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3d printing of skull models in horse, cattle and pig

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ABSTRACT:

In this study, it was aimed to physically create skull models of large-sized animal sample horse, cattle and pig species used in veterinary anatomy education with three-dimensional printing technology and to determine the suitability of these models anatomically. The anatomical structures on the skull models obtained for this purpose were examined comparatively and the advantages and disadvantages of the models in terms of their usability in education were revealed. For the study, 3D reconstruction and segmentation processes were performed digitally on the cross-sectional images of horse, cattle and pig skulls obtained by computed tomography scanning and printed. Anatomical structures were comparatively analyzed on the produced 3d plastic replicas and organic skulls. Anatomical accuracy of the 3d models, printing quality, printing errors, advantages and disadvantages were evaluated. Plastic models were found to be approximately 45% lighter than organic models in horses, 55% lighter in cattle and 60% lighter in pigs. The weight (g)/printing time (s) ratio was calculated as 11.8 for equine skull models, 12.7 for bovine models and 7.4 for porcine models. It was determined that the anatomical accuracy of the models was at a high level, important anatomical structures could be printed in accordance with the original skulls, and only some sutures between the skull bones and holes with a diameter of less than 2 mm could not be clearly visualized due to scanning and printing quality. As a result, it was determined that the plastic replicas obtained can be used in veterinary anatomy education in terms of anatomical accuracy, as well as important advantages such as being lighter, more resistant to effects such as falling, impact, cleaning, easy storage, low cost, reprinting when necessary and making corrections on the model.

At, sığır ve domuz 3 boyutlu baskı kafatası modelleri

ÖZET:

Bu çalışmada, veteriner anatomi eğitiminde kullanılan büyük cüsseli hayvan örneği olan at, sığır ve domuz türlerine ait kafatası modellerinin üç boyutlu baskı teknolojisiyle fiziksel olarak oluşturulması ve bu modellerin uygunluğunun anatomik açıdan belirlenmesi amaçlandı. Bu amaçla elde edilen kafatası modelleri üzerindeki anatomik yapılar karşılaştırmalı olarak incelenerek, modellerinin eğitimde kullanılabilirliği yönünden avantaj ve dezavantajları ortaya konuldu. Çalışma için bilgisayarlı tomografi taraması ile elde edilen at, sığır ve domuz kafataslarına ait kesit görüntüleri üzerinden dijital ortamda 3b rekonstrüksiyon ve segmentasyon işlemleri yapılarak baskı alındı. Üretilen 3b plastik replikalar ve organik kafatasları üzerinde karşılaştırmalı olarak anatomik yapılar incelendi. 3b modellerin anatomik uyumluluğu, baskı kalitesi, baskıda oluşan hatalar, avantaj ve dezavantajlar değerlendirildi. Plastik modellerin organik modellerden atta yaklaşık %45, sığırda %55, domuzda %60 daha hafif olduğu görüldü. Ağırlık (g)/baskı süresi (s) oranı at kafatası modellerinde 11,8; sığır modellerinde 12,7; domuz modellerinde 7,4 olarak hesaplandı. Modellerin anatomik doğruluğunun yüksek düzeyde olduğu, önemli anatomik yapıların orjinal kafataslarına uygun biçimde basılabildiği, sadece tarama ve baskı kalitesine bağlı olarak kafatası kemikleri arasındaki bazı dikiş izleri (suturalar) ile 2 mm'den küçük çaptaki deliklerin net olarak görüntülenemediği tespit edildi. Sonuç olarak, elde edilen plastik replikaların hafif olması, düşme, çarpma gibi etkilere karşı daha dayanıklı olması, temizliği, kolay saklanabilir olması, düşük maliyeti, gerektiğinde tekrar basılabilir ve model üzerinde düzeltmeler yapılabilir olması gibi önemli avantajları yanında, anatomik doğruluk açısından da veteriner anatomi eğitiminde kullanılabilir olduğu belirlendi.

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1. Introduction

Three-dimensional printing technology and printers are advanced technologies that have been widely used in the medical field in recent years (1-3). The printing and modeling process is an additive manufacturing technology based on the production of digitally created or computerized images with any three-dimensional scanner in layers with special printers after CAD (computer assisted design) and CAM (computer assisted manufacturing) programs (4). According to the printing material and technology used, there are 3 basic printer models; SLA (Stereolithography), SLS (Selecetive laser sintering) and FDM (Fused deposition modeling). SLA printers use liquid resin as the material. With the effect of laser and UV rays reflected on the liquid resin placed in the printer's tank, the liquid hardens and the desired object is modeled. SLS printers work on the principle of modeling by hardening the powdered material with laser beams. Although both methods provide the highest print quality, their use is limited due to their high costs. The most commonly used printers are FDM printers that melt thermoplastic materials by heating and pour them onto the tray layer by layer (4-6). The most intensive use of 3D printing technology in medicine is educational training and surgical planning through anatomical models. In veterinary anatomy education, animal bone models obtained with 3D printing have been used extensively in recent years (7-9). Apart from this, patient-specific orthosis and prosthesis production, laboratory equipment production, controlled drug release systems and bioprinting, which have been developing in recent years, are other areas where 3D printing technologies are used (4).

The basis of veterinary anatomy education is osteology. The cranium has the most complex anatomical structure among the bones in the skeleton and the region with the highest variation among animals in comparative anatomy education (10). The skull (cranium), which is shaped by a large number of flat bones that begin to fuse with each other in the prenatal period, basically consists of 2 parts: the neurocranium surrounding the brain cavity and the viscerocranium shaped by the facial bones. The cranium is a very complex anatomical structure with many intrusions, protrusions, holes, notches, cavities etc., which has clinical importance due to its vital functions and vital structures on it (11). For this reason, skulls and related organs of different animal species are studied in 3D and comparatively in anatomy practice trainings (12-15).

The skulls used in veterinary anatomy practice education are obtained by cleaning the undamaged and anatomically intact animal heads as a result of the maceration process (16). The source of bone material is primarily necropsied animals, carcasses from slaughterhouses and donors. Due to urbanization, ungulate specimens are both few in number and their anatomical structures are disrupted as their skulls are opened during necropsy. Cattle carcasses can be obtained from slaughterhouses, but their cost is very high due to the edible material on the head. Pork is not widely available in our country, so its supply is very limited. In addition, maceration methods to remove organic material are laborious and time consuming. The chemicals used during maceration have harmful effects. These materials are difficult to store and protect from rodents. Flat skull bones and anatomical structures on the skull are very sensitive to impacts such as falls and bumps and break immediately. For all these reasons, it is very difficult to provide sufficient number of horse, ox and pig skull models in veterinary anatomy practice education. At this point, it is important that plastic-based skull models obtained by 3D printing can be used as an alternative educational material.

This study aims to determine the anatomical accuracy of the replica models to be obtained by computed tomography scanning from horse, cattle and pig skulls used as large breed animal samples in veterinary anatomy practice to determine the errors that may occur in pre-printing, printing and post-printing processes and to reveal the advantages and disadvantages of the models. In addition, with the digital data to be created, material continuity will be ensured by taking reprints when needed.

2. Material and Methods

Three adult horse, ox and pig skulls from the bone collection in the osteology laboratory of the Department of Anatomy, Faculty of Veterinary Medicine, Ankara University, which are currently used as educational materials, were

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used as the data source for the models to be created in the study. Transverse, 1.5 mm thick, contiguous single slices were obtained on a spiral, single-sliced CT scanner (Philips Picker PQ 2000) at a private animal hospital in Ankara, Turkey. Scanning parameters of CT images were given in Table 1.

Table 1: CT scanning parameters
Tablo 1: *CT tarama parametreleri*

	kV	mA	ST (mm)	FOW
Horse	120	50	1.5	480x480
Cattle	120	65	1.5	480x480
Pig	120	65	1.5	480x480

kV; kilovolt power unit, mA; milliampere current unit, ST; slice thickness, FOW; field of view

The obtained DICOM images were prepared for printing using open source 3D design programs 3d slicer (BWH), meshmixer (Autodesk) and cura (Ultimaker). CAD and CAM stages are given in Figure 1. From the created digital 3D models (Figure 2), print models were prepared in the same size as the organic skulls with 15% filling. With the software used, the anatomical accuracy of the printed replicas was increased by correcting the deficiencies, fractures, cracks or distortions in the normal anatomical structure of the organic bones, especially in the teeth, fine protrusions and surfaces, on the digital model. The finalized model with support structures was printed using an FDM printer (anycubic, predator delta) and pla filament (esun pla 1.75 mm, white). The printer, filament and printing parameters used are given in Table 2. After printing, the support material was removed and anatomical evaluation was performed on the final cleaned skulls in comparison with organic skulls.

Table 2: 3d printing parameters
Tablo 2: *3d baskı parametreleri*

	Print temp.	Infill Rate	Print Resolution	Print Speed
FDM	205 C	%15	0.28mm	50mm/s

FDM; fused deposition modeling - additive manufacturing, C; degrees Celsius

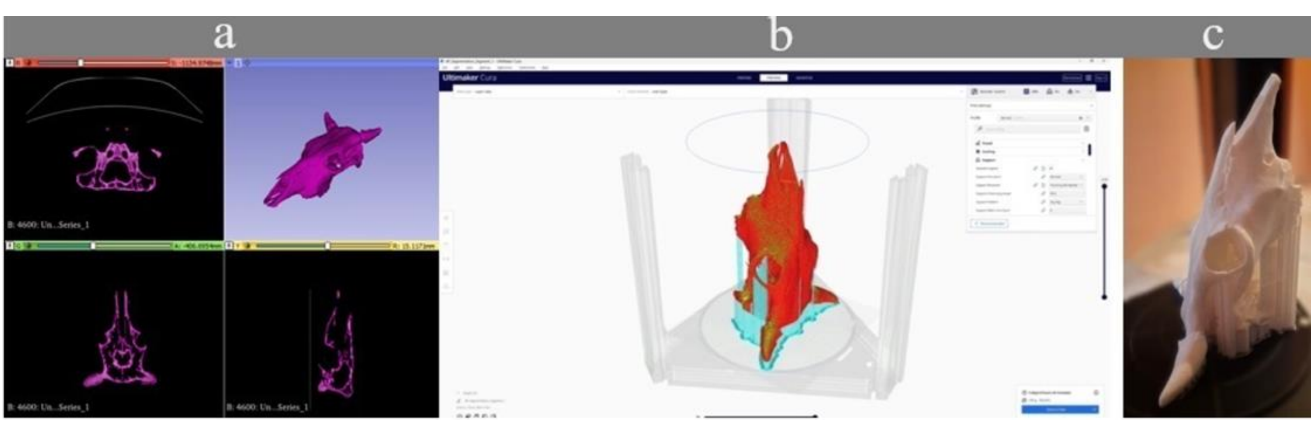

Figure 1: 3d printing process **(a)** 3d reconstruction, **(b)** slicing, **(c)** printings
Şekil 1: *3d basım işlemi (a) 3d rekonstrüksiyon, (b) dilimleme, (c) baskılar*

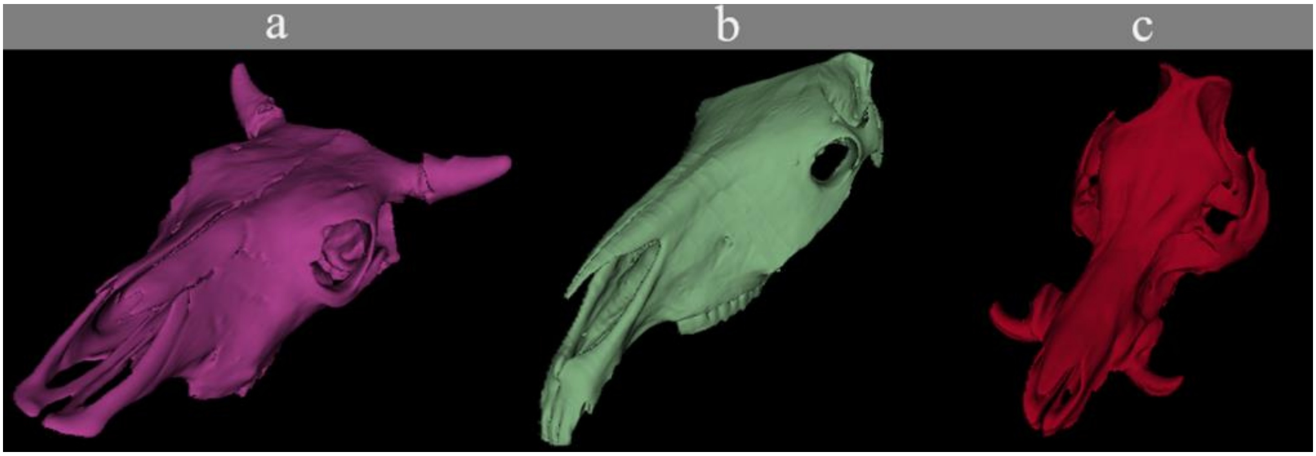

Figure 2: 3d reconstruction models **(a)** ox, **(b)** horse, **(c)** pig
Şekil 2: *3d rekonstrüksiyon modelleri (a) sığır, (b) at, (c) domuz*

3. Results

In the study, three-dimensional digital and physical printing models were made on CT cross-sectional images of masserated horse, cattle and pig skulls. The weights and weight/printing time ratios of the replicas are given in table 3 in comparison with the real skulls. Plastic models were found to be approximately 45% lighter than organic models in horse, 55% lighter in cattle and 60% lighter in pig. The weight (g)/pressure time (s) ratio was calculated as 11.8 in horse skull models, 12.7 in cattle models and 7.4 in pig models.

In the anatomical evaluation, it was observed that the prominent anatomical structures such as nasal process, orbit, chona, jugulary process, zygomatic arch in the skull of all three animal species had a great anatomical accuracy in detail between replicas and organic models. Anatomical holes and notches larger than 2 mm in diameter could be visualized easily on the exact position. However, for smaller holes, there was a loss of detail due to the thickness of the nozzle tips on the devices used. Similarly, the details of bone joints and sutures, especially on the basal surface of the skull, were lost due to the tresholding and smooting processes during digital modeling. The prominent anatomical structures on the replicas are shown in Figures 3-5.

Table 3: Comparison of weight and weight/printing time ratio of the replicas
Tablo3: *Modellerin ağırlık ve ağırlık/baskısüresi oranlarının karşılaştırılması*

		HORSE(g)	CATTLE(g)	PIG(g)
Time		93.5	59.5	43
Weight	r/g	2064/1104	1672/760	816/320

r/g; replica - cadaver comparison, (g); gram

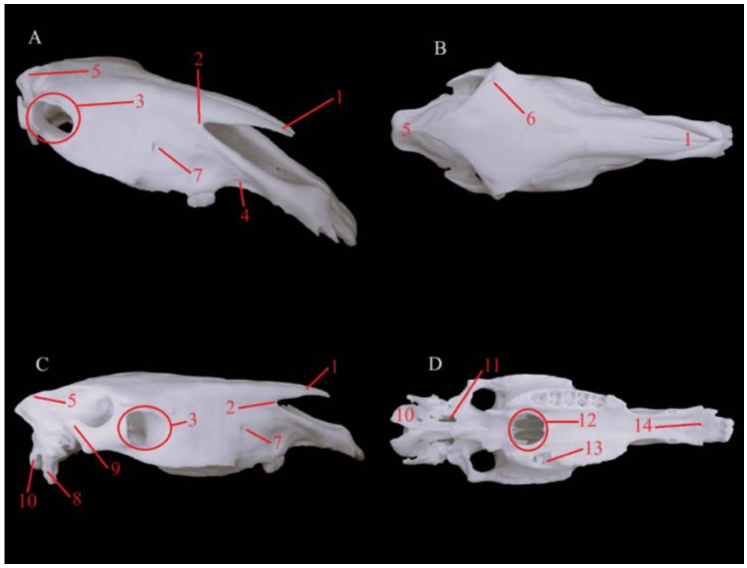

Figure 3: Anatomical structures on the 3d skull replica of horse **(A)** obliq, **(B)** dorsal, **(C)** lateral, **(D)** ventral, **1**. Processus septalis, **2**. Incisura nasoincisiva, **3**. Orbita, **4**. Margo interalveolaris, **5**.Crista sagittalis externa, **6**. Foramen supraorbitale, **7**. Foramen infraorbitale, **8**. Processus jugularis, **9**. Arcus zygomaticus, **10**. Condylus occipitalis, **11**. Foramen lacerum, **12**. Chona, **13**. Alveoli dentes, **14**. Foramen incisivum

Şekil 3: *Atın 3b kafatası modelinde anatomik yapılar*

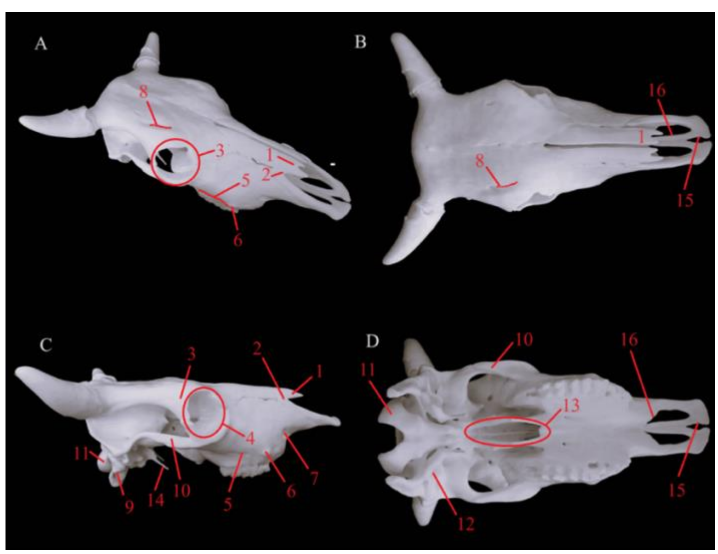

Figure 4: Anatomical structures on the 3d skull replica of cattle **(A)** obliq, **(B)** dorsal, **(C)** lateral, **(D)** ventral, **1**. Processus septalis, **2**. Incisura nasomaxillaris, **3**. Orbita, **4**. Arcus orbitalis, **5**. Crista facialis, **6**. Tuber faciale, **7**. Foramen infraorbitale, **8**. Foramen supraorbitale et sulcus supraorbitalis, **9**. Processus jugularis, **10**. Arcus zygomaticus, **11**. Condylus occipitalis, **12**. Bulla tympanica, **13**. Chona, **14**. Processus muscularis, **15**. Fissura incisiva, **16**. Fissura palatinum.

Şekil 4: *Sığırın 3b kafatası modelinde anatomik yapılar*

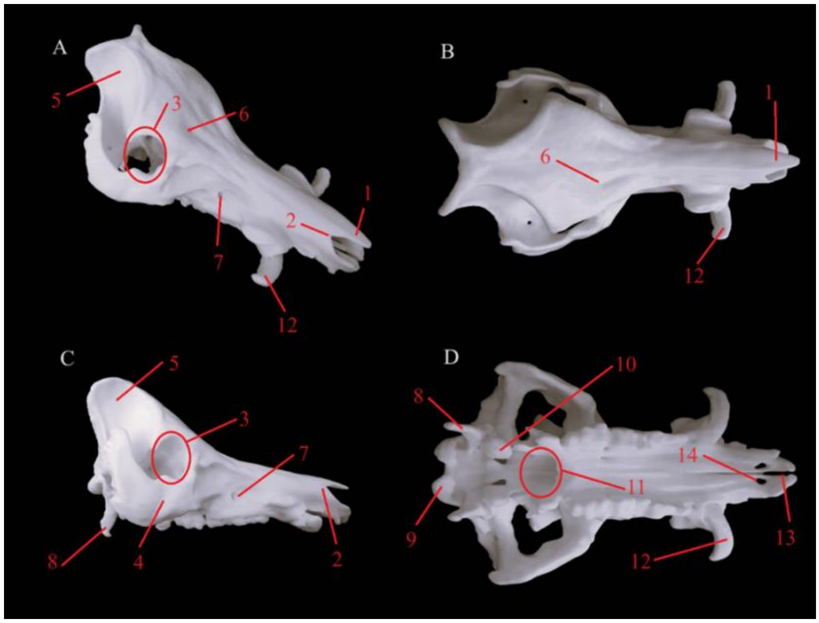

Figure 5: Anatomical structures on the 3d skull replica of pig **(A)** obliq, **(B)** dorsal, **(C)** lateral, **(D)** ventral, **1**. Processus septalis, **2**. Incisura nasoincisiva, **3**. Orbita, **4**. Arcus zygomaticus, **5**.Fossa temporalis, **6**. Foramen supraorbitale, **7**. Foramen infraorbitale, **8**. Processus jugularis, **9**. Condylus occipitalis, **10**. Bulla tympanica, **11**. Chona, **12**. Dens caninus, **13**. Fissura incisiva, **14**. Fissura palatinum

Şekil 5: *Dommuzun 3b kafatası modeli üzerinde anatomik yapılar*

4. Discussion and Conclusion

The quality of the models produced in our study depends primarily on high anatomical accuracy and then on the practical usability of the models. From the scanning method to the type of material used, each stage of the printing process affects the quality of the models to a certain extent. In this context ;

Surface scanning, microCT, CT, MRI and USG methods are used for 3D printing of bone tissues (4). Surface scanners does not allow the printing of internal structures, MR and USG scans provide high resolution in soft tissues rather than bone tissue imaging. Micro tomography provides the best detail, but the small volume of the tissues examined limits the use of the method for anatomical modeling. For all these reasons, the best resolution images for large volumes of bone tissues are obtained by computed tomography (17). In our study, modeling was performed on cross-sectional images scanned with computed tomography to obtain the highest anatomical resolution.

Software that allows segmentation, mesh refinement and slicing stages are used in the digital creation of three-dimensional models (18). In addition to very high-cost and high-precision software (e.g. Mimics), there are also open source programs that can be accessed by everyone. In our study, 3D slicer, Meshmixer and Cura programs, also used by Bücking et al (18), were used. It was seen that open source programs are sufficient in terms of anatomical accuracy, accessibility, and ease of use and can be preferred for models to be used for educational training purposes. In addition, it would be more appropriate to use professional software, printers, and materials with standardized calibration, especially for surgical use, design of prosthesis/orthosis design, and printing of sensitive laboratory tools.

It was determined that the printing parameters (Table 2), which were specified by Comrie et al. (17); Bilal et al. (19); Elizabeth et al. (20); and Sucuoğlu et al. (21) which we used for the models obtained in our study, provided sufficient robustness, dimensional consistency, visual aesthetics and anatomical detail in terms of wall thickness, internal filling ratio and layer thickness of the models. The positioning of the digital model on the tray before printing and the creation of support tissues is one of the factors that directly affect the print quality. It was determined that the best results in animal skull bones were obtained by placing the model in an upright position with the nuchal region sitting on the base.

As a result, the advantages of skull models obtained by three-dimensional printing such as being lighter, stronger, and less costly compared to organic bones, more suitable cleaning and storage conditions, being correctable and reprintable when necessary, and having no known harmful effects on health are important in terms of ease of use and preference. In addition, it has been determined that the printed models have high anatomical accuracy and most of the important anatomical structures in the skull can be visualized. However, it was also observed that the sutures between the bones could be lost during printing due to the thresholding process and the printing of holes and notches under 2 mm in diameter due to the nozzle diameter of the printer. It is thought that the models can be used as an example in theoretical and practical training of veterinary anatomy and that models with higher detail can be obtained in the near future with the widespread use of technology and decreasing costs.

Conflict of Interest

The authors declared that there is no conflict of interest.

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Authors' Contributions

Idea/concept: Çağdaş OTO
Design of experiments: Orçun GÜVENER
Auditing/Consultancy: Çağdaş OTO
Data collection: Orçun GÜVENER
Data analysis and interpretation: Çağdaş OTO, Orçun GÜVENER
Literature review: Orçun GÜVENER
Writing of the article: Çağdaş OTO, Orçun GÜVENER
Critical review: Çağdaş OTO

Ethical approval

An ethical statement was received from the authors that the data, information and documents presented in this article were obtained within the framework of academic and ethical rules and that all information, documents, evaluations and results were presented in accordance with scientific ethics and moral rules.

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