Miscellaneous

3D Printing an Explodable Dog Skull for Veterinary Education

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Abstract

Veterinary education often relies on cadaveric specimens, but there is increasing demand for alternatives due to limited resources and ethical considerations. To address this, we developed a 3D printed 'explodable' model of a dog cranium with detachable, magnetized cranial components for teaching anatomy to students. This model was generated from a computed tomographic scan of a juvenile dog cranium for which cranial sutures were still partially open and segmented such that major cranial bones were isolated. All bones are printed at actual size and retain openings for cranial nerves and major vessels. This interactive model enhances anatomical education by supplying a hands-on tool that can be used either in the classroom setting or for independent learning and can be incorporated at the high school, college, or veterinary school level. It is currently being integrated into the first-year anatomy foundation course at Cornell University's College of Veterinary Medicine. The model can be printed using any hobbyist or specialist 3D printer and we outline assembly instructions on how to attach magnets at prefabricated attachment points. Using both digital and 3D printed resources, we hope to help to address current shortages of anatomical resources and also inspire future generations of practicing veterinarians by making anatomy more accessible and engaging.

Keywords: Anatomy, Cranium, Education, Outreach, Teaching

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INTRODUCTION

The dog (*Canis familiaris* Linnaeus, 1758) is the foundation of modern veterinary education. At veterinary schools such as Cornell University, the University of Florida, and the University of Pennsylvania, the dog is the focal species studied by first-year veterinary students to teach small animal anatomy. While these introductory anatomy courses are commonly supplemented in a variety of ways following their first semester (e.g., ruminant anatomy, equine anatomy, etc.), many veterinary students will rely on their dog anatomy course to provide them with a map to the body as they delve into topics such as pathology and physiology. The importance of anatomy does not just relate to future coursework and clinical years, but has been more broadly demonstrated to be foundational in daily clinical practice (Arráez-Aybar *et al*., 2010; Wheble and Channon, 2021).

Despite the importance of veterinary medicine programs, there is currently an animal welfare crisis due to a national shortage of veterinary technicians and specialists (Bunke *et al*., 2024). In the past decade, funding for veterinary education has drastically declined while the cost of tuition has more than doubled, creating animal care deserts, especially for animal shelters and non-profit clinics (Eyre, 2011; Kogut *et al*., 2024). Increasing student retention in both pre-veterinary and veterinary programs is critical and helping to develop new interactive materials to get students interested in veterinary medicine earlier in their academic careers is one part of the solution to this multifactorial problem. Additionally, pre-veterinary programs commonly do not have resources such as real bones due to both cost and ethical concerns, which would otherwise help their students gain a more intimate knowledge of anatomy. Therefore, there is a need to increase the availability of educational resources while making the content more engaging and hands-on.

3D visualization tools and models, including digital and printed models, make complex anatomical content more accessible for students and provide immersive learning experiences (Berreto *et al*., 2022; Murgitroyd *et al*., 2015; Ricketts *et al*., 2018). 3D digital models (3DDMs) generated by either surface scans, computed tomography (CT), or magnetic resonance imaging (MRI) can be imported into software (e.g., Meshlab, PrusaSlicer, Simplify3D, Slic3r, Ultimaker Cura, 3D Slicer), allowing for virtual manipulation of anatomical structures (Kapoor *et al*., 2024). 3DDMs can complement atlas illustrations, especially when learning very small, intricate, and tightly associated structures, such as the nervous system (Murgitroyd *et al*., 2015). In addition to 3D visualization software, virtual reality (VR) and augmented reality (AR) can serve as practical alternatives to traditional dissection that do not require real cadavers (Kapoor *et al*., 2024).

Like 3DDMs, 3D printed models (3DPMs) have helped to revolutionize teaching anatomy at multiple education levels. 3D printing, or additive manufacturing, is the production of a three-dimensional object by building up layers of material, typically plastic or resin (Gokhare *et al*., 2017; Kapoor *et al*., 2024; Leonardi *et al*., 2021; Quinn-Gorham and Khan, 2016; Savini

Inv nr.	Description
M3#1858	Segmented cranial bones with pre-fabricated magnet casings and shelves for assembly following 3D printing
M3#1859	Segmented cranial bones of the "Bottom" cranial component (smaller additional bones)

Table 1. List of models of the cranium of the specimen CUHL 9 (*Canis familiaris*). Collection: Cornell University veterinary teaching collection, Ithaca, USA.

and Savini, 2015; Stoughton, 2023; Wilhite and Wölfel, 2019). 3D printable files are prepared by converting CT and MRI files into surface files (e.g., STL, OBJ) with segmentation software (Gokhare *et al*., 2017; Kapoor *et al*., 2024; Wilhite and Wölfel, 2019) or directly through the production of surface models using either a surface scanner or photogrammetry (Chapinal-Heras *et al*., 2024; Yang *et al*., 2021). Thus, as long as a CT, MRI, or surface file is available, any anatomical structure can now be reproduced accurately, cheaply, and quickly (Bakici *et al*., 2025; Baretto *et al*., 2022; Brumpt *et al*., 2023; Huri and Oto, 2022; Kapoor *et al*., 2024; Suñol *et al*., 2018; Wilhite and Wölfel, 2019; Ye *et al*., 2020). Unlike their biological counterparts, 3DPMs are more resistant to long-term 'taphonomic' wear by veterinary cohorts, and are more easily replaced when broken (Bakici *et al*., 2025; Brumpt *et al*., 2023; Kapoor *et al*., 2024; Pokines *et al*., 2017; Ye *et al*., 2020). They are also customizable and can be tailored to suit the specific learning objectives of any veterinary course or program (Bakici *et al*., 2025; Kapoor *et al*., 2024; Leonardi *et al*., 2021). Although 3D printing has been around since the 1980s, it has only been embraced by veterinary schools within the last decade as printer hardware as well as maintenance and material costs have dramatically decreased (Quinn-Gorham and Khan, 2016; Savini and Savini, 2015). Because of this, 3DPMs are being integrated into veterinary curricula, from the classroom to the clinic (Bakici *et al*., 2025; Hadžiomerović *et al*., 2025; Huri and Oto, 2022; Quinn-Gorham and Khan, 2016; Wilhite and Wölfel, 2019). In the classroom, the use of 3DPMs, as well as their real biological counterparts, improved student test scores, with students preferring the 3DPMs for their accuracy, accessibility, and cleanliness while acknowledging the benefits of examining the real material, which possess natural variation (Bakici *et al*., 2025). 3DPMs are also affordable and resistant to repeated use, providing students with many opportunities to practice on a model specimen before entering the clinic and operating on a live animal (Hadžiomerović *et al*., 2025). To help fill this gap, private companies (e.g., embodi3D) have begun developing specialized 3D printing services for veterinary programs.

Here, we introduce a 3DDM and 3DPM of the dog cranium, complete with magnetized cranial components to encourage experimental learning both in and out of the classroom. Our 3DDM is free to download for educational use by veterinary programs and students as well as non-veterinary educators and their students with the dual goals of increasing accessibility to key anatomical resources and broadening student interest in joining the field of veterinary medicine.

METHODS

Scanning the cranium and segmenting 16 cranial components

To generate 3DDMs of dog cranial bones, a juvenile mixed breed dog (less than one year of age) from Cornell University's veterinary teaching collection (CUHL 9) with partially opened sutures was microCT scanned (Nikon HMXST 225 micro-computed tomographic scanner) at the Center for Nanoscale Systems of Harvard University. The scan was performed at 106.27 µm resolution and 85 kV and 85 µA. The TIFF image stack was then imported into Avizo® (version 2022.1; Thermo Fisher Scientific-FEI) for digital segmentation, where the cranial bones were segmented along sutures into 16 cranial components (see table 1 and 2). Here, "cranial bones" refer to the real structures within the dog cranium, whereas "cranial components" refer to our model structures, some of which are composites of two or more cranial bones that are too small to be segmented out and 3D printed in our 3DPM as their own individual structures (e.g., the "Bottom" cranial component is a composite of the ethmoid, vomer, palatine, presphenoid, pterygoid, and basisphenoid cranial bones). These composite structures ensure the structural integrity of the final model. Additionally, larger holes and some recesses were filled to increase structural support and reduce the chance that the models would break when handled (Figure 1A).

To provide additional opportunities for learning cranial anatomy, we segmented the "Bottom" cranial component into its constituent cranial bones (ethmoid, vomer, palatine, presphenoid, pterygoid, and basisphenoid), but we did not create magnet casings for these composite components. Again, this was done to maintain the structural integrity of the final 3DPM. Wavefront type OBJ files of these composite cranial components are freely available for download, along with the rest of our dog 3DDM, to be visualized and virtually manipulated by students using visualization software. Note that we successfully sliced all our files in MeshLab; other 3D visualization software has not been tested.

Creating magnet casings and shelves for the model

Fifty-six casings and two shelves supporting the magnets were manually constructed in Avizo® as separate materials within their respective cranial components (Table 3). Magnet casings were created by first interpolating a cylindrical volume using custom round brush radius and frame distance settings within their appropriate segmentation plane. Then a smaller round brush radius and frame distance were used to remove a magnet-sized volume from the cylinder by interpolation (Table 4). The size standardization settings ensured that magnets would fit snugly into the casings after 3D printing. These settings were made to fit disc-shaped (6 mm x 3 mm) neodymium magnets. With the exception of the zygomatic and nasal bones, a minimum of two magnet casings were built for all cranial components to increase structural integrity once the model is assembled.

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Component Number	Component Name	Cranial Bones within Component
Component 1	RIncisive	Right incisive
Component 2	LIncisive	Left incisive
Component 3	RMaxilla	Right maxilla with canine, premolars, molars
Component 4	LMaxilla	Left maxilla with canine, premolars, molars
Component 5	RNasal	Right nasal
Component 6	LNasal	Left nasal
Component 7	RFrontal	Right frontal, right lacrimal
Component 8	LFrontal	Left frontal, left lacrimal
Component 9	RParietal	Right parietal
Component 10	LParietal	Left parietal
Component 11	RZygomatic	Right zygomatic
Component 12	LZygomatic	Left zygomatic
Component 13	RTemporal	Right temporal
Component 14	LTemporal	Left temporal
Component 15	Occipital	Supraoccipital, exoccipital, basioccipital
Component 16	Bottom	Ethmoid, vomer, palatine, presphenoid, pterygoid, basisphenoid

Table 2. List of cranial components and the cranial bones they contain.

3D printing the model

Here, we provide an example of how to print the dog 3DPM using a resin-based (low force stereolithography) 3D printer. However, any 3D printer brand and type (fused deposition modeling, stereolithography, digital light processing) should be capable of adequately printing our cranial components. Be aware that issues may be encountered when printing our dog 3DPM because each printer has its own set of configuration parameters, such as print quality, quantity, and size, and infill percentage (Stoughton, 2023).

Surface data of the cranial components were exported as wavefront type OBJ files and printed using a Formlabs Form 3B printer, Form Wash, and Form Cure (Formlabs Ohio Inc., Ohio, United States). Our process involved three steps: (1) printing the cranial components with White Resin V4 for 6 hours on average (print rate = 100 mm/hour) and at 35°C for the first 30 min, (2) washing the prints in 99% isopropyl alcohol (IPA) for 30 min and setting them to dry for 5 min, and (3) curing the prints in a dryer for 1 hour at 60°C. Gloves were used for all stages of the printing process to avoid direct contact of resin or IPA with skin. As each batch takes approximately 7.5 hours to fully cure, it is recommended that the second batch is started as soon as the first batch is transferred from the printer to the washer. All cranial components necessary for assembling one cranium model can be printed in 3 iterations of these steps on the Formlabs 3B printer (left, right, and middle).

Assembling the model

Following printing, 56 disc-shaped (6 mm x 3 mm) neodymium magnets were set to the magnet casings of the printed cranial components using cyanoacrylate glue and left to fix for 5 min. Prints were rotated such that each received one magnet at a time, ensuring that each magnet had sufficient time to cure before additional magnets were set. After all magnets were set, prints were left unassembled for 24 hours to fully cure (Figures 1B-C). Once cured, the model can be assembled and used by students (Figure 1D).

Since each 3D printer has its own set of configuration parameters, the magnet casings may print smaller or larger than intended depending on the printer brand and type used (Stoughton, 2023). If the magnets do not fit snugly within their casings, we recommend adjusting our default magnet casing settings or purchasing differently sized magnets (Table 4).

DISCUSSION

Tools and models for 3D visualization, including 3DDMs (visualization software, VR, AR) and 3DPMs, make complex anatomical content more accessible and immersive for students (Berreto *et al.*, 2022; Murgitroyd *et al.*, 2015; Ricketts *et al.*, 2018). 3DPMs in particular are durable, customizable learning aids that can now be printed cheaply and quickly while preserving the anatomical accuracy of their biological counterparts (Bakici *et al.*, 2025; Baretto *et al.*, 2022; Brumpt *et al.*, 2023; Huri and Oto, 2022; Kapoor *et al.*, 2024; Leonardi *et al.*, 2021; Suñol *et al.*, 2018; Wilhite and Wölfel, 2019; Ye *et al.*, 2020). Although veterinary schools commonly supply students with real skulls to learn from during their anatomy instruction, many secondary and undergraduate programs lack the resources to provide these same experiences. Moreover, complete skulls used for education are in short supply and frequently damaged, often broken from years of use by previous cohorts (Pokines *et al.*, 2017). 3DPMs reduce the need to replace costly skulls when they are damaged in veterinary curricula since components can be reprinted quickly and at low cost. Finally, our 3DPM can be disassembled, enabling students to get a better understanding of how the bones of the dog cranium articulate providing additional learning opportunities than would be possible when learning from a fused, adult skull.

Our dog cranium 3DPM has already been integrated into the first-year anatomy foundation course at Cornell University's College of Veterinary Medicine (VTMED 5100: The Animal Body). To quantify learning outcomes, we intend to survey students about how impactful our 3DPM was on their introduction to veterinary anatomy in their respective program of study. We

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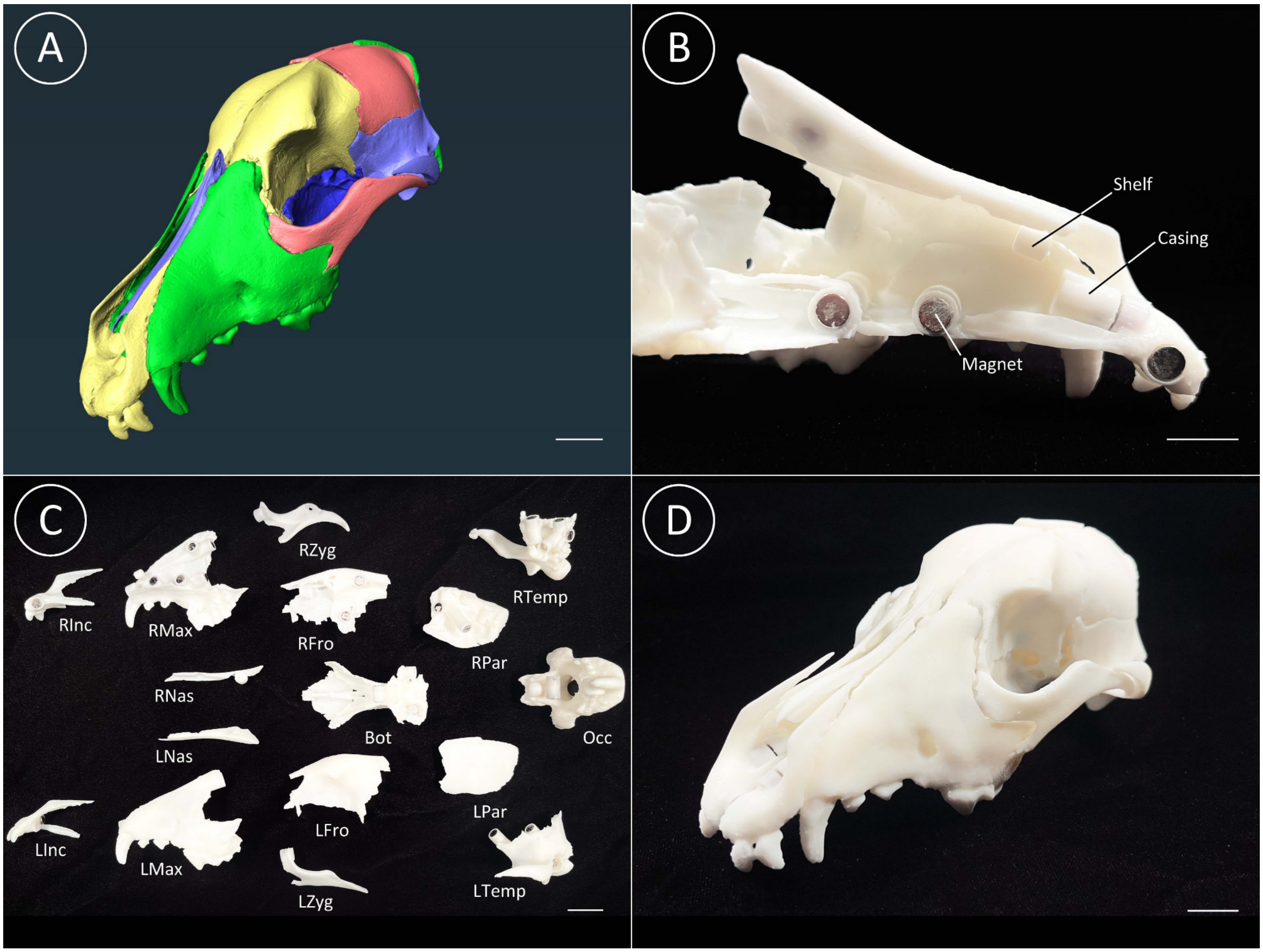

Figure 1. A) Portrait view of the dog model in Avizo® (version 2022.1; Thermo Fisher Scientific-FEI). (B) Close-up view of a neodymium magnet, magnet casing, and shelf. (C) View of the disassembled ('exploded') 3D printed model with all 16 of its constituent cranial components. The left cranial components, shown in external view, are positioned opposite their respective right cranial components, shown in internal view. Cranial component abbreviations: bottom (Bot), frontal (Fro), incisive (Inc), maxilla (Max), nasal (Nas), occipital (Occ), parietal (Par), temporal (Temp), and zygomatic (Zyg). (D) Portrait view of the assembled 3D printed model. Scale bar = 1 cm.

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Component Number	Component Name	Magnet Casings	Shelves	Connected Components
Component 1	RIncisive	2	0	LIncisive, RMaxilla
Component 2	LIncisive	2	0	RIncisive, LMaxilla
Component 3	RMaxilla	5	1	RIncisive, RNasal, RFrontal, RZygomatic, Bottom
Component 4	LMaxilla	5	1	LIncisive, LNasal, LFrontal, LZygomatic, Bottom
Component 5	RNasal	1	0	RMaxilla
Component 6	LNasal	1	0	LMaxilla
Component 7	RFrontal	5	0	RMaxilla, LFrontal, RParietal, RTemporal, Bottom
Component 8	LFrontal	5	0	LMaxilla, RFrontal, LParietal, LTemporal, Bottom
Component 9	RParietal	4	0	RFrontal, LParietal, RTemporal, Occipital
Component 10	LParietal	4	0	LFrontal, RParietal, LTemporal, Occipital
Component 11	RZygomatic	1	0	RMaxilla
Component 12	LZygomatic	1	0	LMaxilla
Component 13	RTemporal	4	0	RFrontal, RParietal, Occipital, Bottom
Component 14	LTemporal	4	0	LFrontal, LParietal, Occipital, Bottom
Component 15	Occipital	5	0	RParietal, LParietal, RTemporal, LTemporal, Bottom
Component 16	Bottom	7	0	RMaxilla, LMaxilla, RFrontal, LFrontal, RTemporal, LTemporal, Occipital
		56	**2**	

Table 3. List of cranial components, the number of magnet casings and shelves they contain, and the adjacent components they connect to.

Segmentation Plane	Zoom	Round Brush Radius	Casing Thickness (Number of Slices)
XY	2:1	125/150	10/20
XZ	2:1	125/150	20/40
YZ	2:1	125/150	20/40

Table 4. Settings for creating the magnet casings in Avizo® (version 2022.1; Thermo Fisher Scientific-FEI). Round brush radii and casing thicknesses for each segmentation plane are presented as fractions, where the numerator represents the radius and thickness of the smaller magnet casing (the material to be removed from the larger casing), and the denominator represents the radius and thickness of the larger magnet casing (the material to be added to the segmented cranial component). Casing thickness is equivalent to the number of slices (TIFFs) within a segmentation plane. Note that the XY segmentation plane has magnet casings that are half the thickness of the XZ and YZ planes. This is so because the complete TIFF stack of the dog cranium was too large to process in Avizo® and was subsequently halved in size.

strongly encourage users at other veterinary schools to do the same. Our next step will be to develop full skeletal 3DPMs of the dog and other taxa. The horse, for instance, is a frequently requested 3DPM by veterinary students and faculty at Cornell's College of Veterinary Medicine. Learning the turbinate bones (nasal conchae) of the horse is an essential aspect of clinical training, but running an endoscope down a live animal can be a stressful, and potentially traumatic, experience for both the student and patient. Practicing on a 3DPM of a horse skull, however, reduces student stress and eliminates any possibility of accidentally inflicting injury. Moreover, the student can practice as many times as they need to get comfortable with the tool before working on a live animal.

Our 3DPM was constructed using a Formlabs Form 3B printer and thus we recommend users test out other 3D printer brands and types. Since each 3D printer has its own set of configuration parameters, some of our 3DDMs may need to be adjusted prior to printing (Stoughton, 2023). The size of the magnet casings, which may print smaller or larger depending on the printer brand and type used, may need to be adjusted as well (Table 4).

Our method for magnet casing construction in Avizo® has three limitations: (1) casings can only be placed in the XY, XZ, and YZ planes, restricting their orientation to just three possibilities (the inner cranium is a complex surface that is often not parallel to any of the three planes); (2) adjustment of casing position after initial placement requires deleting material around the dog 3DDM, making test printing the alignment of any two cranial components challenging and time consuming; and (3) the smallest cranial bones (constituents of the "Bottom" cranial component, for example) cannot be individually segmented and magnetized because the "brush" tool is not a perfect circle. However, these limitations can be addressed in the future when making new veterinary 3DPMs. We first suggest utilizing the "transform editor" tool in Avizo®, which can adjust the (1) orientation and (2) position of a selected material. Magnet casings, which were created as separate materials within a label field for their respective cranial component, can be rotated and moved in 3D space with respect to the cranial component. The orientation and position of entire label fields (cranial components and their respective magnet casings) can also be adjusted with

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the "transform editor." In addition to Avizo®, graphic design software (e.g., Blender, Zbrush) have enhanced capabilities for adjusting 3D objects after 3DDMs have been generated. In situations where very small cranial bones must be segmented (and even magnetized), we recommend inflating the entire 3DDM (all label fields and their associated materials) using the "grow selection" tool in Avizo®. An enlarged 3DDM improves visualization in segmentation software, segmentation along the path of sutures, and given magnet sizes, can allow attachment of casings without significantly altering the shape of smaller bones.

Moreover, digital segmentation can be avoided altogether. Instead, one magnet casing can be created as an individual material in Avizo®. A set of 56 of these casings can be printed and mounted to the cranial bones of a real disarticulated dog skull using adhesive. The individual "cranial components" (disarticulated cranial bones with 3D printed magnet casings adhered) can then be 3D surface scanned, the surface files of which can be sent directly to the 3D printer – no segmentation required. The magnet casings will already be properly aligned (this can be confirmed on the real specimen) if printed to scale. The only limitation of this approach is that a teaching specimen must be sacrificed; however, an unlimited number of replacements can be printed in its place.

Within the past decade, veterinary schools have recognized the educational value of 3DDMs and 3DPMs, especially as the cost of 3D printers, their operation, maintenance, and materials, have dramatically decreased (Bakici *et al.*, 2025; Huri and Oto, 2022; Quinn-Gorham and Khan, 2016; Savini and Savini, 2015; Wilhite and Wölfel, 2019). Our free-to-download dog cranium 3DPM can help to inspire a new generation of future veterinarians. Since our model is made of resin and not bone, a 3D printed cranium may make students more inclined to learn skeletal anatomy without the need for dissection or handling real bones, which would potentially be unappealing for many, especially younger K-12 (pre-elementary to high school) students. Our 3DPM may also be of particular interest to students and professionals in the fields of zooarchaeology and vertebrate paleontology, who often encounter skulls as partial and fragmentary remains. However, 3DDMs and 3DPMs cannot replace their biological counterparts in all contexts, as natural variation, color, texture, and fine anatomical details can be important (Bakici *et al*., 2025). At the veterinary level, our 3DPM can serve as a supplement to the real biological material encountered in traditional gross dissection and atlas illustrations.

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