques is essential for final year veterinary students, as this will allow them to interpret images obtained during case investigations and facilitate decision making for the benefit of the patient. A particular challenge may be encountered when students must incorporate a three-dimensional (3D) visual map of a complex structure, often learned using cadavers in the early years of veterinary school, into two-dimensional (2D) clinical imaging techniques. One example of this is when final year students are called upon to interpret echocardiographic images; a greyscale, 2D representation of a complex, moving structure. A common way for students to be introduced to echocardiographic anatomy is by being verbally guided through an echocardiogram as it is being performed by a veterinary cardiologist. This may not be the best method to help many students understand the anatomical structures that are being imaged, and using 3D models has been shown to improve medical students' understanding of spatial anatomy (1).

Models of anatomic structures have been used in teaching and learning for many years, initially made from resin and plaster, then more recently using plastics. 3D printing is a technique for building physical models using an extruded plastic polymer, which is built around a computer-generated 3D image of a structure (the source data). In veterinary and medical patients, source data are often derived from numerous 2D slices of anatomic structures, such as those obtained from a computed tomography (CT) or magnetic resonance imaging study. In this way, 3D printed anatomic models can be manufactured which reflect particular species- or breed-specific anatomy and therefore provide an authentic representation from which students can learn (1). Anatomic models of diseased organs can also be printed, which may help further in undergraduate education, specialist post-graduate training (2) and surgical planning (3, 4).

In human medicine, using 3D printed models has been shown to complement the curriculum of body-wide anatomy education (5), and 3D printed cardiac models were reported to improve undergraduate student test scores compared to the use of cadaver-derived material (6) or traditional small-group seminars (7). In addition, using 3D printed models of the heart has been shown to improve engagement and communication between members of the public and clinicians (8). However, using a 3D printed model compared to using traditional models of the heart did not improve test scores or student satisfaction in another study (9). Similarly, using a 3D computer model (not printed) of hepatobiliary anatomy did not show test-performance benefit over use of an instructional textbook, but student satisfaction scores were higher with the 3D on-screen model (10).

In veterinary undergraduate students, 3D printed models from clinical imaging datasets have shown academic and student satisfaction benefits in addition to standard teaching methods (11-14). In addition, 3D printed models have the added benefit of not involving the handling of animal tissues, which may present a biohazard and limit the opportunities for study outside of a specific, controlled environment (14).

Currently, no data evaluating the use of 3D printed cardiac models in teaching veterinary anatomy have been published. Our overall project aim was to evaluate the fitness of 3D printed models of the heart as a learning tool for veterinary cardiac anatomy in a clinical context. We hypothesized that using 3D models in addition to a video guide to echocardiographic anatomy would result in higher test scores and more positive student feedback after a self-directed learning exercise for final year veterinary students.

Materials and methods

Source data and modelling

Raw data from a CT scan [a] of an 8-year-old, male neutered lurcher (weighing 26 kg) was used to generate the 3D computer models. Images had been obtained during investigation of a cardia arrhythmia, but no primary heart disease was identified on echocardiography, and the results of the CT scan were reported to be normal by the attending radiologist. Intravascular contrast was used to delineate cardiac structures and the great vessels.

Images (DICOM format) were imported into Materialise Mimics v21.0 (Materialise, Leuven, Belgium) and segmented to remove non-cardiac structures, as previously described (ref doi: 10.1148/radiol.2422051994). Computer models were then imported into 3-Matic post processing software (Materialise) and reviewed by a veterinary cardiologist (KB). They were cut in four standard echocardiographic image planes as follows: right parasternal long-axis 4-chamber view; right parasternal long-axis 5-chamber view; right parasternal short-axis view at the level of the papillary muscles, and right parasternal short-axis view at the level of the left atrium and aortic root. This produced four pairs of computer models, which each represented the heart bisected at an angle to represent a standard clinical echocardiographic image view.

3D printing

The finalised computer models were exported life size from 3-Matic as STL files, a format suitable for import into the 3D printer specific software Preform (Formlabs, Somerville, MA, USA). Models were printed on a Form 2 3D printer (Formlabs) using white V4 resin (FLGPWH04, Formlabs). Once printed, the models were washed in isopropanol in a Form Wash station (Formlabs), then cured using a Form Cure (Formlabs), both according to the instructions of the manufacturer. Supports, which had been previously built around the model to support the printing, were removed manually. Paper was cut into an appropriate shape and used as a substitute material for heart valves. These were attached using superglue in an anatomically accurate position where required within each model (Figure 1).

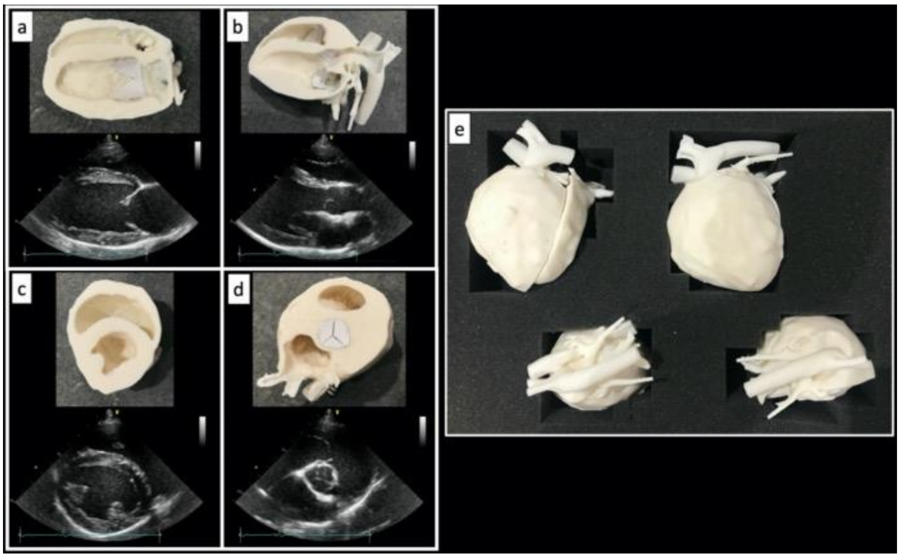

Figure 1: Photographs of the 3D models in cut-section (a-d) and in position as whole hearts, displayed to students upon opening the storage case (e). Models were designed to represent the four most important echocardiographic views: (a) right parasternal long-axis 4-chamber; (b) right parasternal long-axis 5-chamber; (c) right parasternal short-axis at the papillary muscles, and (d) right parasternal short-axis at the aortic root.

Experimental design

Study design was approved by the University of Bristol CREATE Ethics Approval Process. Final year veterinary students were eligible for participation if they provided signed consent after reading a participant information sheet. Students were recruited in one of two ways: first, those undertaking an elective 1-week rotation in cardiology (known as a “track rotation”) were invited to participate during their scheduled week; second, students not choosing to undertake the track rotation were invited by email to participate (these students were working elsewhere in clinics or on-site study). All students had completed a previous “core” cardiology rotation of 2 days’ duration, in addition to clinical lectures on the subject (anatomy – including cadaver specimens – and physiology in year 1, pharmacology and clinical cardiology including basics of imaging-anatomy in year 3). The students undertaking the track rotation received teaching around clinical cases, including discussion of echocardiographic anatomy, during the time course of the study. This was not the case for non-track students, who were undertaking non-cardiology rotations during this time.

Enrolled students were assigned a unique identification number, and then randomised to one of two groups using a random number generator.[c] The control group were assigned a self-directed learning exercise using an online video, in which a veterinary cardiologist (KB) guided them through canine echocardiographic anatomy (online supplementary material S1). The test group were assigned the same exercise, but were allowed to use the 3D printed models alongside the video to consider the relationships between the 2D video images and 3D anatomic structures. It was clearly stated that there was no time limit for the learning exercise and that the video could be re-watched if so desired. Students underwent pre- and post-intervention testing of their anatomic knowledge using an online quiz,[d] and were asked to provide feedback on the learning experience after they had completed the exercise (Figure 2). Unique identification numbers were used throughout to anonymise data.

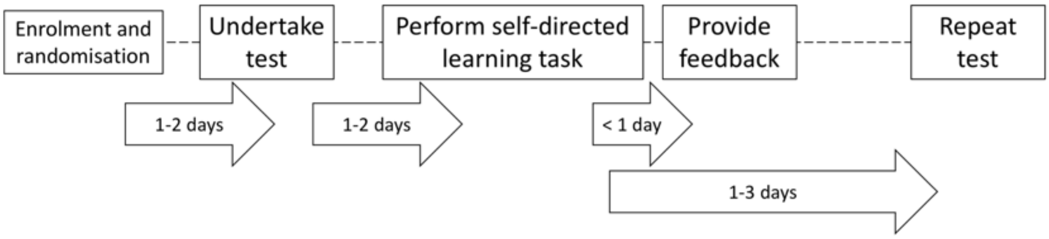

Figure 2: Timeline of tasks for students enrolling in the study. Each student was involved for no more than one 5-day week.

The test used was designed to be a simple and rapid assessment of the students' ability to recognise a cardiac chamber or blood vessel on echocardiographic video loops. Questions were of the extended matching question (EMQ) type; the same answer options were available for each question, so as not to provide a leading set of answers or limit the students' options for their response. Each question had a set of 15 possible answers, including 14 anatomic structures and one option for "I don't know". Only one answer was correct and others were marked as incorrect. Eight different, but standard, echocardiographic views were used to formulate questions, with one video showing an abnormality and two showing a left-sided view (not featured in the video or 3D models; Table 1).

Question	**Echocardiographic view**	**Structure indicated**
1	Right parasternal short-axis view at the papillary muscles	Right ventricle
2	Right parasternal long-axis 4-chamber view (mitral valve)	Left ventricle
3	Left apical 4-chamber view (left ventricular inflow)	Pulmonary vein
4	Right parasternal short-axis view optimised for the pulmonary artery	Pulmonary artery
5	Right parasternal long-axis 5-chamber view (aortic valve)	Aorta
6	Right parasternal short-axis view optimised for the left atrium and aortic root (normal left atrial size)	Left atrium
7	Left-apical 4-chamber view (left ventricular inflow)	Right atrium
8	Right parasternal short-axis view optimised for the left atrium and aortic root (dilated left atrium)	Left atrium

Table 1: Echocardiographic views used as test material, with the anatomic structure indicated for each. The views for questions 3 and 7 were not shown during the video tutorial.

The feedback form was divided into two sections; first, a series of statements evaluating various aspects of the learning experience using a 5-point Likert scale, followed by a free-text box for participants to input additional information (online supplementary material, S2).

Analysis

Test scores before and after intervention were compared between the groups 3D models and video (3DM) vs. video only (VO), and between track and non-track rotation groups, using a Wilcoxon signed rank test. Feedback was compared between 3DM and VO groups, including review of free-text statements. Statistical significance was set at $p<0.05$. Because of small sample sizes, a trend towards statistical significance was defined as $p<0.1$.

Results

Participants

Out of a year-group of 143 students, 31 (22%) volunteered consent to participate in the study. Failure to complete one or more elements of the study occurred in 5/16 cases (31%) of the VO group (Figure 3), but none of the 3DM group.

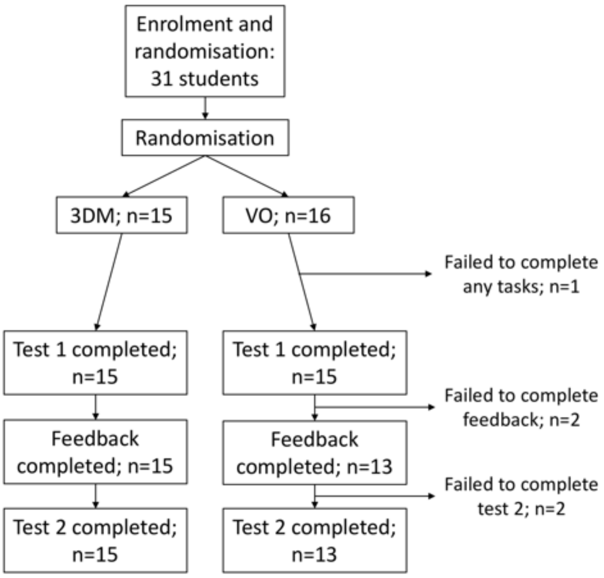

Figure 3: Flowchart to show dropout rate of students at various stages. One of the video only (VO) group did not undertake any tasks after providing consent. Two further students failed

to complete feedback (but did complete test 2), and a different two students failed to complete test 2 (but did give feedback). This left 13 students in the VO group for analysis. None of the 3DM group of students withdrew from the study and all completed all required tasks.

Test scores

The VO group for analysis of test scores (n=13) comprised 6 non-track and 7 track students. The 3DM group (n=15) was composed of 7 non-track and 8 track students. Median test scores were not different between 3DM and VO groups (5/8 pre-intervention, 6/8 post-intervention for both). However, when the demographics were broken down, non-track and track students appear to have benefitted from different learning materials (Figure 4). In the video only group, no significant difference was identified in test scores before and after the intervention for non-track students (p=0.5). In contrast, test scores improved significantly in track students between test 1 and test 2 (p=0.016). In the 3D models group, non-track students' test scores increased between the first and second test (statistical trend: p=0.062), but track students' test scores did not (p=0.75).

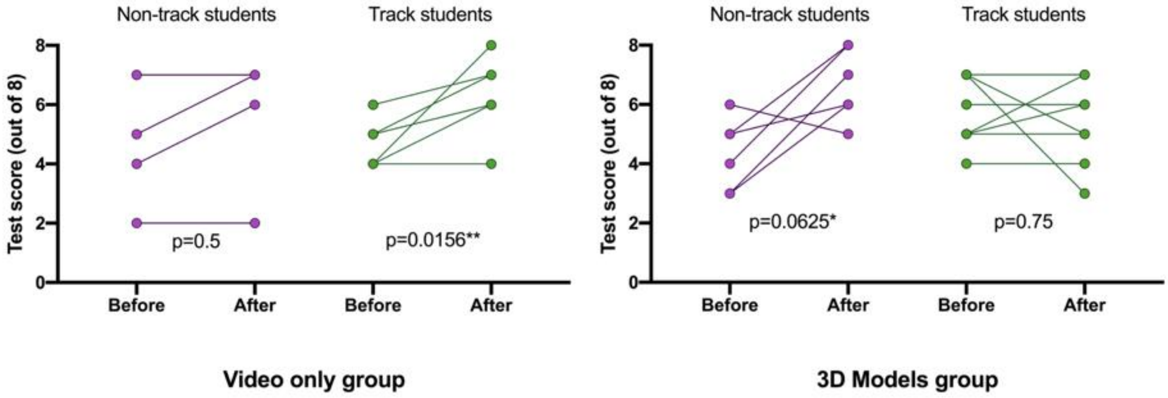

Figure 4: Paired dot plot to show pre- and post-intervention test scores for students undertaking the different echocardiographic anatomy learning exercises, split into non-track and track groups. The data suggests that 3D models were most beneficial for non-track students, but the video tutorial was more helpful for those undertaking the track rotation. (=trend towards statistical significance p<0.1; **=statistically significant at p<0.05).*

Feedback scores

Feedback was generally positive about both types of learning resource. Results are summarised in Table 2. All students in both groups enjoyed using the learning materials. In the 3DM group, all students agreed that their knowledge had improved after the learning session, whereas two students in the VO group had mixed feelings. The majority of students in VO listed negative or mixed feelings about there being sufficient time to use the learning materials, whereas the majority of 3DM students gave positive responses. However, both groups expressed some concerns about the time allowed for the learning exercise, despite no time limit being set.

Whilst the majority of both groups felt positively that 3D models should be used more in teaching anatomy, when looking in detail at the breakdown of "strongly" agree to "partially" agree statements, the 3DM group has a greater proportion of strongly positive statements in response (Figure 5).

Aspect of using learning materials	**Video only group (n=13)**			**3D models and video group (n=15)**		
	Positive (4&5)	Neutral (3)	Negative (1&2)	Positive (4&5)	Neutral (3)	Negative (1&2)
Materials were enjoyable to use	13	0	0	15	0	0
Materials improved my confidence	11	2	0	15	0	0
Materials improved my knowledge	11	0	2	13	1	1
Materials were easy to understand	13	0	0	14	0	1
Sufficient time was allowed for learning	3	5	5	7	3	5
More clinical material should be used in teaching anatomy	12	1	0	14	1	0
3D models should be used more in teaching anatomy	11	2	0	14	1	0
Learning echo anatomy has helped me to become a better vet	11	0	1	13	1	1

Table 2: Responses to the feedback questions regarding students' experiences of using the learning materials. Likert scores 4 and 5 were positive ("partially" and "strongly" agree, respectively), score 3 conferred a neutral response ("I have mixed feelings") and scores 1 and 2 were more negative ("strongly" and "partially" disagree, respectively).

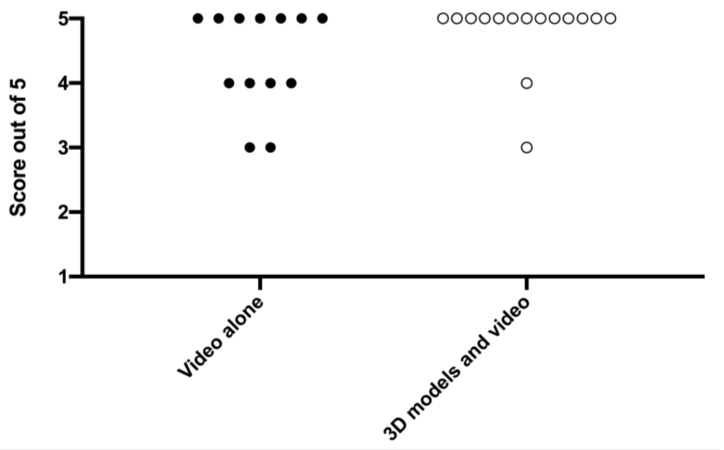

Figure 5: Breakdown of responses to the feedback questionnaire statement, "I would like to use more 3D models in learning anatomy". Likert scores ranged from 1-5, respectively representing: strongly disagree, partially disagree, mixed feelings, partially agree and strongly agree. A greater proportion of students strongly agreed with the statement if they had used the 3D models in the learning session.

Free text feedback

Free text comments were made by 8/13 (62%) in the VO group and 11/15 (73%) in the 3DM group.

Students in the 3DM group generally commented that the models helped them to understand echocardiographic anatomy more clearly: *"The use of 3D models alongside the echo loops allowed for proper orientation and allowed the whole architecture of the heart to be appreciated",* and *"The models helped visualise the layers of the heart being observed when using M mode and helped me to see why the papillary muscles…"* One student considered that the models may specifically help people who would consider themselves to be of particular learning preferences: *"For practical and visual learners the 3D model is amazing alongside the videos of the echos."* Some more negative comments included a thought that perhaps the 3D printed models were not as good as using cadavers: *"Combining reviewing actual cardiac anatomy i.e. dissecting real hearts in the views that you take on each may be easier than 3D models".* In addition, one student commented that the models did not always look exactly like the images on videos of the echocardiogram: *"The left atrium to aortic view model did not match very well with the echo used in the video which made it slightly confusing to learn from".* Students also commented positively on the video tutorial: *"The video teaching material was really good, especially the echo clips."*

Students in the VO group generally found the video helpful in their learning: *"Really useful, we had nothing like this in years 1-4 and the video made echo anatomy much clearer, especially for the second and third views/probe orientations"* and *"This was a really good and fun additional learning resource!"* More than one student felt that the video moved too quickly: *"Really enjoyed the commentary on top of the video to explain the different views but I think the video should give the viewer more time to adjust to the different views and work out the anatomy before explaining the reason for the view."* In addition, some comments were made to express a desire to have a 3D model alongside the video: *"I also feel like having a 3D model in front of me whilst watching the video would help orientate myself and create a better understanding of the anatomy and how they correlate to the image seen on the echo screen."*

Discussion

We have shown that 3D printed cardiac models that are recognisable to undergraduate veterinary students can be easily produced from a canine CT dataset. Data from our study suggests that using 3D printed models alongside more traditional learning resources may be helpful for a sub-group of students to study cardiac anatomy in a clinical context, and users of the models strongly believed that they should be used in teaching more often.

In this trial, the 3D models seemed to improve test scores in students not undertaking the cardiology track rotation. For students on the track rotation, no difference in test scores was identified. In contrast, test scores improved for track students in the video only group, but not for non-track students. Feedback overall was positive for both video and models, which students found enjoyable and useful for improving their knowledge and confidence. Students in the 3DM group felt more strongly that anatomy teaching should utilise more 3D models. Interestingly, the drop-out rate from the VO group was high and a lower proportion of students left free text feedback comments, which may suggest that students in the 3DM group were more engaged in the process than those in VO.

Lim *et* al (2016) reported that undergraduate test scores increased after the use of 3D printed models as an adjunct teaching aid (6), and Su *et al* (2018) reported improved structural conceptualisation in students taught using a set of 3D models (7). Our data shows that some students score higher on a test after using 3D heart models, but this benefit was not consistent across our small group of participants. Students on the track rotation – an electively chosen week of further cardiology study, during which students receive echocardiographic anatomy teaching around cases seen every day – did not seem to gain the same benefit from using 3D models as students not choosing to undertake the cardiology track rotation (non-track students). In fact, the test scores of two track students using 3D models decreased by 25% or more after using the learning materials. It is possible that the track students were more confident visualising echocardiographic anatomy in 2-dimensions, as this method was familiar to them, and the 3D models provided another level of complexity and thereby potential confusion. This is supported by the observation that the test scores of track students in the VO group significantly improved, where having to re-think anatomy in 3-dimensions was not required. Non-track students' test scores seemed to improve after the use of 3D printed models, perhaps because they did not begin the session with a strong cognitive map of how they visualised echocardiographic anatomy. If this were the case, it argues for the introduction of anatomy teaching using 3D printed models early in the veterinary undergraduate curriculum.

Another aspect of this finding is that using 3D printed models may help foster inclusive learning, by allowing students with a lower background knowledge or less confidence in a particular topic to engage with a subject in a different manner, because of the novelty of the models compared to standard imaging-based teaching material, and also the authenticity of the models – they are from a real dog, not a theoretical ideal. Using novel devices and technology can help to trigger situational interest, the first step on the four-phase model of interest (15), which in turn can bring students into a subject and facilitate engagement with the topic, seeking meaning and leading to better outcomes (16). However, interest-based study is often perceived as more time-consuming by students (16), which may account for our observation that several students felt short on time to use the learning resources, despite no time limit being set.

Despite these differences between the track and non-track students, the student feedback for using 3D printed models was broadly positive, in concordance with reports from similar studies in medical (5-7, 10) and veterinary students (11-14). Although the majority of students in both groups agreed that 3D printed models should be used more in anatomy teaching, those who had actually used the 3D printed heart models showed a stronger agreement. This suggests that students believed the models to be useful when they had not used them, and this belief was affirmed by their use for the majority of students. In addition, students in the 3DM group showed evidence of being more engaged in the process of the study, with no students failing to complete any study tasks (compared to 5 students in the VO group) and a higher proportion of 3DM students completing free text feedback. Engagement, defined as the "time and effort students dedicate to educationally purposeful activities" (17), is vital in the development of deeper learning (18). Although multifactorial, immediate feelings such as enjoyment and interest can stimulate students to become engaged (19), which may be the basis of our observation in this study. Also, the authentic nature of 3D printed anatomy (1) provides an engaging learning environment for students (20), which may also explain our finding. Student engagement is a consideration for higher education quality assurance programmes (21, 22), so the use of learning technology like 3D printed models may impact the wider University, beyond students on the veterinary course.

This study is subject to a number of limitations. First, the population of students is relatively small. Since less than 30% of the final year accepted the invitation to take part in the study, it may not be a representative sample. It is possible that for these final year students, where demands on their time are high, only a small proportion had intrinsic motivation to learn more about cardiac anatomy by volunteering to take part in a study. As we know, many students are extrinsically motivated to learn, with a focus on exam success and learning core material, rather than developing knowledge "for its own sake" (23). In future, more could be done to raise awareness of a study like this within the student body, such as incentives (for example, entry into a prize draw) to help motivate people to participate or liaising with student-led relevant societies (e.g. https://www.m3dicube.co.uk). Also, inclusion of 3D model use as part of a core curriculum tutorial would probably motivate more students to take part, as they might perceive the use of models as "more important" to their learning, rather than a distraction. In addition, only students from a single institution were included in the present study, while a multicentre study would broaden inclusion and increase relevance to the broader veterinary student body. The self-selection of students into track rotation groups adds a possible confounding factor – although in these data it raises some interesting points about inclusive learning opportunities.

It is possible that the present study investigated the utility of 3D printed models to help learn cardiac anatomy too late in the veterinary course. At our centre, students first are taught cardiac anatomy in the early months of the degree course. This may be a better point at which to study the effect of 3D printed models on academic scores and student confidence, as at that time students are less likely to have preconceived ideas of cardiac anatomy and may correct errors in factual learning more easily as a result. Also, at that point the level of knowledge amongst the student body may be more uniform and their own preferences about career path (influencing their track rotation choices) may be less strong, thus removing a confounding factor in evaluating the overall effect of using 3D printed models.

An obvious way to improve our models would be to increase the authenticity by not printing in a single colour (white) but printing a composite of a more realistic colour (red/pink material) or using colours to help label anatomic structures (e.g. right side of the heart blue, left side of the heart red). We may also be able to add notation to the computer model, so that text labels would be printed on the physical models to aid students in identifying important structures. In addition, a set of virtual models could also be tested or provided as well as the physical 3D models, whereby the STL files can be displayed in the forms of user-friendly 3D PDF files that students could navigate, rotate and label.

Despite these drawbacks, our systematic approach to assessing the utility of 3D printed heart models in helping students approach learning the complexities echocardiographic anatomy is a starting point for larger-scale projects evaluating the use of this technology for veterinary student education. Our hypothesis that using 3D printed models would positively impact test scores and student feedback is supported by these data, but only in particular groups or aspects of feedback. This area merits further study, and a larger study evaluating the use of 3D cardiac models at the time of initial teaching in cardiac anatomy would be a logical next step. A cross-over study design may be useful, in which students are randomised to sequentially take part in both study groups and are tested after each. If this could be standardised in a multi-centre study, or undertaken over several sequential year-groups, the population size is more likely to be representative than the current data set.

Conclusions

Creation of 3D printed canine cardiac models was feasible using a clinic-derived CT dataset. Using 3D printed heart models may benefit veterinary students learning echocardiographic anatomy by engaging them in the learning process and offering a learning technology which fosters inclusive learning.

Footnotes

[a] Siemens Somatom eMotion 16-slice scanner, Siemens Healthcare, Camberley, UK
[b] Materialise Mimics, Southampton, UK
[c] Siri for iPhone 7, Apple Inc., Cupertino, CA, USA
[d] Microsoft Forms, Microsoft Inc., Redmond, WA, USA

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