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RESEARCH ARTICLE

The Efficiency of 3D-Printed Dog Brain Ventricular Models from 3 Tesla (3T) Magnetic Resonance Imaging (MRI) for Neuroanatomy Education

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ABSTRACT

Neuroanatomy is widely regarded as one of the most complex subjects in veterinary education and clinical practice. Understanding the brain ventricles in particular can be quite challenging for learners. In addition to classical methods, three-dimensional (3D) printed models can provide an efficient learning process. This study aimed to assess the effectiveness of 3D-printed models (3DPM) depicting the dog brain ventricular system as educational tools in neurology and neuroanatomy. Additionally, it outlines the process of creating these models, from imaging specimens with a 3 Tesla magnetic resonance (MR) to 3D printing. MR imaging was performed on four mesocephalic dogs. The semi-automatic technique was performed on MR images to generate a 3D reconstruction of the brain ventricles. 3D digital images were used to create 3DPM with an FDM printer. An evaluation survey for learners was also conducted to evaluate the efficiency of 3DPM for neuroanatomy education. The ventricular system and associated anatomical structures were easily identified on MR images. A detailed 3D model of the ventricular system was created by this method. It was determined that 3DPM was easily handled, quickly reproducible, cost-efficient, and storable. Besides, a significant number of students stated that the use of 3DPM is necessary and will be more useful in learning neuroanatomy. This technique could help not only education partners like lecturers and learners but also clinicians like radiologists and surgeons to understand canine ventricular anatomy better.

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INTRODUCTION

A thorough understanding of neuroanatomy is indispensable for clinicians to effectively manage neurological cases in veterinary practice. Neuroanatomy can be considered as one of the most complex courses for the learners. Some neurological structures may need to be imagined well to be understood better. The brain ventricular system includes structures with a series of cavities and holes located between them. The primary task of veterinary anatomy education is to provide sufficient information about complex structures, such as the brain ventricles (Adams and Wilson, 2011; Schoenfeld-Tacher *et al.*, 2017; Li *et al.*, 2018; Yi *et al.*, 2019).

While dissection has traditionally been an effective method in anatomy education (Adams and Wilson, 2011; Vaccarezza and Papa, 2015), ethical concerns regarding the large number of animal cadavers used have led to restrictions. This has become the most important challenge in recent years while providing education services by using cadavers and biological specimens. On the other hand, neuroanatomic visuals in various references or electronic sources are mostly two-dimensional (2D) learning materials, and understanding the shape and relationship of the structures can be demanding. Using 2D learning materials to understand three-dimensional (3D) structures often does not bring the desired success (Adams and Wilson, 2011; Shepherd *et al.*, 2017; Smith and Jones, 2018). These previous studies report that instructors and researchers should find alternative educational approaches that reduce animal use and provide more effective learning for students.

Anatomy generally uses fresh-fixed cadavers, plastinates, computer-aided learning tools, and routine books with 2D pictures. However, anatomists are still looking for more effective learning methods instead of those mentioned above when teaching complex structures such as the brain ventricles (Adams and Wilson, 2011; AbouHashem *et al.*, 2015; Schoenfeld-Tacher *et al.*, 2017; Yi *et al.*, 2020).

At this point, it would be appropriate to explain the advantages of 3D-printed models (3DPM) compared to previously mentioned educational materials. 3DPM can easily be used for complex anatomical structures. Individual-specific features can be created in desired configurations. In addition, 3DPM can be prepared at any size and multiple copies can be produced. Therefore, the application of 3DPM has been rapidly developing and becoming widespread in the field of anatomy education in recent years (Adams and Wilson, 2011; AbouHashem *et al.*, 2015; Schoenfeld-Tacher *et al.*, 2017).

The purpose of this research is to evaluate the efficiency and preferability of the 3DPM through the canine brain ventricular system as a learning material for neuroanatomy education and to present the full process of creation of these models from 3 Tesla magnetic resonance (MR) imaging to 3D printing of new-generation learning tools.

MATERIALS AND METHODS

Ethical statement: All the experimental procedures were approved by the Bilkent University Animal Experiments Local Ethics Committee (Approval Number: 2016/42). The required approvals for survey analyses were also obtained from the Ethics Committee of Ankara University of Health Sciences (Approval Number: 2023-02-09).

Magnetic resonance imaging: Four clinically healthy mesocephalic dogs were used for this study. MR scans and image datasets were generated by using a 32-channel human head coil designed for 3 Tesla MR devices (Trio, Siemens, Erlangen, Germany). The images taken with T1 and T2-weighted space sequences on the dorsal, sagittal, and transversal planes were examined by Leonardo Workstation software (Siemens Medical Solutions, Erlangen, Germany).

Segmentation & 3D-Printing: The segmentation of MR images of the canine brain ventricular system, stored in DICOM format, was conducted. Anatomic formations of the ventricular system were created in segmentation process. 3D-reconstructed images of the ventricular system were acquired with free, open-source 3D Slicer software (3D Slicer, GitHub, San Francisco, USA). The semi-automatic technique was applied for the segmentation by using the thresholding tool (grayscale values were selected for defining the object). The digital images have been meticulously processed to render the ventricular system. Postprocessing was performed by a software smoothing tool (Fedorov *et al.*, 2012; Czeibert *et al.*, 2020). 3D digital models of the ventricular system were recorded and Ultimaker Cura (Version 4.8.0, USA) was used for the slicing of final stereolithographic (.stl) images. These images were used to produce 3D-printed models with a Fused Deposition Modelling (FDM) printer (Anycubic I3 Mega, Shenzhen Technology, China) with polylactic acid (PLA) filament. The methodological approach of the procedures taken for the development of the 3D-printed ventricular system model is presented (Fig. 1).

Survey analyses: In the last stage of the study, an evaluation questionnaire for the learners was conducted. 158 undergraduate students from Ankara University Faculty of Veterinary Medicine who are taking neuroanatomy courses, were included in the study. A focus group questionnaire was administered to the students to evaluate the effectiveness of the 3DPM created from digital images of organic specimens used in the anatomy practice.

Every year, approximately 200 new students begin to receive veterinary anatomy courses in six different groups for the first time within the scope of veterinary undergraduate education at the faculty. When the confidence interval was 95% and the marginal error was 5%, the minimum number of participants in the survey was determined to be 132 (Krejcie and Morgan, 1970).

In the first stage of the survey analysis, statistics describing the socio-demographic, enrollment, and achievement characteristics of the students were calculated. For the second stage, the factor structures of 20 questions (5-point Likert scale) were determined by explanatory factor analysis. The Kaiser-Meyer-Olkin (KMO) test was used to measure sampling adequacy in the first stage of explanatory factor analysis. The KMO value was found to be 0.830. The fact that the measurement value is close to 1 indicates that the data group is suitable for explanatory factor analysis. In addition, whether the correlation matrix obtained in the analysis is the unit matrix where all diagonal terms are 1 and non-diagonal terms are 0 was tested using Barlett's test. The null hypothesis, which states that the correlation matrix of the scale is zero, was rejected (Barlett's test p=<0.001). As a result of these two tests, it was decided that the sample was suitable for explanatory factor analysis. In the second stage, the evaluation distributions of the students for the general evaluation of the anatomy course and the use of 3DPM in learning the brain ventricles were calculated. Median values and quartiles for each proposition were calculated with SPSS 21 software.

RESULTS

Magnetic resonance imaging: Different tissues were easily distinguished with the adjustment of the sequences in 3 Tesla MR imaging. Therefore, the different grayscales can become visible for rendering the images during the reconstruction process (Fig. 2). It was determined that MR images displayed with the T1-weighted sequence, had the opportunity to render more easily. The digital reconstruction of the ventricular system clearly demonstrated the lateral ventricles, third ventricle, cerebrospinal aqueduct, and fourth ventricle (Fig. 3). The imaging, segmentation, post-processing, and construction times of the 3D digital models were determined to be approximately 60 minutes. 3D digital images were found to be easily interchangeable in a variety of ways. In addition to that, the segmentation stage of the anatomical structures can be performed individually, so the desired structures can be removed or labeled.

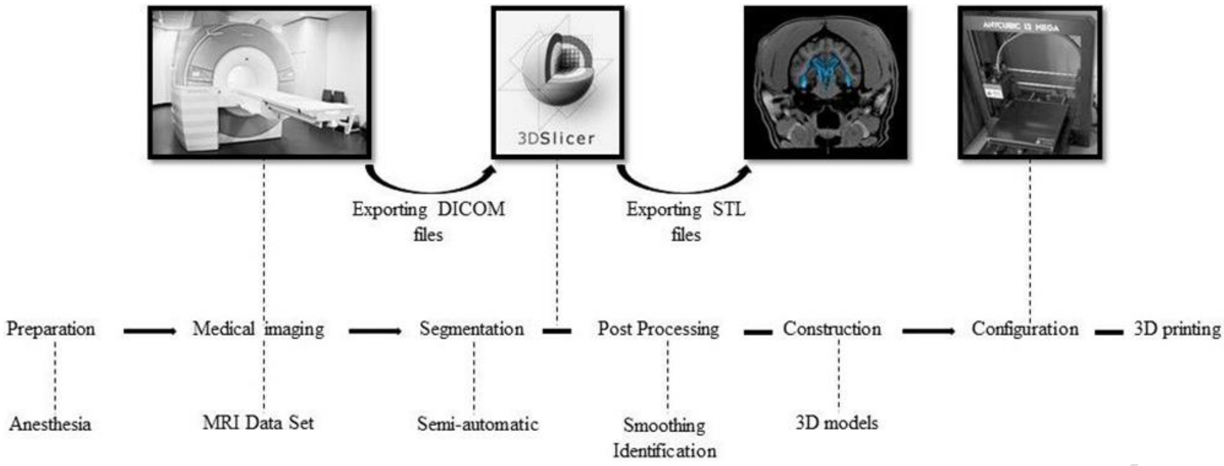

Fig. 1: Schematic diagram of an overview of the printing procedure workflow from the animal preparation to the 3DPM.

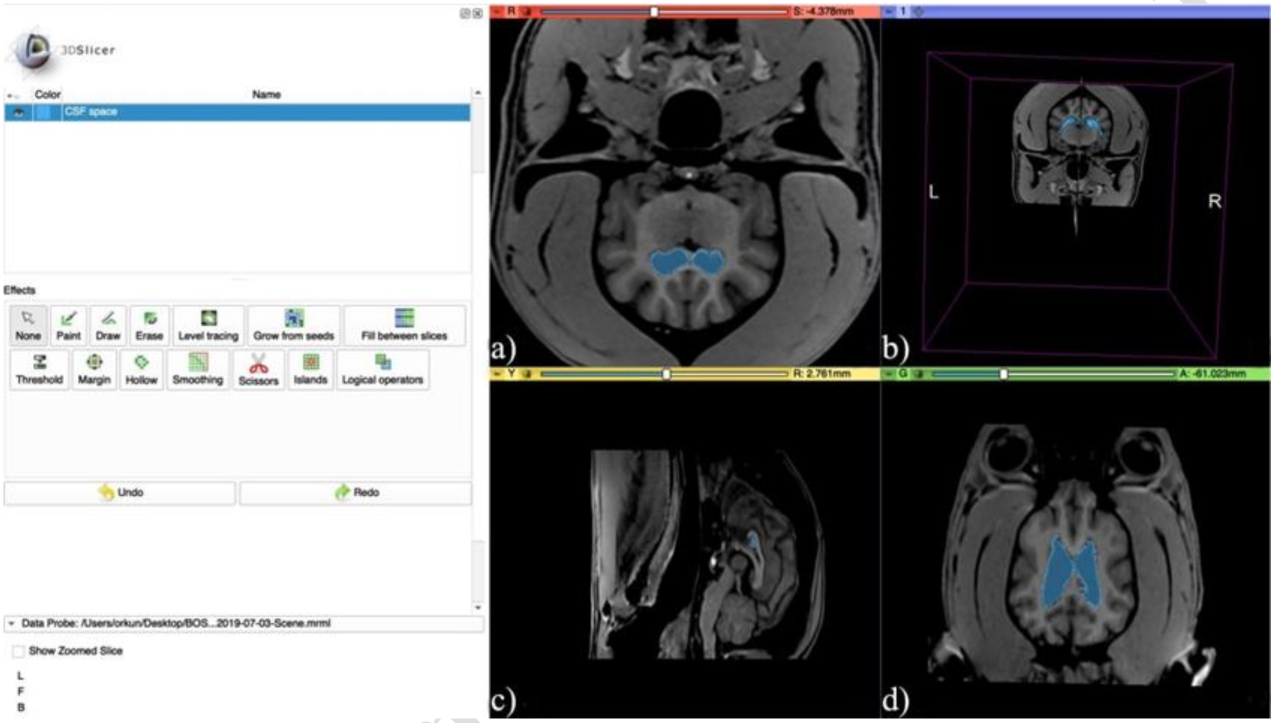

Fig. 2: MRI-based segmentation process of brain ventricular system model of a dog and performing corrections on the different MR planes at the same time. a. The lateral ventricle is defined as the reign of interest (blue) in the transverse view of the T1-weighted MR image sections. b. "Points" are added to the lateral ventricles in the sagittal view of the T1-weighted MR image sections. c. 3D model of the reconstructed brain ventricular system model of a dog on the transverse section. d. The lateral ventricle is defined as the reign of interest (blue) in the dorsal view of the T1-weighted MR image sections

3D-Printed models: Finally, the 3D-printed concrete models of the canine brain ventricles were created (Fig. 4). The time from starting the printing process to obtaining the 3DPM suitable for learners' (including the removal of supporting layers) use was also 60 minutes approximately. The print thickness and wall thickness were measured at 0.2 mm and 1.2 mm, respectively. The exact model of a dog's ventricular system is 39.4 mm in width, 72.7 mm in length, and 29.2 mm in height (Fig. 4a). The 3DPM had high anatomical accuracy. The 1:1 size correlation between the original anatomical form and the 3D digital reconstructions (and 3DPM as well) was at the same size and, if desired, they could be resized. One of them was even designed larger than the actual size (Fig. 4b).

Survey analyses & statistics: Statistics describing the socio-demographic, enrollment and achievement characteristics of the students are reported in Table 1. For the second stage, the factor structures of 20 questions were determined by explanatory factor analysis.

As mentioned above, the evaluation survey questions had a 5-factor structure, and the percentage of total variance explained by the factors was calculated at 70.289%. In this study, Cronbach's alpha coefficient, which is a measure of the internal consistency or homogeneous structure of the questions, was calculated as 0.839. This result indicated that the questions were consistent with each other and measured the same feature. In the last stage of the survey analyses, the evaluation distributions of the students for the general evaluation of the anatomy course and the use of 3DPM for learning the brain ventricles were stated in Fig. 5 and 6.

Table 1: Distribution of socio-demographic, enrollment, and achievement characteristics for veterinary undergraduate students.

Variables	Categories	N	%
Gender	Female	100	63.3%
	Male	58	36.7%
Examination Score for Anatomy	A	31	19.6%
	B	50	31.6%
	C	49	31.0%
	F	28	17.7%
Order of Preference for XXX University Faculty of Veterinary Medicine	1-5	97	61.4%
	6-10	30	19.0%
	10+	24	15.2%
Reason for Choosing XXX University Faculty of Veterinary Medicine	Family	14	8.9%
	Interest in Animals	82	51.9%
	Employment Opportunities	26	16.5%
	Staying in XXX / XXX University	16	10.1%
	Other	20	12.7%
Age (Mean±Std Deviation)	19.75±2.32 (min: 18; max: 41)		
University Entrance Exam Score/Overall Turkey Ranking (Mean±Std Deviation)	50564±6031 (min: 25000; max: 76000)		
Overall academic score (Scoring out of 4) (Mean±Std Deviation)	3.29±0.45 (min: 1.57; max: 4.00)		

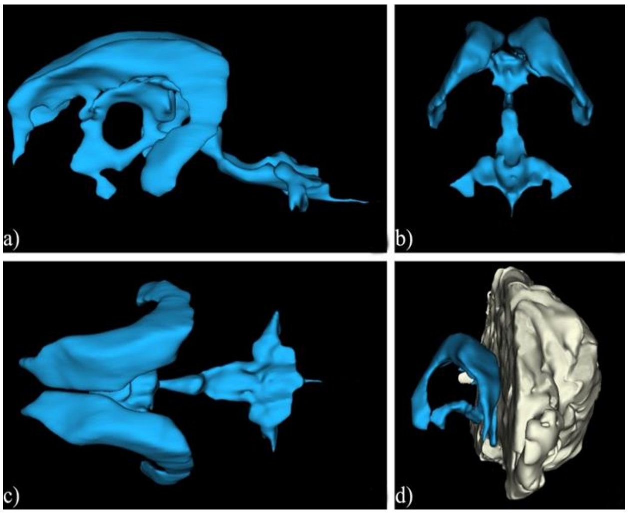

Fig. 3: Volume-rendered STL files of the brain ventricular system model of a dog. These 3D views are useful for orientation for the student user. a. Left lateral view of the brain ventricular system. b. Dorsal view of the brain ventricular system. c. Caudal view of the brain ventricular system. d. Cranial view of the brain ventricular system with the midsagittal section of the brain

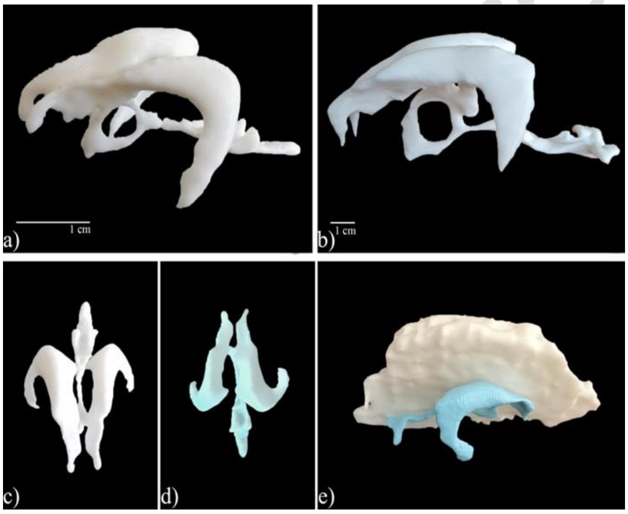

Fig. 4: Photographs of different three-dimensional printed ventricular system models. a. Normal 3D-printed ventricular model of a dog, craniolateral view. b. Larger 3D-printed ventricular model of a dog, lateral view. c. Normal 3D-printed ventricular model of a dog, craniodorsal view. d. Normal 3D-printed ventricular model of a dog, dorsal view. e. Normal 3D-printed brain and the whole ventricular system, craniolateral view. The right half of the brain was removed to reveal aspects of the whole ventricular system

In the overall evaluation of the anatomy course, student satisfaction was pleasingly high. However, the number of undecided and dissatisfied students should be taken into account in terms of the sufficiency of the theoretical and especially practical hours. In addition, it was noted that the rate of undecided and dissatisfied individuals about satisfaction with the examination system was also noted (Fig. 5).

A significant number of students stated that the biological specimens, alone, are not sufficient in learning brain ventricles in anatomy practices and that the use of 3DPM is necessary and will be more useful in learning neuroanatomy (Fig. 6).

DISCUSSION

As stated above, one of the most important factors that complicate learning neuroanatomy is undoubtedly the brain ventricular system. Dissection has always been an effective tool in anatomy education. However, since the ventricular system has not a tight texture and consists of a series of cavities, it can be difficult for learners to understand it through dissection alone. Also considerable number of cadaver requirements and long specimen preparation hours are among the biggest problems encountered in anatomy practices (Adams and Wilson, 2011; Vaccarezza and Papa, 2015; Yi *et al.*, 2019; Czeibert *et al.*, 2020; Yi *et al.*, 2020). An efficient education material should be used by learners and also produced cheaply, and quickly for the instructors (Preece *et al.*, 2013; Estai and Bunt, 2016; Schoenfeld-Tacher *et al.*, 2017; Yi *et al.*, 2020). Another important factor is the durability of the models, which can change depending on the material used. PLA was the most available, cheap, rapid, and easy-to-use filament for this purpose (Cojocaru *et al.*, 2022). 3DPM produced with FDM printer were durable, and reproducible rapidly and easily. Besides, 3DPM costs relatively less than other learning materials (less than 2$). Larger models can cost more than $2. But, it will still be incomparably cheaper than the cost of plastinates or cadavers.

Although it is not always possible to achieve this for anatomical specimens, dry and relatively clean models are preferred by students (Estai and Bunt, 2016; Schoenfeld-Tacher *et al.*, 2017). 3DPM is at the forefront with these features. Whether the model is plastinated, dissected, or 3D-printed, the elapsed time to acquire an education model

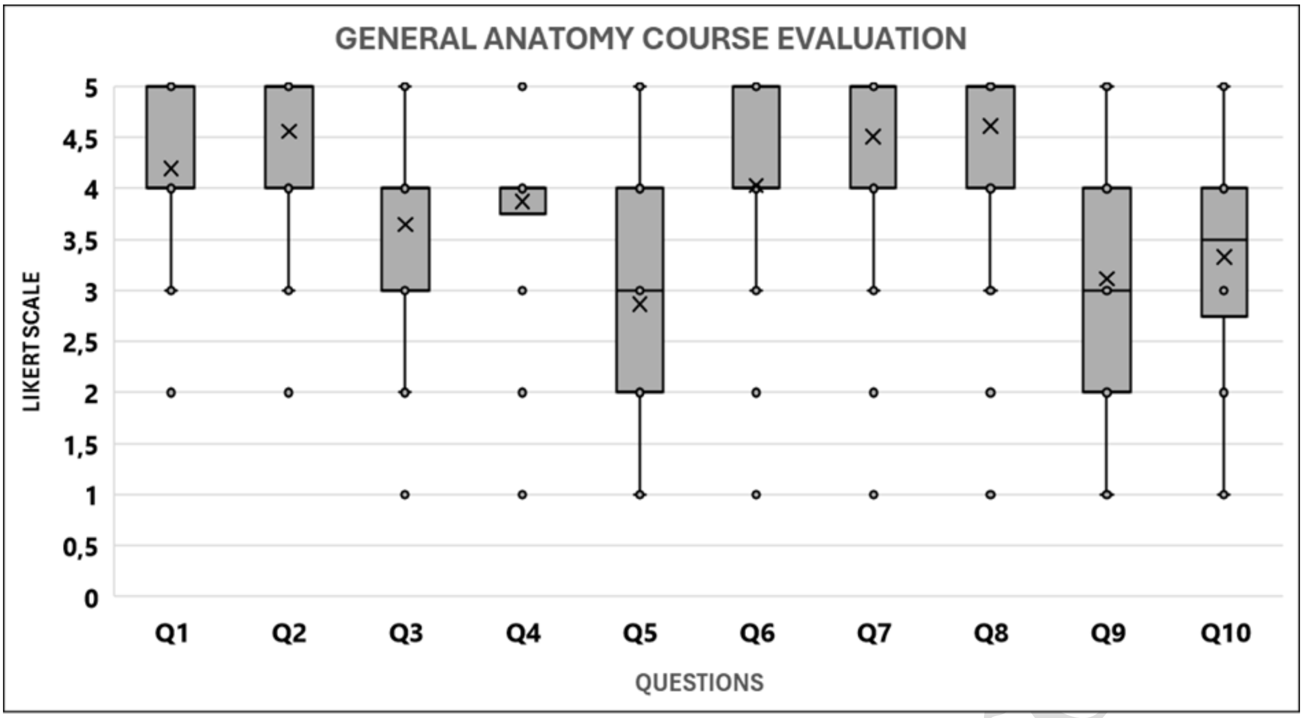

Fig. 5: General anatomy course evaluation distribution of the veterinary undergraduate students. *Q1: I find the classroom and infrastructure facilities of the Department of Anatomy sufficient, Q2: I think anatomy education is important for my professional life, Q3: I find the weekly theoretical course hours of anatomy education sufficient, Q4: I find the theoretical learning materials of the anatomy course sufficient, Q5: I find the weekly practical course hours of anatomy education sufficient, Q6: I find the practical learning materials of the anatomy course sufficient, Q7: I am satisfied with the competence and interest of the anatomy educators, Q8: I think anatomy education is fundamental to veterinary medicine, Q9: I am satisfied with the assessment methods of anatomy education, Q10: I think anatomy exams are sufficient to assess the student's knowledge; Likert scale: 1: Strongly Disagree, 2:Disagree, 3: Undecided, 4:Agree, 5: Strongly Agree.*

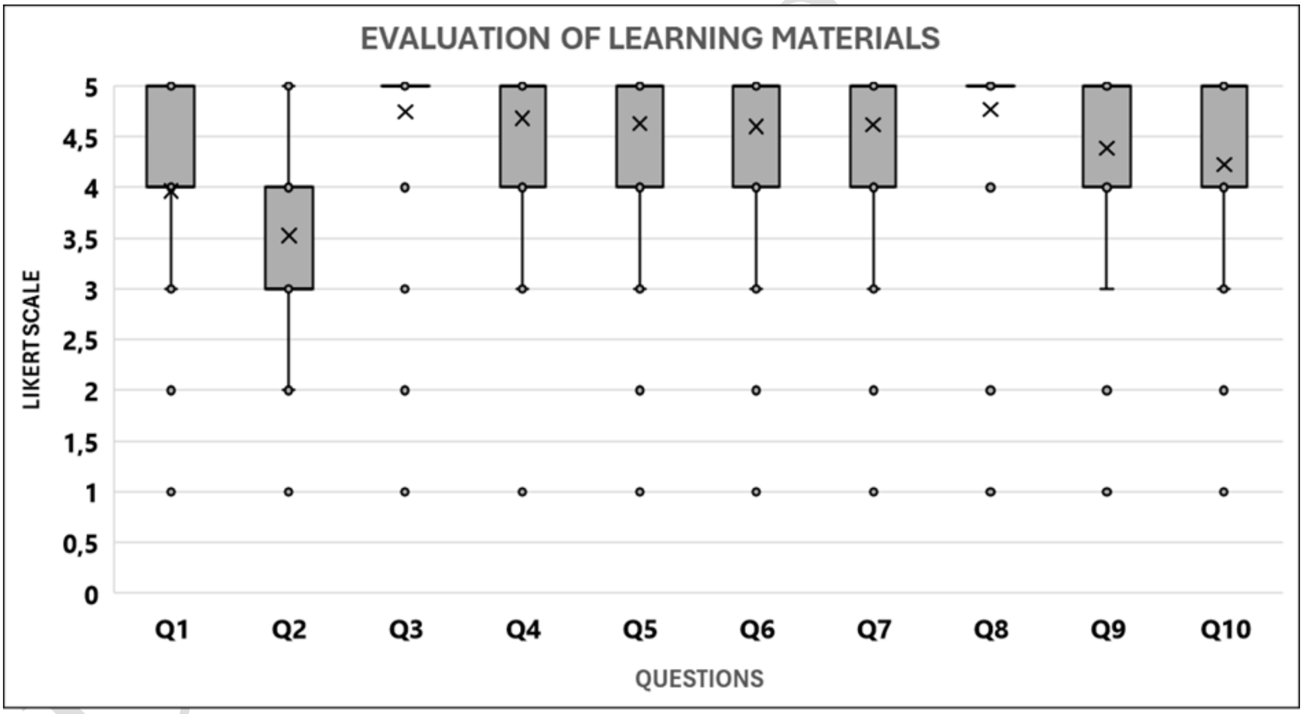

Fig. 6: Evaluation distribution of anatomy undergraduate students about the use of learning materials and 3D printed models. *Q1:Biological specimens such as cadavers etc. are sufficient for me to learn in anatomy practice, Q2: Biological specimens such as cadavers, etc. are sufficient for me to learn the structures of the brain ventricular system in anatomy practice, Q33DPM and models should be used in practical anatomy education, Q4 The use of 3DPM in anatomy practice will be more beneficial for me to comprehend and learn the subject, Q5: The use of 3DPM in practice will be useful in focusing on the subject., Q6: 3DPM should be used instead of cadavers, especially for brain ventricular system anatomy education, Q7: The use of 3DPM produced from brain ventricular system structures will be more beneficial for me to understand and learn the subject, Q8 The biological specimens such as cadavers and etc. and the 3DPM should be used together in practical anatomy education, Q9: Besides the biological specimens, 3DPM should be used more frequently in practical training of anatomy education, Q10 I believe that I will be more successful if 3DPM are used beside the biological specimens in practical training of anatomy education.*
Likert scale: 1: Strongly Disagree, 2:Disagree, 3: Undecided, 4:Agree, 5: Strongly Agree.

is highly valuable. Compared to other time-consuming methods, 3D printing is advantageous in that it can be produced both in a short time and repeatedly (Estai and Bunt, 2016; Schoenfeld-Tacher *et al.*, 2017).

The most obvious difficulty experienced by learners is the imagination of 3D anatomical structures by using 2D educational materials. When the 3DPM are examined, it is noticed that they reflect the unique morphology of the canine ventricular system. Instead of 2D learning materials, 3DPM will provide a 3D perspective and increase the student's ability to imagine and remember the neuroanatomy. 3DPM of canine brain ventricles which cannot be fully demonstrated in the cadavers, can directly affect students' performance and learning quality in practices (Aimar *et al.*, 2019).

Throughout the world, the use of live animals for education tends to be limited by new types of educational materials like 3DPM (Schoenfeld-Tacher *et al.*, 2017). Although the 3R rule seems to be related to experimental animals, its relevance to our subject becomes clearer when it is considered in terms of the reduction or replacement of biological materials and therefore live animals to be used in anatomy applications (Zevnik *et al.*, 2022). 3D-printed brain ventricle models, instead of biological specimens, will also reduce the number of animals to be sacrificed in the long term. Additionally, fresh or fixated cadavers, especially for the nervous system, can be non-persistent and deform quickly (Krassner *et al.*, 2023). Besides, it has been proven today that most of the fixative chemicals used in cadaver preparation are very harmful to health (Yunus *et al.*, 2022). 3DPM can overcome these problems in practical labs.

Although MRI is known as the best clinical diagnosis technique to examine the brain (Giesel *et al.*, 2009; Czeibert *et al.*, 2020), these images alone may not be sufficient, and alternative methods and approaches will be demanded by the clinicians and surgeons as well (Gutmann *et al.*, 2020; Su *et al.*, 2020). Especially before surgical operations, a physical model that can demonstrate the disorder in the operation area can be very useful. 3DPM should also be evaluated with these superior features in clinics. MRI enables easy segmentation/reconstruction of gray and white matter, or imaging in different planes. It has been previously stated that manual segmentation can take a long time and may create bias in the user. On the other hand, fully automatic segmentation can cause difficulties in distinguishing anatomical structures. For these reasons, semi-automatic segmentation applications are the most preferred (Giesel *et al.*, 2009). MRI was performed with a 3T MR device, and both with T1 and T2-weighted sequences to display detailed images of the brain ventricular system in this study. Due to the properties of the imaging system, the semi-automatic segmentation process was performed easily. Tissues such as white matter, gray matter, and ventricles were easily and quickly distinguished from each other on T1-weighted images (Fig. 2).

It has been proven by various studies that students' neuroanatomy learning capacity and competence could not only be improved by biological specimens or standard dissection procedures. We should find alternative learning tools and design new-generation models such as 3D digital models and their 3D-printed versions (AbouHashem *et al.*, 2015; Estai and Bunt, 2016). Although our focus group questionnaire was limited to the learners of Ankara University, survey analyses reflected the necessity of alternative learning tools for the practical education of veterinary anatomy. Not only for the brain ventricular system but also for different anatomic structures or systems, 3DPM can be a convenient learning material. It was an expected result for all trainers that students would demand more practical hours. However, students also built consensus on the effectiveness of 3DPM to understand complex anatomical structures better in practical courses. Besides the supervised anatomy practice in the labs with routine cadavers, new-generation veterinary students also want to create their own practical hours by using non-hazardous and safe alternative learning tools such as 3DPM. 3DPM provides a distinctly positive effect on the learning performance of the students even in different learning mediums. Self-directed learning and peer-assisted learning are two effective tools for the practical learning of anatomy (Lee *et al.*, 2010; Cremers *et al.*, 2014). While studying through anatomy books, recorded videos or any other electronic learning materials (Pujol *et al.*, 2016), the presence of anatomical practice materials for the learners increases the efficiency of self-directed or peer-assisted learning even in class or out of class. However, this type of learning, without supervision, would be risky in terms of biological safety or lab security regulations when classically fixated cadavers or fresh specimens are used. 3DPM can overcome this problem with the specified features mentioned above. Besides, storage and transportation are also easy and safe for 3DPM.

While numerous articles focus on 3D bone modeling of the cranium, there is a lack of literature concerning the modeling of nervous organs, particularly the brain ventricular system (Giesel *et al.*, 2009; Adams and Wilson, 2011; Yi *et al.*, 2019; Yi *et al.*, 2020). Our study presents a comprehensive review of the above-mentioned issue and creates a suitable discussion opportunity for those interested. This study determined that ventricles of the brain were well resolved in 3D images, and the nervous tissues can easily be distinguished from adjacent tissues with MRI (Fig. 2). Ventricular system models were created of good quality by 3D printing (Fig. 4).

In conclusion, authors can state that 3DPM for not only the ventricular system but also for the various structures will be an effective learning alternative compared to dissection or plastination. 3T MRI provided a superiority for visualization and modeling of the nervous tissue. One of the important advantages was that these models could make efficient and visible educational material for students. These models were cheap, durable, accessible, reproducible, and time-efficient educational materials. Due to all the advantages mentioned, it is thought that the models produced by 3D-printing technology will be a preferable training material for anatomy lecturers.

Authors' contribution: Conceptualization, OE, CB, and ÇO; methodology, OE, CB, AA and OA; visualization, OA and ÇO; data management, OE and AA; software and printing, OE and CB; statistical analyses AA. All authors have read and agreed to the published version of the manuscript. There is no conflict of interest among authors.

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