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REVIEW ARTICLE

Animal Anatomical Teaching Models for Enhanced Veterinary Anatomy Education and Learning

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A B S T R A C T

Animal teaching models are transforming veterinary anatomy education by providing accurate, engaging, and ethically aligned alternatives and complements to cadaver-based instruction. Advances in 3D printing enable the production of durable, low-cost, species-specific models derived from CT/MRI data, improving spatial understanding, reducing exposure to formalin, and expanding access to standardized specimens across cohorts. Evidence from veterinary anatomy education shows that 3D-printed and digital 3D models improve learning outcomes compared to traditional methods, along with strong acceptance from students and faculty. Simulation-based training with 3D-printed models enhances student confidence, motivation, and readiness for veterinary clinical skills, while facilitating a smoother transition to live-animal work and reducing the need for cadavers. These anatomical models also address the safety, logistics, and cost constraints associated with cadaver storage and maintenance. However, high-fidelity full-body simulators may be limited by expense and maintenance requirements. Implementation frameworks emphasize rigorous anatomical accuracy, iterative validation with educators and students, and alignment with veterinary curricular outcomes, leveraging fused deposition modeling and stereolithography to strike a balance between fidelity and affordability. While long-term effects on skill transfer and knowledge retention warrant further controlled studies, current evidence supports integrating physical and virtual 3D models with conventional dissection and computer-assisted learning to create blended, multimodal anatomy curricula. This approach advances pedagogical effectiveness, accessibility, and ethical standards in veterinary education, ultimately supporting improved clinical competence and animal welfare. In conclusion, Anatomical models are essential in the veterinary curriculum to give students a hands-on, interactive learning experience that improves spatial understanding, supports animal welfare, and enhances clinical and communication skills necessary for veterinary practice.

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INTRODUCTION

Veterinary anatomy forms the cornerstone of veterinary education, serving as the foundation upon which clinical, surgical, pathological, and diagnostic competencies are built (Choudhary *et al.*, 2023; Choudhary *et al.*, 2025). It is widely accepted that a robust understanding of animal/veterinary anatomy enhances a student's capacity to interpret physiological processes, assess pathological conditions, and perform surgical interventions with precision in domestic and wild animals. However, teaching and learning anatomy, particularly in veterinary contexts, pose unique challenges for the veterinary students. Unlike human anatomy education, which often benefits from well-resourced cadaver donation programs and specialized laboratories, veterinary anatomy education must address the anatomical diversity of multiple species, variations in organ structure and position, and species-specific clinical relevance (Choudhary *et al.*, 2025).

Historically, veterinary anatomy has been taught through dissection of formalin-preserved cadavers, lectures using two-dimensional (2D) diagrams on boards, and the use of anatomical atlases and standard veterinary anatomy reference textbooks (Fig. 1). While these anatomical methods have undeniably served as the gold standard for decades, they come with notable limitations. The acquisition and preservation of cadavers present ethical, logistical, and financial challenges for veterinary anatomy education. For example, cadaver embalming is banned by the Indian government as it requires euthanasia; hence, the anatomy teachers must see other alternatives for veterinary anatomy education (Choudhary and Daga, 2024). Furthermore, cadavers tend to decompose if the formalin concentration is not maintained in the formalin tank, and using formalin for preservation poses health risks to both students and instructors (Varner *et al.*, 2021). The availability of animal bodies, particularly those of exotic or endangered species, may be restricted due to legal and conservation regulations in many countries. Additionally, limited opportunities for repeated dissection and tissue degradation over time impact the quality of the learning experience in veterinary anatomy education. Animal donation from the owners after the animal's death is an alternative to preparing anatomical specimens without embalming, but it requires the consent of the animal owner (Lombardero *et al.*, 2017). Proper impregnation of formalin in the muscles and tissues of the viscera is necessary; otherwise, it may degrade within a few hours of formalin preservation. Recently, there has been a significant shift toward incorporating anatomical models—both physical and digital—into veterinary curricula (Kapoor *et al.*, 2024). These models are being developed to complement or, in some cases, replace traditional teaching with cadavers. They span a range of formats, from plastinated specimens and silicone replicas to highly sophisticated three-dimensional (3D) printed models, augmented reality (AR) simulations, and virtual dissection platforms. This transition aligns with the global trend in medical education to integrate technology-enhanced learning tools to improve pedagogical outcomes in veterinary anatomy education (Kapoor and Singh, 2022; Kapoor *et al.*, 2024).

The development of anatomical models for veterinary education is not merely a technological advancement; it reflects a paradigm shift in how veterinary anatomy is taught and understood (Schirone *et al.*, 2024). Anatomical models offer numerous advantages: they are reusable, hygienic, customizable, and safe for teaching and learning processes. More importantly, they allow for repeated practice, tactile engagement, and interactive learning without the constraints of time or bioethical limitations (Edelmers *et al.*, 2021). These tools are helpful in resource-limited settings where animal cadavers may not be readily available in many veterinary institutions due to ethical or permission restrictions from the government. They also align with the principles of the 3Rs (Replacement, Reduction, and Refinement), promoting ethical practices in veterinary education by reducing the reliance on animal bodies for educational purposes (Choudhary, 2025; Louis-Maerten and Shaw, 2025). Moreover, with the advent of technologies such as 3D scanning, photogrammetry, additive manufacturing (also known as 3D printing), and immersive digital platforms, it has become increasingly feasible to develop detailed and anatomically accurate models (Kantaros *et al.*, 2023; Kapoor, 2024). These tools have been essential in creating representations of complex anatomical structures that are often hard to dissect or preserve in cadaveric form. As veterinary institutions worldwide seek to modernize their anatomy teaching methods, these models are finding broader applications not only in teaching but also in student assessment, diagnostic, clinical skills, and surgical planning.

Educational research supports the integration of anatomical models in veterinary curricula (Mahdy *et al.*, 2022). Numerous studies have reported improved student satisfaction, better spatial understanding of anatomical relationships, and enhanced retention of anatomical knowledge when students use anatomical models in conjunction with traditional teaching and learning methods (Tripodi *et al.*, 2020; Mahdy *et al.*, 2022). Furthermore, the use of anatomical models caters to diverse learning preferences- benefiting visual, tactile, and kinesthetic learners- and fosters active, student-centered learning environments in veterinary institutions. As veterinary institutions continue to adopt hybrid models of education that incorporate both online and in-person components, the portability and accessibility of these models further underscore their value (Tripodi *et al.*, 2020). Despite their apparent advantages, the development and adoption of anatomical models are not without challenges. The cost of high-fidelity models can be prohibitive, particularly for institutions in developing countries. Standardization and validation of anatomical models across different veterinary institutions remain a concern, as does the training of faculty to effectively integrate these tools into their teaching. Moreover, while digital models offer interactivity and simulation capabilities, they require substantial infrastructure, such as hardware, software, and technical support, which may be beyond the reach of some institutions (Carr *et al.*, 2022; Domínguez-Oliva *et al.*, 2023). Considering these points, this review article examines the evolution, development, and influence of anatomical models in veterinary anatomy education. It provides a detailed examination of the types of models available, the technological and material advancements driving their development, and the pedagogical value they offer (Domínguez-Oliva *et al.*, 2023). This paper also examines how these models are evaluated and integrated into veterinary curricula, the ethical considerations associated with their use, and the global trends influencing their adoption. The articles for this review were searched on the PubMed engine using the keyword "veterinary anatomical models in teaching." We found 217 articles with these keywords on PubMed; however, we finalized the articles based on their relevance to this review.

Through this comprehensive analysis, the aim is to present a compelling case for the continued investment in anatomical modeling to enhance veterinary anatomy education in both developed and developing contexts. The objective of overarching is to establish how anatomical models- when thoughtfully designed and strategically implemented-can transform the teaching of veterinary anatomy from a static, passive experience to a dynamic, engaging, and ethically sound endeavor. Ultimately, these models are not just tools; they are pedagogical innovations that hold the potential to redefine how future veterinarians learn, practice, and internalize one of the most fundamental subjects in their degree programs.

Evolution of anatomical models: The development of anatomical models represents a significant evolution in the history of anatomical education, bridging art, science, and pedagogy (Narang *et al.* 2021). Long before the advent of modern technologies, educators recognized the importance of three-dimensional representations in understanding the spatial relationships of anatomical structures (Narang *et al.* 2021). Over time, these models have evolved from rudimentary artistic representations to highly accurate, life-sized, interactive teaching tools used extensively in contemporary veterinary anatomy education. The historical trajectory of anatomical model development in veterinary education is deeply intertwined with broader trends in medical science, technology, and ethical perspectives (Kapoor *et al.*, 2024; Choudhary *et al.*, 2025).

Early representations and pre-modern models: The roots of anatomical modeling can be traced back to ancient civilizations, where rudimentary representations of animal and human bodies were used for ritualistic, artistic, and educational purposes (Habbal, 2017). The ancient Egyptians, Greeks, and Romans created clay and wooden effigies to represent internal organs, often as part of spiritual or mythological narratives (Habbal, 2017). However, the systematic use of anatomical models for education only began during the Renaissance, an era marked by a resurgence of interest in human and animal anatomy, driven by figures such as Leonardo da Vinci and Andreas Vesalius (Ghosh and Kumar, 2019). Although Vesalius' De Humani Corporis Fabrica (1543) focused on human anatomy, it indirectly influenced veterinary anatomy by promoting dissection and empirical observation over speculative reasoning. Around this period, wax anatomical models- also known as ceroplastics- became increasingly popular (Ghosh and Kumar, 2019). Italian anatomists and artisans created intricate wax models of both human and animal anatomy, which served as durable, reusable alternatives to cadavers. The Museo La Specola in Florence still houses one of the most extensive collections of these models, many of which feature comparative veterinary anatomy (Markovi *et al.*, 2010; Riva *et al.*, 2010). These wax models were valuable educational aids, especially when cadavers were scarce due to religious, legal, or logistical reasons (Markovi *et al.*, 2010; Riva *et al.*, 2010). However, their creation required exceptional artistic skill, and they were often fragile, expensive, and limited in anatomical detail, especially for smaller species or deeper structures.

The 19th and early 20th century: Industrialization and standardization: The industrial revolution brought about significant advances in materials science and manufacturing techniques, leading to the development of more durable anatomical models made from papier-mâché, wood, and early forms of plastic. German anatomist Louis Auzoux gained fame in the mid-19th century for his "anatomie clastique"—dissectible anatomical models made of papier-mâché (Ortug and Yuzbasioglu, 2019). Auzoux's models were used widely in medical and veterinary institutions across Europe and the United States, as they allowed for repeated dissections and demonstrations without the constraints of decay or odour associated with real anatomical specimens (Ortug and Yuzbasioglu, 2019; Delcambre and Allsop, 2024).

These models represented a key innovation: they were mass-producible and modular, allowing educators to disassemble and reassemble them for demonstrations to the veterinary students. While most were based on human anatomy, veterinary-specific models also began to emerge, particularly for equine and bovine anatomy, reflecting the growing importance of animal health in the agriculture and transport industries of the time (Domínguez-Oliva *et al.*, 2023). With the rise of veterinary institutions/ schools across Europe and North America in the late 19th and early 20th centuries, the demand for veterinary-specific anatomical models grew (Boyd, 2011). However, the variety of species studied in veterinary programs posed a challenge for anatomical model makers. Models needed adaptation to account for species-specific anatomical differences, which restricted the scalability and cost-effectiveness of creating significant and varied model collections (Mukherjee *et al.*, 2022).

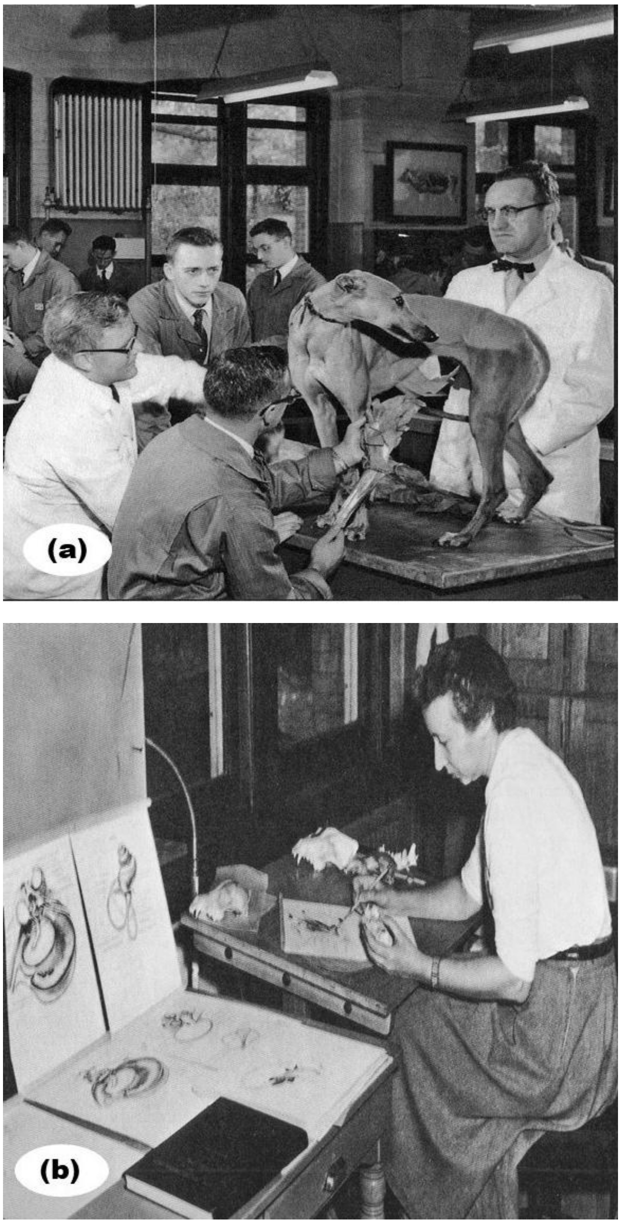

Fig. 1: (a) A class at the old Veterinary College (now the site of the I & LR School). Herman Meyer (seated) and Professor Malcolm Miller (1954) are the instructors. (b) Marion Newson, Medical Illustrator (1955) (Evans, 2013).

Mid 20th Century: plastics, dissection specimens, and pedagogical shifts: The post-war period saw drastic changes in anatomical education, driven by advances in synthetic polymers and a broader shift toward formalized medical curricula (Azer and Azer, 2016). With the development of durable plastics like polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS), educational manufacturers began to produce affordable, lightweight, and resilient anatomical models (Arráez-Aybar, 2025). These anatomical models were widely adopted in veterinary colleges for teaching and learning purposes during the 1950s and 1960s, particularly in North America, Europe, and parts of Asia (Jaber *et al.*, 2018; Alcázar-Chávez *et al.*, 2021).

In parallel, the mid-20th century also saw the standardization of veterinary anatomy teaching, with primary textbooks and anatomical atlases (such as Sisson and Grossman's Anatomy of the Domestic Animals) defining core learning objectives (Sisson and Grossman, 1953). This standardization encouraged model developers to align their products with textbook references, enhancing anatomical model educational utility.

Veterinary anatomy continued to rely heavily on cadaveric dissection during this period. However, physical models gained prominence as supplementary tools-especially in demonstrating complex 3D structures, such as the cranial nerves, pelvic girdle, or vascular branching patterns, which were difficult to appreciate in flat illustrations or decaying cadavers (Varner *et al.*, 2021).

Late 20th Century: Plastination and educational innovation: A pivotal moment in anatomical model development came in the late 1970s with the invention of plastination by Dr. Gunther von Hagens (Moore and Brown, 2004). Plastination involves replacing water and fat in tissues with polymer resins, producing odourless, durable specimens that maintain anatomical integrity over decades (Sora *et al.*, 2019). Initially developed for human anatomy, plastination was quickly adapted for veterinary education, providing long-lasting, high-fidelity models of real tissue (Riederer, 2014). Veterinary institutions around the world began to establish plastination laboratories or procure plastinated specimens to enrich their teaching collections. Plastinated models offer a solution to the challenges of cadaver preservation and waste management, becoming particularly valuable for displaying delicate or complex anatomical structures, such as equine hoof or the avian respiratory system (Nurunnabi *et al.*, 2023). This era also witnessed a growing interest in active learning pedagogies, such as problem-based learning (PBL), team-based learning (TBL), and self-directed study, which benefited from the flexibility and accessibility of anatomical models. Models became focal points for small-group learning, revision exercises, and assessment simulations in veterinary anatomy education (Seel, 2017).

21st century: Digital and 3D printed revolution: The 21st century has marked a revolution in anatomical modeling through digital technology and 3D printing (Wickramasinghe *et al.*, 2022). The availability of high-resolution CT and MRI scans of animal bodies, combined with software for segmentation and anatomical modeling (e.g., Blender, MeshLab, Mimics, ImageJ), has allowed educators to create highly accurate digital reconstructions of animal anatomy (Abreu de Souza *et al.*, 2023). These anatomical models can then be printed using a range of materials, such as PLA, ABS, resin, and silicone, tailored to replicate the texture, flexibility, or color coding of tissue (Jin *et al.*, 2021). Initially expensive and labour-intensive, 3D printing has become more accessible, with many veterinary colleges/ institutions setting up in-house labs to produce custom models for regional or exotic species (McMenamin *et al.*, 2014).

Digital models have also found life in virtual reality (VR) and augmented reality (AR) environments. Platforms such as Anatomage Table, 3D4Medical, and Unity-based VR simulators provide immersive experiences that allow students to explore internal anatomical structures, conduct virtual dissections, or simulate surgical approaches (Al-Ansi *et al.*, 2022). These tools have expanded the boundaries of anatomical teaching beyond the physical classroom, especially during global disruptions such as the COVID-19 pandemic (Choudhary, 2021a; Kapoor and Singh, 2022) (Fig. 2).

Veterinary-specific progress and global trends: While many innovations in anatomical modeling were initially developed for human medical education, veterinary institutions have progressively adapted and pioneered species-specific models (Erolin, 2019; Narang *et al.*, 2021). Institutions such as the Royal Veterinary College (UK), Cornell University (USA), the University of Veterinary and Animal Sciences (Pakistan), and Bihar Animal Sciences University (BASU), India, have invested in digital dissection tables, interactive apps, and multi-species model libraries. In India, resource-constrained veterinary colleges have successfully developed low-cost silicone and 3D-printed models for veterinary anatomy education and learning (Kiran *et al.*, 2024; Kapoor *et al.*, 2024; Choudhary *et al.*, 2024). These initiatives demonstrate how innovation, when aligned with local needs and technical capacity, can yield sustainable and impactful teaching aids for the veterinary anatomy discipline. International veterinary organizations, including the World Organization for Animal Health (OIE) and the World Veterinary Association (WVA), have also emphasized the ethical dimension of reducing animal use in veterinary education (Turner *et al.*, 2015). Anatomical models, particularly when integrated with simulation-based training, are recognized as crucial to achieving these ethical and educational objectives (Elendu *et al.*, 2024; Wood *et al.*, 2025).

Types of anatomical models in veterinary education: Veterinary anatomy is a foundational pillar in the education of veterinary professionals. Mastery of animal anatomical structures, their relationships, and their functional relevance is critical for successful clinical diagnosis and veterinary practice (Rojas, 2021; Choudhary *et al.*, 2024). To enhance understanding and address the ethical, practical, and pedagogical limitations of cadaveric dissection, a variety of anatomical models have been developed and integrated into veterinary curricula (Azer and Azer, 2016; Rojas, 2021). These models differ in form, function, materials, and technological complexity, offering multiple approaches to anatomy education (Naidoo *et al.*, 2020). Broadly, anatomical models used in veterinary anatomy education can be categorized into physical models (including plastic, silicone, and taxidermic models), digital models (such as virtual, AR, and VR models), hybrid models (which combine physical and digital features), and biologically preserved models. Each type plays a unique role in reinforcing anatomical knowledge, skill acquisition, and ethical practice (Rojas, 2021).

Physical anatomical models: Physical animal anatomical models are tangible, three-dimensional representations of anatomical structure. These models are among the most traditional and widely used resources in veterinary anatomy labs for educational purposes because of their durability, reusability, and ability to support hands-on learning.

Plastic and resin-based models: These are commercially produced, often using injection-molded plastic or composite resin, and are highly durable. Commonly available models include canine skulls, equine limbs, bovine uteri, and entire small animal figures. These

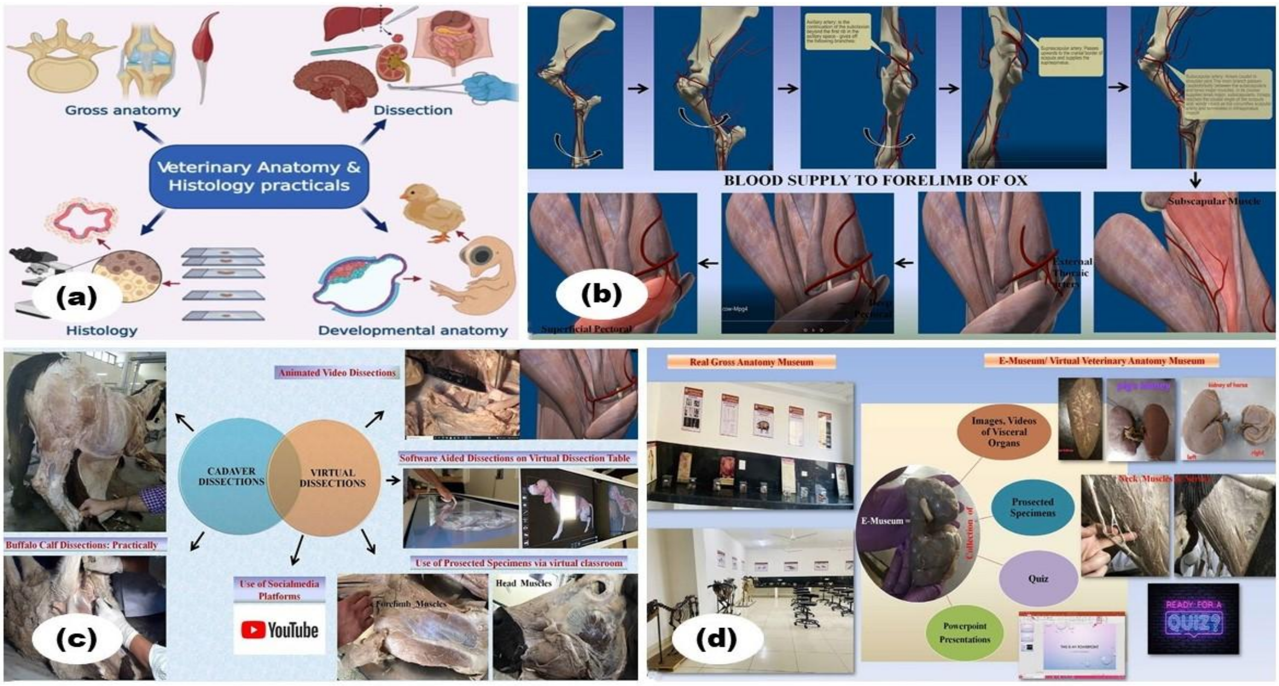

Fig. 2: Showing (a) an illustration of hands-on practical in veterinary anatomy and histology (Choudhary, 2021a); (b) Collective illustrative stills from virtual simulation model of cow showing three-dimensional (3D) animations which can be used to understand blood supply to muscles of forelimb; (c) Comparative pictures showing cadaver dissection versus various modes of virtual dissection that can be utilized for better understanding and benefits during COVID-19 restrictions; (d) Representative pictures showing differences between real gross anatomy museum versus components of E-Museum or virtual veterinary anatomy museum (Kapoor and Singh, 2022).

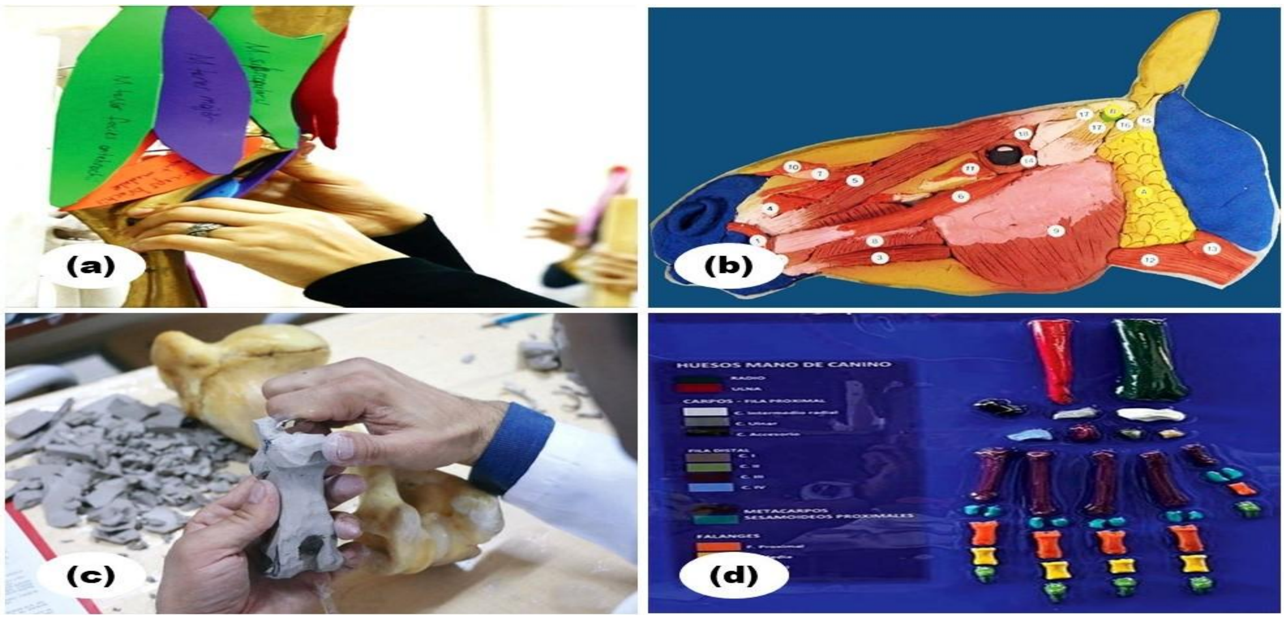

Fig. 3: Showing (a) dressing of muscle and ligament templates on a plastic model (Onuk *et al.*, 2019); (b) plasticine plate of superficial muscles of the face of the horse (Saber *et al.*, 2016); (c) sculpting steps of the clay models were designed by veterinary students (Onuk *et al.*, 2019); (d) canine front paw bone embedding in polyester resin (Rodríguez-Pilloni *et al.*, 2025).

anatomical models are typically segmented and color-coded to illustrate various anatomical systems, including skeletal, muscular, nervous, and circulatory structures (Sakaue *et al.*, 2024; Rodríguez-Pilloni *et al.*, 2025). They can be disassembled for layer-by-layer study, which helps students visualize the spatial relationships between organs. Plastic models are particularly beneficial for introductory veterinary anatomy courses, where foundational understanding of topography and orientation is required (Saber *et al.*, 2016; Sakaue *et al.*, 2024) (Fig. 3). Moreover, their robustness allows for repeated handling without degradation. However, they may lack fine anatomical details or pathological variations and are often based on idealized, standard specimens rather than actual anatomical diversity.

Silicone-based models and simulators: Silicone anatomical models are increasingly used for simulating soft tissue and functional training scenarios in veterinary anatomy (Fig. 4). These models are flexible, lifelike, and often designed to mimic specific procedures such as rectal palpation in cattle, buffalo, equine, canine intubation, or ovine parturition (Díaz-Regañón *et al.*, 2024). They offer realistic resistance, texture, and manipulation feedback, making them ideal for developing psychomotor skills of veterinary students. Unlike rigid plastic models, silicone models can simulate complex interactions such as muscle contractions, distension, or blood flow when integrated with pumps or sensors. These models facilitate procedural learning and are frequently used in veterinary surgical skills laboratories and clinical skill centers. In addition, silicone models reduce the need for live animal use, aligning with the 3Rs (Replacement, Reduction, Refinement) ethical framework (Choudhary, 2025).

Taxidermy and bone articulations: Taxidermy-based anatomical models involve preserved animal specimens with mounted skeletal systems or stuffed external features. Articulated bones, especially those of common species such as cattle, horses, dogs, pigs, and fowl, remain helpful in teaching osteology (Choudhary *et al.*, 2025) (Fig. 5). These models are derived from real animals and offer anatomical realism that synthetic models do not easily replicate. While taxidermic models offer high anatomical fidelity, they have limitations, including ethical concerns, fragility, and limited adaptability (Demirkan *et al.*, 2016; Hendriksen, 2019; Ross, 2020). Additionally, taxidermy does not allow internal dissection or interactive exploration for veterinary students. As veterinary education increasingly shifts toward ethical, reusable alternatives, the use of taxidermy has declined in favor of synthetic and digital models (Demirkan *et al.*, 2016; Hendriksen, 2019; Ross, 2020).

Digital anatomical models: Digital anatomical models refer to computer-generated 3D representations of animal anatomical structures. These models are designed for interaction through screens, tablets, or immersive devices such as virtual reality headsets for veterinary anatomy education. With increasing digital fluency among students and improvements in software, digital models have become a cornerstone of veterinary anatomy education in the modern era (Fig. 6).

3D computer models: These 3D computer models are interactive, screen-based tools that enable learners to rotate, dissect, and isolate anatomical structures for the educator and learner in veterinary institutions. Popular platforms such as Vet-Anatomy, Visible Animal, and Anatomy Learning offer species-specific anatomy mapped from

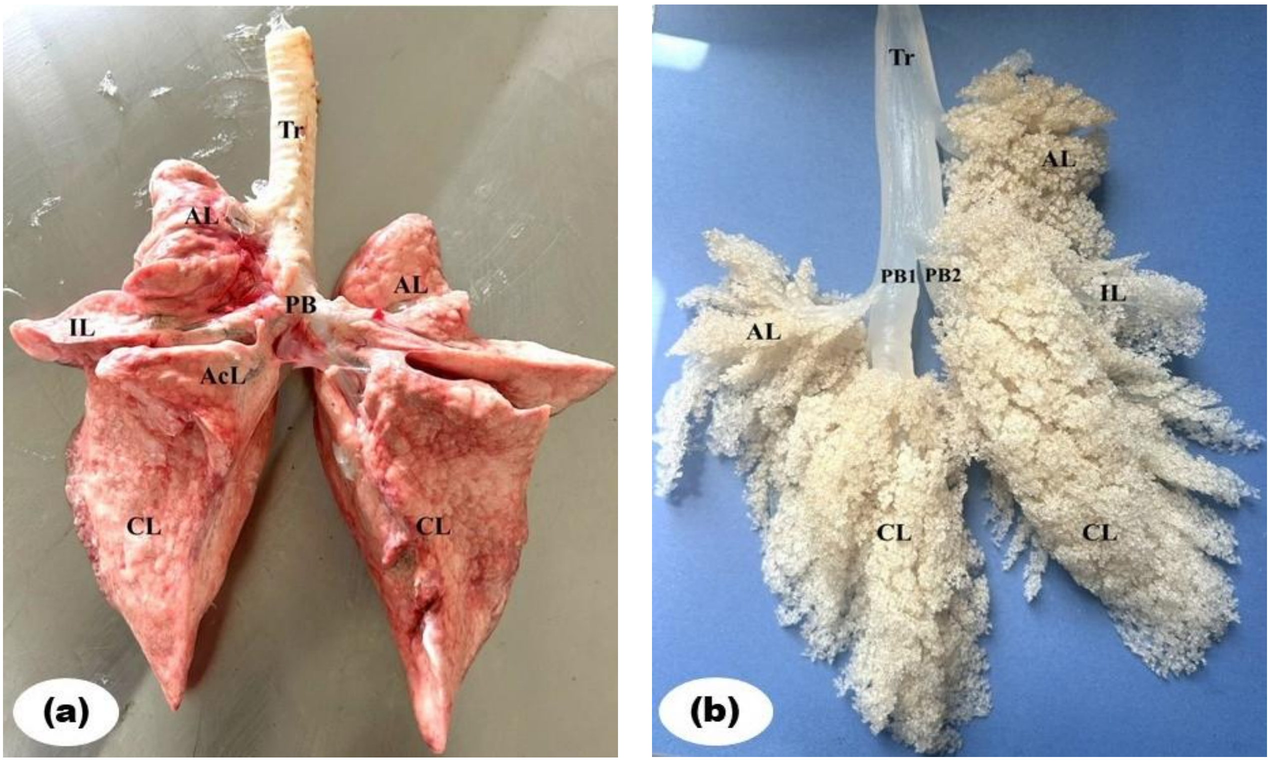

Fig. 4: a. Ventral surface of silicon-filled lung for preparation of corrosion cast of the lung; b. Dorsal view of the corrosion cast lung of a goat lung showing apical lobe (AL), intermediate lobe (IL), caudal lobe (CL), and principal bronchus (PB1,2). (This specimen was prepared at the College of Veterinary Science, Rampura Phul, India, for undergraduate teaching.)

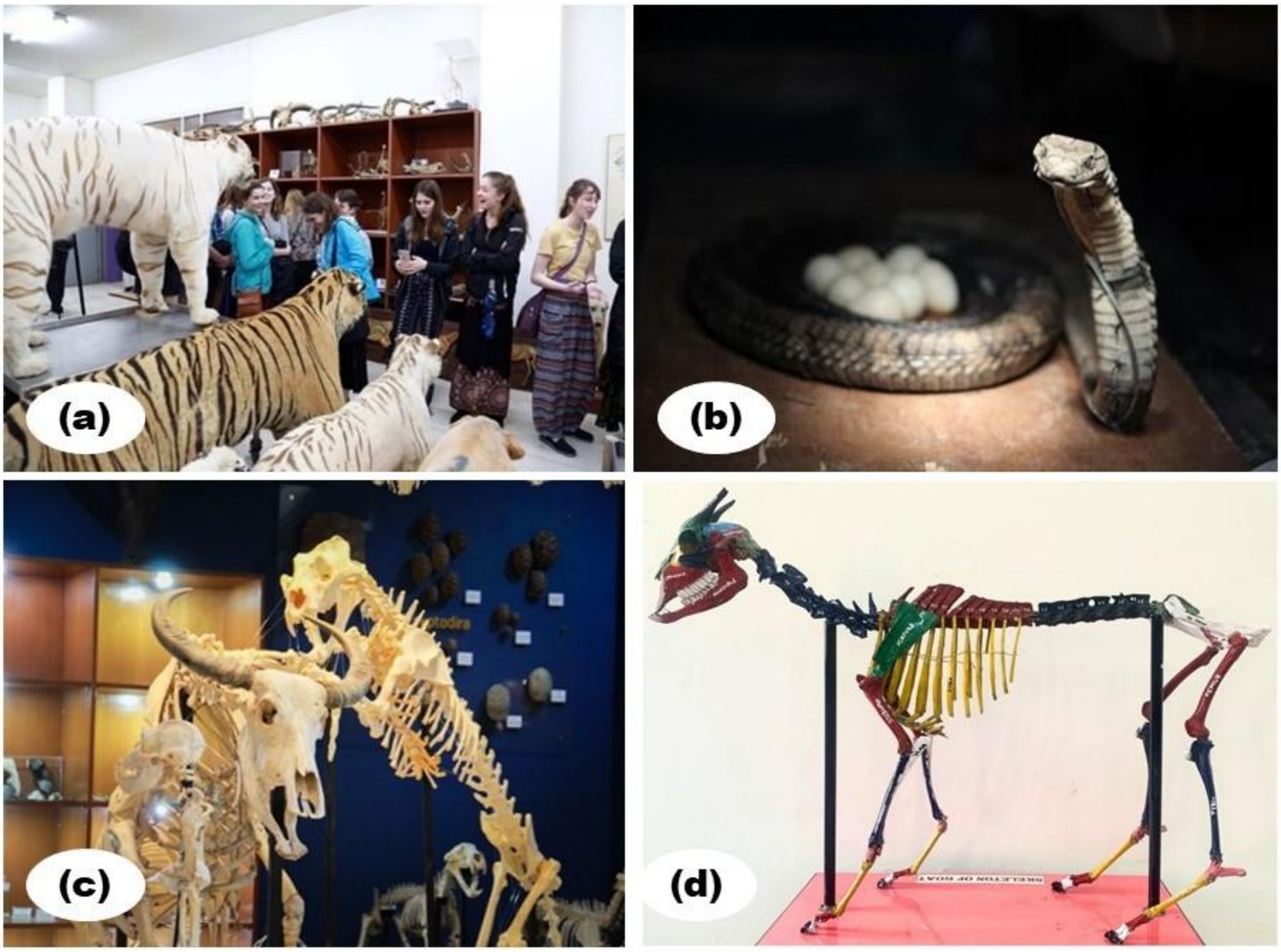

Fig. 5: Showing (a) the old veterinary museum located at Chiang Mai University (Kongtueng and Yotanyamaneewong, 2021). (b) dry specimen of king cobra (Taxidermy) (Ramkrishna and Leelavathy, 2017). (c) new veterinary museums located at Chiang Mai University (Kongtueng and Yotanyamaneewong, 2021). (d) coloured goat skeleton model prepared for practical classes for undergraduate students (Choudhary *et al.*, 2024).

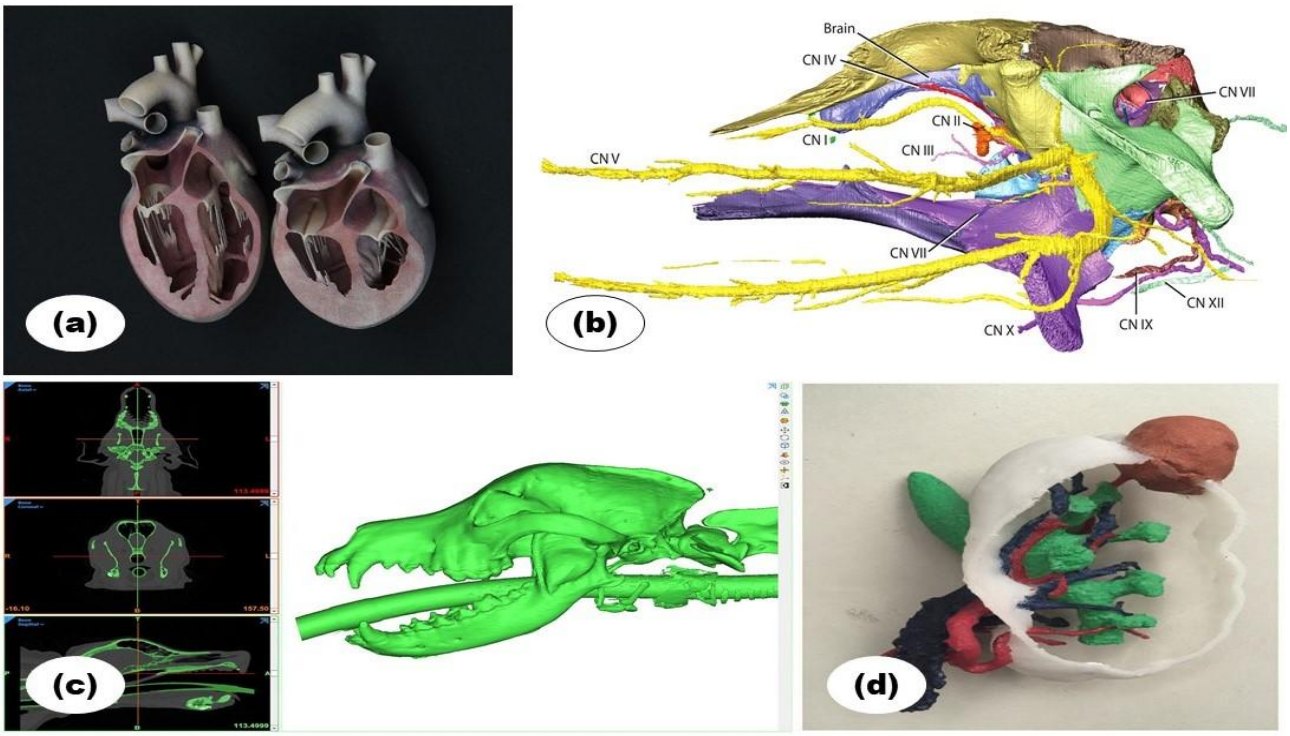

Fig. 6: Showing (a) 3D-printed models of the feline heart long-axis view in diastole (left) and systole (right) (Wilhite and Wölfel, 2019). (b) Osteological and Nervous Relationships. 3D reconstruction of alligator cranial elements (MUVC AL623), cranial nerves (MUVC AL031), and the brain (MUVC AL031) (Lessner and Holliday, 2022). (c) Computer screenshot depicting an automated thresholding process for segmentation and 3D computer model generation (Klasen *et al.*, 2022). (d) Three-dimensional (3D)-printed physical anatomic kidney model (Fan *et al.*, 2019).

actual CT and MRI scans (Blázquez-Llorca *et al.*, 2023). Teachers and students as learners can zoom in, label structures, and view cross-sections at different angles. Computer-based 3D models are beneficial in understanding complex spatial relationships, such as those in the nervous or circulatory systems (Blázquez-Llorca *et al.*, 2023). They also enable pathology overlay, allowing students to compare normal and abnormal anatomical differences. These platforms are scalable, affordable, and perfect for remote or self-guided anatomy learning (Chaudhari *et al.*, 2023).

Augmented reality (AR) models: AR integrates digital anatomical content into the real world using mobile devices or AR glasses in the modern era of veterinary education (Fig. 7). For instance, students can view a canine skeleton overlaid onto a mannequin or desk surface via a tablet, interacting with the model in real-time. AR platforms, such as Insight AR and Merge EDU, offer highly interactive and engaging learning experiences for veterinary students (Bölek *et al.*, 2021; Williams *et al.*, 2025). The advantage of AR lies in its portability and minimal hardware requirement-most AR tools work through smartphones or tablets. These models support real-time annotation, quizzes, and even collaborative study, making them ideal for blended or flipped classroom models (Bölek *et al.*, 2021; Williams *et al.*, 2025).

Virtual reality (VR) and immersive simulation: VR models create a fully immersive environment, allowing students to walk around or "enter" virtual anatomical structures (Kaggwa, 2025). Platforms like Anatomage VR, 3D Organon, or custom-built veterinary simulations enable learners to manipulate organs, simulate dissections, and even perform virtual surgeries (Darras *et al.*, 2019; Fusaro *et al.*, 2025). VR is particularly effective for teaching spatially complex regions such as the equine limb or the pelvic cavity of different animals. It also provides a risk-free environment for veterinary students to practice dissection and surgical planning. While VR requires headsets and compatible computers, its high engagement potential and scalability make it an asset in modern veterinary education (DeBose, 2020; Kapoor and Singh, 2022).

Hybrid anatomical models: Hybrid models combine physical structures with digital enhancements to offer a multisensory learning experience for veterinary anatomy. These models are rapidly gaining traction due to their capacity to integrate touch, visual feedback, and interactivity.

Haptic-enabled models: Haptic anatomical simulators incorporate tactile feedback, allowing veterinary students to "feel" structures through designed instruments. For example, a rectal palpation simulator can simulate uterine horns or ovarian follicles that vary in size and texture, helping learners practice palpation techniques and develop diagnostic reasoning skills for veterinary students (Kinnison *et al.*, 2009) (Fig. 8). Haptic systems are often paired with screen-based anatomy visualizations, which provide real-time feedback and assessment. These simulators are especially effective for developing procedural confidence in veterinary students without compromising animal welfare (Jaśkowski *et al.*, 2020).

Mixed reality platforms: Mixed reality combines the best of AR and VR by allowing digital content to interact with physical spaces. Using devices like Microsoft HoloLens, students can examine floating, layered anatomical models superimposed on classroom tables or physical dummies (Richards, 2023; Crogman *et al.*, 2025). Veterinary students can dissect, rotate, and examine organs while communicating with their peers in real-time during practical sessions. Mixed reality systems are ideal for collaborative and clinically integrated learning. For example, students may simulate ultrasound-guided procedures or assess lameness using both virtual and tactile feedback. These platforms are resource-intensive but offer unmatched interactivity and realism for veterinary anatomy education (Richards, 2023; Crogman *et al.*, 2025).

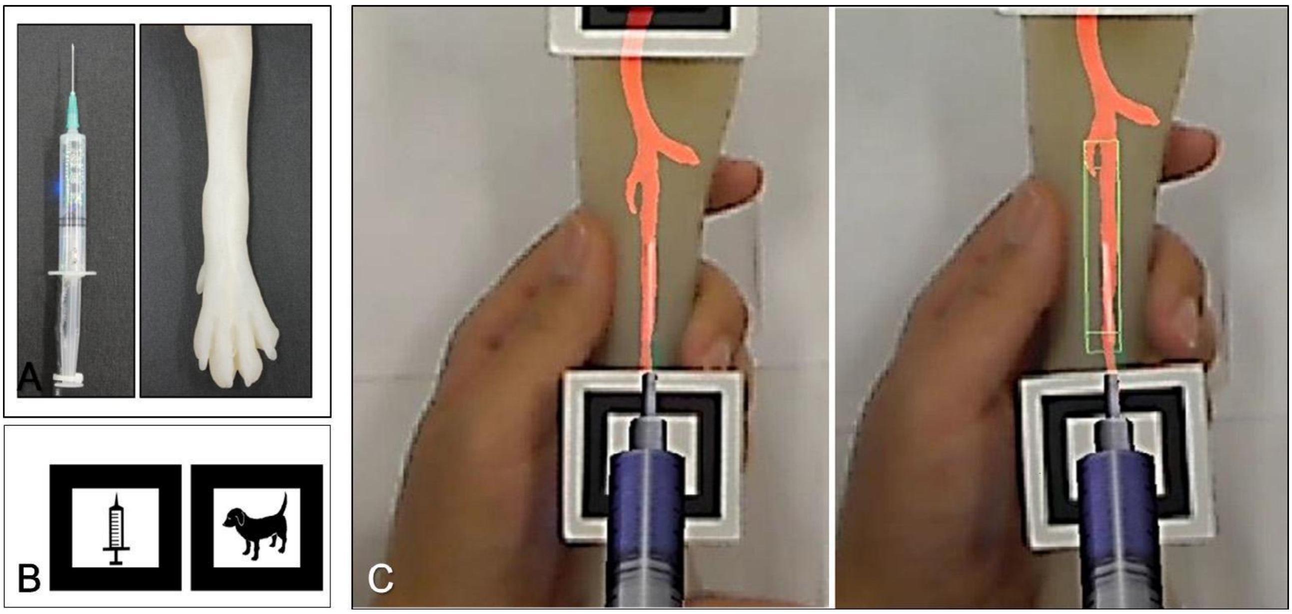

Fig. 7: Showing (A-B) AR-based IV injection simulator. AR markers were affixed to the surfaces of the syringe and the silicone model. (C) The guide box displaying a hexahedron represents the correct injectable area (Lee *et al.*, 2013).

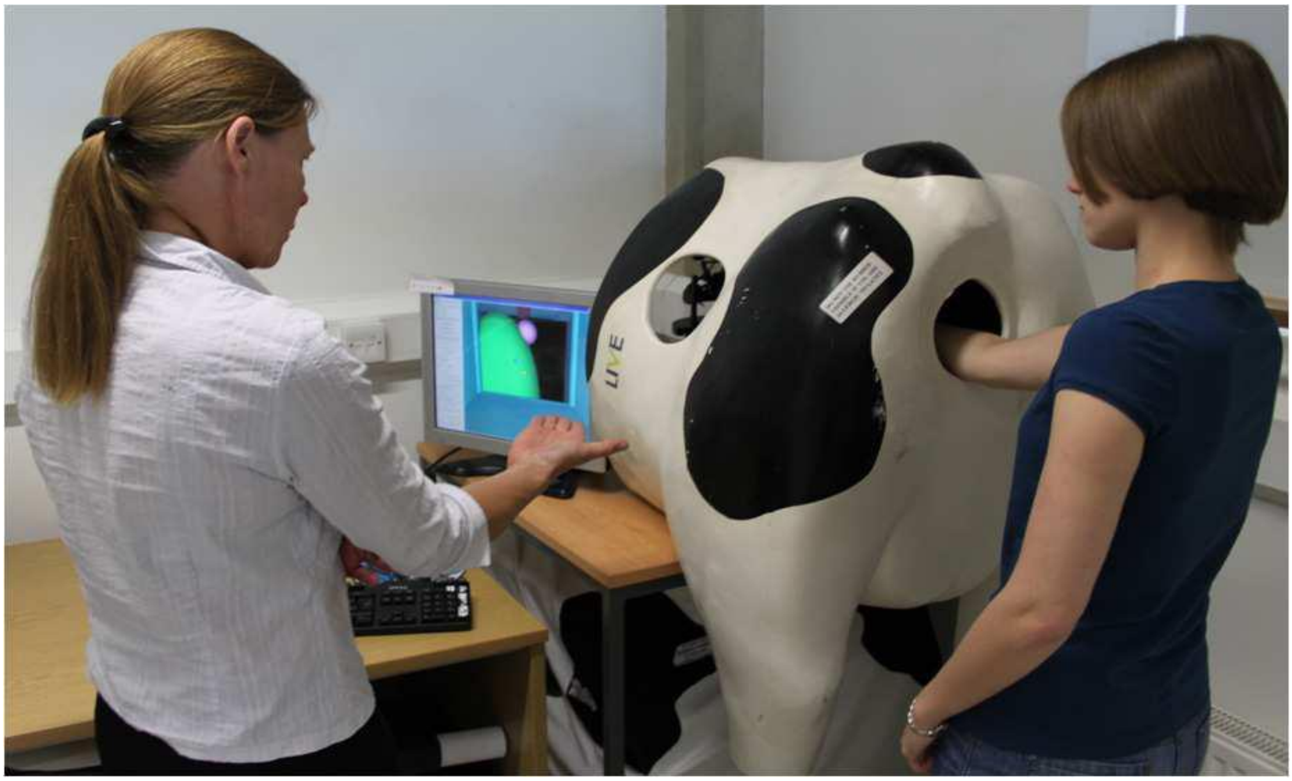

Fig. 8: The student can feel the 3D virtual structures inside the fiberglass model of the cow (haptic model) (Kinnison *et al.*, 2009).

Biologically preserved and plastinated models: Although less common today, biologically preserved models still play a vital role in veterinary anatomy education and learning. These models include glycerine mount specimens, plastinated organs or body parts that are chemically treated to maintain anatomical structure indefinitely.

Plastinated Specimens: Plastination involves replacing body fluids with polymers to produce specimens that are dry, odourless, and durable. These models retain the texture and structure of real tissues and can be handled without the need for refrigeration or dissection tools (Mohamed and John, 2018; Saini *et al.*, 2024). Plastinated models are a good tool for neuroanatomy, internal organ visualization, and comparative studies in veterinary anatomy education. However, they are expensive, challenging to produce in-house, and limited to what was preserved during the original plastination process (Mohamed and John, 2018; Saini *et al.*, 2024).

Embalmed and glycerin-preserved models: Some veterinary institutions use long-term preserved cadaveric specimens in formalin, ethanol, or glycerin to teach anatomy to students (Fig. 9). These models provide realism and can be used for repeated dissection during practical sessions of veterinary anatomy (Mohamed and John, 2018; Saini *et al.*, 2024) (Fig. 10). However, concerns regarding toxic exposure, disposal, and ethical considerations have led to a decline in their usage in veterinary anatomy education. The diversity of anatomical models in veterinary education reflects the complexity of animal anatomy itself and the evolving demands of modern pedagogy. From durable plastic models and silicone simulators to immersive digital platforms and haptic feedback systems, each type offers unique educational benefits for veterinary educators and students. Physical models foster tactile engagement and foundational understanding, while digital tools expand access, interactivity, and ethical compliance (Patra *et al.*, 2022; Adnan *et al.*, 2025). Hybrid models combine these strengths, creating enriched, multimodal learning experiences. The strategic integration of these diverse anatomical models not only enhances comprehension and skill development but also aligns veterinary anatomy education with ethical, technological, and educational standards of the 21st century (Ghosh, 2017; Patra *et al.*, 2022; Adnan *et al.*, 2025). As these anatomical models or tools continue to evolve, their thoughtful use will shape the next generation of veterinary professionals.

Pedagogical value and cognitive impact: The use of anatomical teaching models in veterinary education has significantly transformed pedagogical strategies by offering student-centered, multimodal learning experiences that go beyond traditional methods of teaching and learning (de Brito *et al.*, 2024; Schirone *et al.*, 2024). Traditional cadaveric dissection, while historically central to anatomy education, often presents limitations such as restricted availability, decomposition, biohazard risks, and ethical concerns in veterinary education. Anatomical models—ranging from plastic replicas to advanced virtual and augmented reality simulations—allow for safer, more ethical, and repeated exploration of anatomical structures.

These anatomical models enable students to engage more confidently with complex anatomy topics without the emotional or physical stress sometimes associated with animal dissection in veterinary anatomy education. Anatomical models support active learning pedagogy, where students are encouraged to take a hands-on role in their teaching and learning. This shift from passive

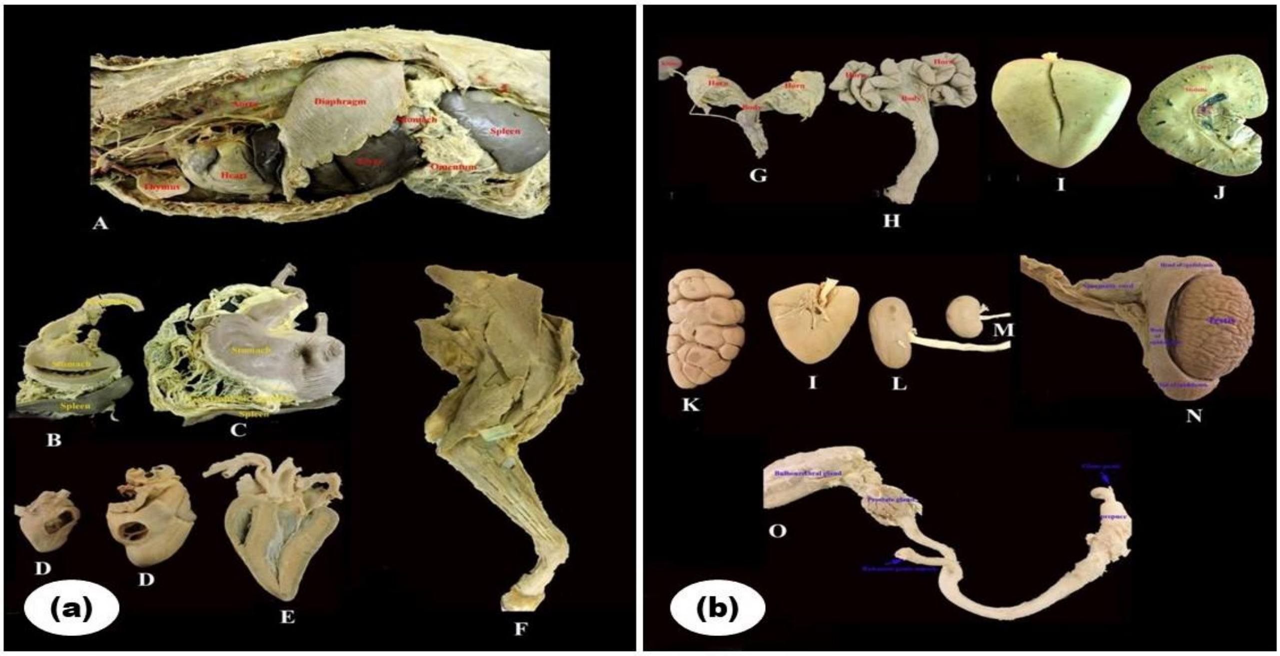

Fig. 9: Showing (a-b) plastinated specimens of ox, horse, dog, and pig (Mohamed and John, 2018).

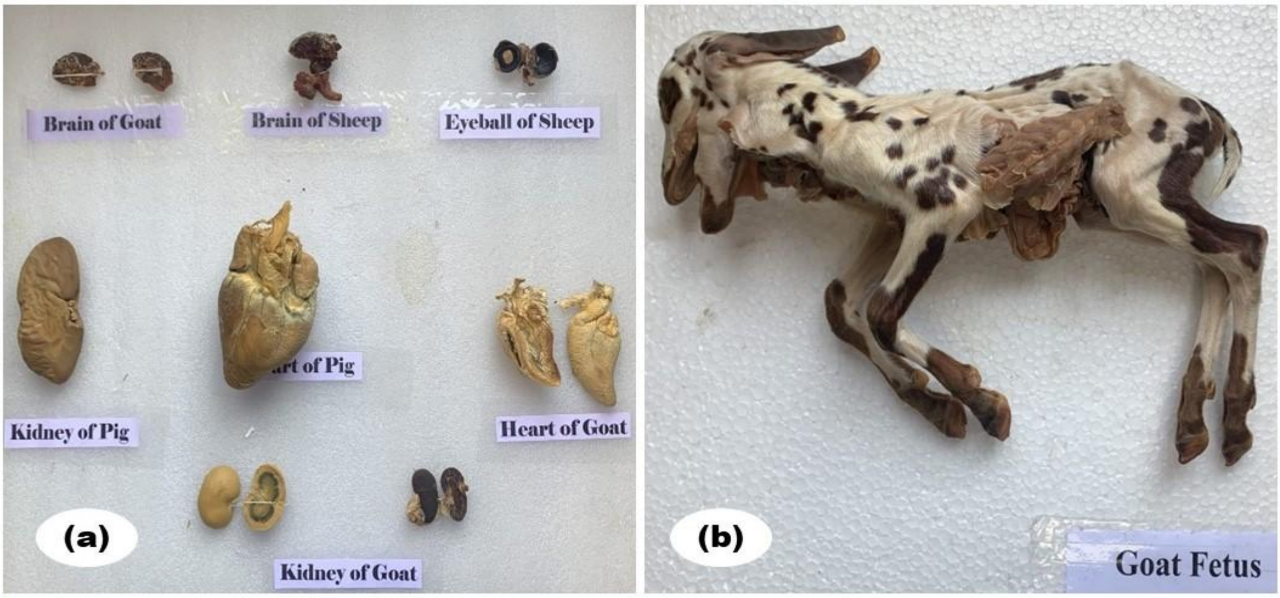

Fig. 10: showing (a) various formalin and glycerine mount specimens of sheep, goat, and pig. (b) a glycerine mount goat fetus (These specimens were prepared at the College of Veterinary Science, Rampura Phul, India, for undergraduate teaching.).

memorization to active engagement facilitates better understanding and retention of anatomical content (Kılıç *et al.*, 2025). By interacting with models- physically manipulating parts, rotating 3D structures, or navigating through layers of virtual systems- students construct their own knowledge frameworks (Tripodi *et al.*, 2020; McNaughton *et al.*, 2025; Kılıç *et al.*, 2025). This aligns with constructivist learning theories, which posit that knowledge is best built through experience and reflection rather than rote memorization in veterinary anatomy education.

From a cognitive perspective, the use of models enhances spatial ability, a critical skill in anatomy and veterinary clinical practice (Fig. 11). Veterinary anatomy involves complex three-dimensional relationships between structures that are difficult to grasp through two-dimensional images or textual descriptions of standard textbooks alone (Ishikawa, 2023; Sharmin *et al.*, 2023; Woodman and Mangoni, 2023). Anatomical models allow students to perceive and manipulate spatial arrangements, which helps develop mental rotation and spatial visualization abilities (Sharmin *et al.*, 2023). This spatial competence is crucial in diagnostic imaging, surgical planning, and veterinary clinical reasoning (Sharmin *et al.*, 2023; Li *et al.*, 2025). Additionally, anatomical models reduce cognitive overload- a common challenge for students new to veterinary anatomy. Traditional dissections in veterinary anatomy education often require students to process vast amounts of unfamiliar information simultaneously, which can be overwhelming. By presenting anatomical content in modular, visually organized formats, models help veterinary students focus on one system or region at a time (Baek *et al.*, 2024). This scaffolding approach promotes cognitive load management, allowing learners to gradually build their knowledge without becoming mentally fatigued or frustrated (Ishikawa, 2023; Woodman and Mangoni, 2023).

Another key benefit of these anatomical models is the promotion of repetitive practice and the consolidation of long-term memory of anatomical structures. While cadaver access may be limited and irreversible, models—especially digital or 3D-printed versions- allow for repeated, on-demand review. Repetition is a cornerstone of long-term retention, and revisiting anatomical content in multiple practical sessions supports the encoding of knowledge into long-term memory. This repetition is particularly valuable during exam preparation or the development of veterinary clinical skills for students. Anatomical models also encourage self-directed learning, a vital skill in the veterinary profession. Many modern platforms offer interactive features, such as quizzes, labelling exercises, and guided dissections, that allow students to monitor their own progress. This encourages autonomy, responsibility, and tailored learning paths (Abinaya *et al.*, 2024). Furthermore, mobile and cloud-based anatomical applications allow veterinary students to study outside of formal classroom settings, extending the learning environment and promoting continuous learning.

In collaborative settings, anatomical models serve as practical tools for peer-to-peer learning and education. Small groups working with models foster communication, teamwork, and collective problem-solving. These interactions not only reinforce anatomical knowledge but also help develop professional soft skills such as explanation, critical discussion, and clinical decision-making for veterinary students. When students teach and explain anatomical structures to one another using these models, they engage in deep processing, which further solidifies their understanding of these concepts. Moreover, these anatomical models can be customized to fit different learning preferences. Visual learners benefit from detailed, color-coded representations; kinesthetic learners gain from hands-on manipulation; and auditory learners can engage with narrated digital walk-throughs in veterinary education (Alabi, 2024). This flexibility makes anatomical models inclusive and accessible to a wider range of students, including those with learning difficulties or disabilities, thus enhancing overall educational equity and effectiveness in veterinary training. Anatomical teaching models also support the integration of veterinary clinical correlations, bridging the gap between preclinical anatomy and clinical application in veterinary sciences. For example, models that simulate common pathologies or surgical procedures enable students to visualize anatomy within the context of real-world cases (Zhao *et al.*, 2023; Alabi, 2024). This not only improves understanding but also motivates learners by demonstrating the practical relevance of foundational knowledge. Such context-rich learning enhances clinical reasoning and prepares students for the diagnostic and procedural challenges of veterinary practice (Chigerwe *et al.*, 2017; Zhao *et al.*, 2023).

Finally, the cumulative cognitive impact of using veterinary anatomical teaching models is a significant improvement in students' confidence, competence, and ethical awareness. By engaging with anatomically accurate and ethically produced anatomical models, students feel more prepared for hands-on clinical procedures and less dependent on traditional cadaveric dissection (Daniela, 2021; Arráez-Aybar, 2025). This fosters a more compassionate and modern approach to veterinary anatomy education, one that values both scientific rigor and animal welfare. As educational technologies evolve, the pedagogical value and cognitive benefits of anatomical models will only grow, making them indispensable tools for training the next generation of veterinary professionals (Daniela, 2021; Arráez-Aybar, 2025).

Developmental process and material selection: The development of animal anatomical teaching models is a multidisciplinary process that involves collaboration among veterinary anatomists, model designers, engineers, and material scientists. The initial stage of development typically begins with the identification of specific

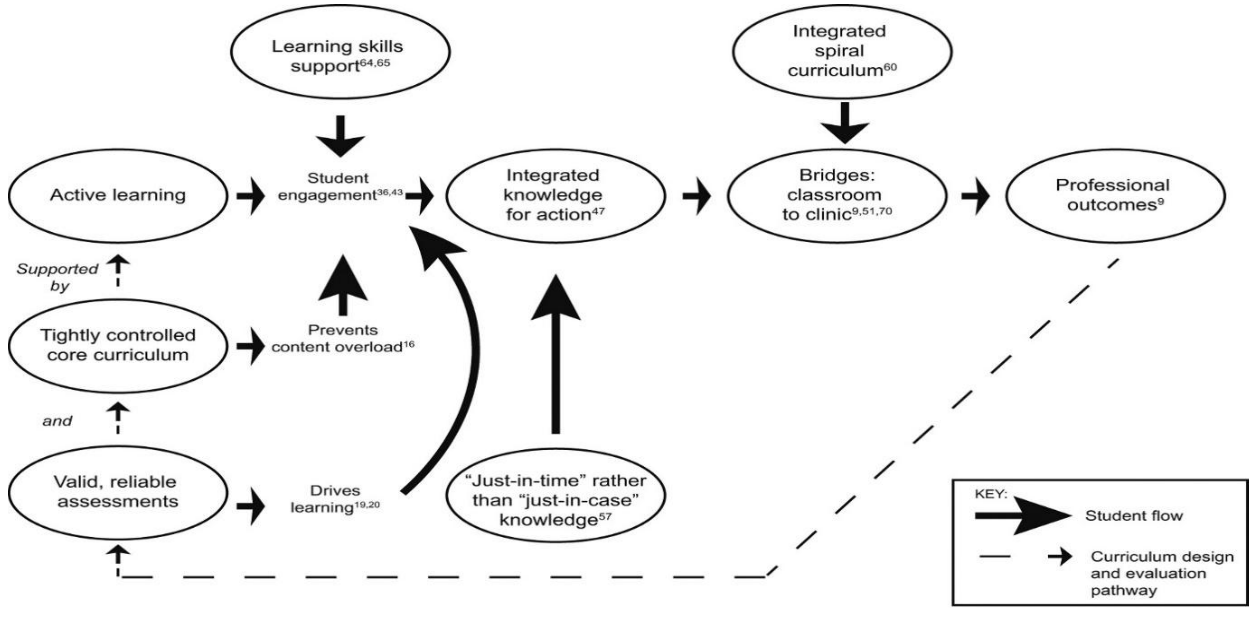

Fig. 11: Pedagogical support for scaffolded active learning for an education system (May and Silva, 2015).

educational objectives, such as the anatomical region to be modelled, the target student level, and the intended use-whether for demonstration, dissection practice, or surgical simulation (Choudhary *et al.*, 2025; Sirasanagandla *et al.*, 2025). This step ensures that the final model aligns with the veterinary curriculum and addresses actual learning needs within veterinary anatomy education (Choudhary *et al.*, 2025; Sirasanagandla *et al.*, 2025).

Following the definition of objectives, the next phase involves the acquisition of anatomical data, often using imaging technologies such as CT (computed tomography), MRI (magnetic resonance imaging), and 3D surface scanning of cadaveric specimens (Florkow *et al.*, 2022; Ozen and Sahin, 2020). These high-resolution datasets enable the accurate reconstruction of anatomical structures, preserving even the most minute details and spatial relationships. Digital segmentation of these digital images is performed using specialized software, allowing individual structures to be isolated, enhanced, and converted into 3D-printable or moldable formats (Florkow *et al.*, 2022; Ozen and Sahin, 2020).

The digital modeling and design phase is crucial in transforming imaging data into anatomically accurate, printable structures. Designers work closely with veterinary anatomists to verify anatomical precision and correct structural relationships necessary for veterinary anatomy education. Computer-aided design (CAD) tools are frequently used to adjust scale, enhance features, and integrate interactive components like removable parts or color coding for educational clarity (Budi and Sukmono, 2023). The anatomical models may also be developed in layers to simulate tissue hierarchy, such as skin, muscles, vessels, and bones of domestic and wild animals, thereby offering a more immersive and layered learning experience (Moniz *et al.*, 2020; Budi and Sukmono, 2023).

Material selection for the preparation of animal anatomical models is a critical consideration that directly influences the educational utility, durability, realism, and cost of the model (Table 1). For rigid models such as bones or skulls, materials like resin, polylactic acid (PLA), and acrylonitrile butadiene styrene (ABS) are commonly used due to their affordability, ease of printing, and structural stability (Salmi *et al.*, 2013). These materials are suitable for models that require fine detail, resistance to wear, and lightweight portability. In contrast, soft tissues such as muscles, ligaments, or internal organs are often constructed from silicone rubber, thermoplastic elastomers (TPE), or polyurethane to mimic the texture and flexibility of real tissues.

Some high-fidelity models incorporate multi-material printing or composite casting to achieve greater anatomical realism. For example, synthetic blood vessels can be embedded in transparent, tissue-like materials, allowing students to trace vascular pathways visually. Hybrid models may include rigid skeletal components combined with flexible muscle overlays, offering tactile feedback that closely approximates real-life surgical scenarios. Such realism enhances not only anatomical understanding for veterinary students but also practical skills training for future veterinary clinical practices (Choudhary *et al.*, 2024).

In recent years, 3D printing has revolutionized the developmental process by enabling rapid prototyping, customization, and cost-effective production. 3D printers of various brands available do this printing for anatomical specimens (Fig. 12). Institutions can now produce species-specific models, adjust features to reflect normal or pathological anatomy, and scale models for group or individual use (Jin *et al.*, 2021; Oleksy *et al.*, 2023) (Fig. 13). Open-source digital anatomy repositories and cloud-based sharing platforms have also democratized access to high-quality anatomical data, facilitating collaboration among veterinary institutions globally (Iftekar *et al.*, 2023; Oleksy *et al.*, 2023).

Plastination remains another effective method of anatomical model creation, especially for preserving real animal specimens. This technique involves replacing biological fluids and lipids with curable polymers such as silicone or epoxy resin, resulting in dry, odourless, durable anatomical specimens (Riederer, 2014; Sora *et al.*, 2019). While expensive and labor-intensive, plastinated models retain exact anatomical features and are invaluable for long-term teaching in gross veterinary anatomy and pathology (Riederer, 2014; Green and Whitburn, 2016).

Environmental sustainability is emerging as a major concern in material selection for the preparation of these anatomical models. The widespread use of petroleum-derived plastics in model production has raised ecological questions (Ncube *et al.*, 2020). In response, some institutions are exploring the use of biodegradable polymers such as PLA derived from cornstarch or employing recycling systems for failed prints. Using sustainable materials not only supports institutional green goals but also encourages environmental ethics among veterinary students. (Enbaia *et al.*, 2024).

The final stages of development include model testing, validation, and refinement. Pilot use in classroom settings enables student and faculty feedback, which guides further modifications to enhance usability, anatomical accuracy, and durability (May, 2013). Veterinary educators may request features such as detachable parts, color-coded segments, or interactive labels. User-centered refinement ensures the model achieves its full pedagogical potential and aligns with student learning outcomes in veterinary anatomy education (May, 2013).

Table 1: Different materials used for the preparation of the anatomical models.

Criterion	Desired Property	Material Examples
Realism	Simulates tissue elasticity or bone hardness	Silicone, latex, TPU
Durability	Withstands repeated handling and cleaning	ABS, resin, composite plastic
Cost-effectiveness	Affordable for institutions or bulk production	PLA, foam-core
Anatomical accuracy	Fineness of detail and color differentiation	PolyJet printing, hand-painted resin
Biocompatibility	Safe for student handling	Non-toxic, formalin-free
Modifiability	Allows surgical cuts or practice	Silicone, gelatin, layered plastic

In conclusion, the development and material selection for animal anatomical models are sophisticated processes that blend anatomical science, engineering, and pedagogy. Each model is the result of careful planning, material engineering, and iterative refinement. As technological advancements continue, the process will become even more streamlined and accessible, opening new possibilities for high-fidelity, customizable, and ethically sound teaching models in veterinary anatomy education.

Fig. 12: (a) Form 2 SLA printer. Image from Forml abs.com. (b) Lulzbot TAZ6 FDM printer. Image from Lulzbot.com. (Wilhite and Wölfel, 2019).

Fig. 13: 3D printed models of the spermatozoa, neurons, and kidneys using 3D printers. (adapted from Choudhary *et al.*, 2025).

In many cases, animal anatomical models incorporate multiple materials. For example, a 3D-printed skull might include rubberized discs to mimic intervertebral discs or blood vessels made of latex tubing (Barré-Sinoussi and Montagutelli, 2015).

Technological innovations and digital integration: Technological innovation is revolutionizing veterinary anatomical education by enhancing the visualization, teaching, and internalization of anatomy (Choudhary *et al.*, 2023, 2025). With the convergence of 3D printing, virtual reality (VR), augmented reality (AR), artificial intelligence (AI), and simulation technologies, anatomical models have transitioned from static teaching aids to dynamic, interactive platforms (Kong, 2021; Bhardwaj *et al.*, 2025). This integration not only increases access and engagement but also aligns with modern veterinary educational paradigms emphasizing student-centered, experiential, and multimodal learning (Kong, 2021; Bhardwaj *et al.*, 2025). This section explores the cutting-edge technological advancements that are reshaping veterinary anatomical model development and their integration into digital learning environments.

3D imaging and reconstruction: At the heart of modern anatomical model development lies high-resolution imaging, particularly CT and MRI. These imaging modalities enable the capture of anatomical data at both micro and macro scales, allowing for detailed visualization of bones, muscles, nerves, and organs of animal origin. In this technological workflow, DICOM imaging data is first exported from CT or MRI scans (Bidgood *et al.*, 1997; Choudhary, 2021b; Talanki *et al.*, 2022; Kapoor *et al.*, 2024). This data is then processed using segmentation software such as Materialise Mimics or OsiriX, which isolates specific anatomical structures of interest. Next, 3D modeling software like Blender or ZBrush is used to refine and enhance these digital forms, ensuring accuracy and visual clarity. The resulting model can then be rendered digitally for virtual study or used for physical production through 3D printing technologies (Choudhary, 2021b; Kapoor *et al.*, 2024). This process empowers educators to create species-specific models, including pathological variations such as tumors, congenital malformations, or complex surgical scenarios, for a better understanding of veterinary students. As a result, anatomical learning is expanded beyond the study of typical structures to encompass clinically relevant cases, enriching students' understanding of real-world conditions (Fredieu *et al.*, 2015).

3D printing and additive manufacturing: 3D printing, also known as additive manufacturing, is one of the most disruptive technologies in veterinary anatomy education (Kapoor *et al.*, 2024; Choudhary *et al.*, 2025). It enables rapid prototyping, customization, and replication of animal anatomical structures. One significant advantage is rapid customization, as institutions can design models specific to their veterinary curriculum. Another benefit is cost savings, since once a digital file is prepared, models can be reprinted at low cost (AbouHashem *et al.*, 2015; Durrani *et al.*, 2024). Accessibility is also enhanced, as open-source model files and low-cost printers allow global sharing and democratization of resources. Recent innovations include the use of multi-material printers, such as the Stratasys PolyJet and Creality Ender, which can produce layered structures that mimic muscle, bone, and vasculature in a single print. Flexible filament printing allows for the creation of jointed models to simulate movement, while transparent materials are used to demonstrate internal organs in situ. Global initiatives, such as “VetPrint” in the UK and “AnatoVet3D” in India, have made STL files of anatomical models freely available, which can be downloaded for printing of the 3D anatomical models (Bücking *et al.*, 2017). This enables veterinary colleges in resource-limited settings to print and use accurate models without the need to purchase expensive commercial kits (Kapoor, 2024; Yusuf *et al.*, 2024).

Virtual reality (VR) in veterinary anatomy education: VR offers fully immersive experiences that enable students to explore veterinary anatomy in 3D space without the need for physical specimens for study. Using VR headsets (e.g., Oculus Rift, HTC Vive), learners can enter a virtual dissection room, rotate models, peel back layers, and even simulate pathology (Radianti *et al.*, 2020; Lilly, 2022) (Fig. 14). Applications include interactive exploration of the canine thoracic cavity, simulated rectal palpation in cattle, and surgical path navigation, such as cranial nerve pathways. The educational benefits of VR in veterinary anatomy education are significant (Baillie *et al.*, 2005). VR supports remote learning, increases spatial awareness, and encourages repeated practice without ethical and moral concerns. However, there are some limitations, such as the need for hardware investment, the potential for motion sickness among some users, and limited haptic feedback compared to physical models. VR platforms, such as 3D Organon, Ivalalearn, and Anatomage VR, are being adapted for veterinary anatomy use, offering cross-species models that can be tailored to veterinary curriculum as per requirements (Radianti *et al.*, 2020; Lilly, 2022).

Augmented reality (AR) and mixed reality (MR): AR overlays digital content on the real world via tablets, smartphones, or smart glasses. MR—a more immersive version of AR- allows users to interact with holograms in real-time while remaining aware of their physical surroundings (Mendoza-Ramírez *et al.*, 2023). In veterinary anatomy education, AR can be utilized in multiple ways. For instance, students can explore AR models of the equine digestive system using HoloLens during laboratory or practical classes. Alternatively, they can use tablet-based AR overlays of the feline muscular system projected directly onto classroom tables during an anatomy practical. MR is also being applied in surgical planning, such as for orthopedic procedures, where it enables detailed, interactive visualization of anatomical structures. These technologies offer several advantages in veterinary anatomy education learning experiences (Lu *et al.*, 2022; Crogman *et al.*, 2025), eliminating the need for extensive laboratory infrastructure or cadavers. They combine digital interaction with real-world context and are valuable tools in both clinical settings and outreach education. Innovative tools supporting this approach include the Insight AR Vet Anatomy App, which provides species-specific anatomical overlays for mobile devices, and Microsoft HoloVet, an emerging MR platform designed for immersive anatomical exploration (Lu *et al.*, 2022; Crogman *et al.*, 2025).

Artificial intelligence (AI) and adaptive learning: AI is now being incorporated into digital anatomy platforms to personalize and optimize learning pathways in veterinary anatomy education (Abdellatif *et al.*, 2022; Choudhary *et al.*, 2023; 2025). Intelligent tutoring systems assess veterinary students’ progress and suggest targeted content or practice based on performance. AI features in anatomy education include adaptive quizzes that change in difficulty based on answers, real-time feedback during virtual dissections, voice-activated navigation in VR/AR environments, and AI tutors that answer anatomical questions based on the model being viewed (Choudhary *et al.*, 2023; 2025; Joseph *et al.*, 2025). AI-enabled platforms can track learning metrics, identify knowledge gaps, and generate individual learning plans, making anatomy education more efficient and tailored (Choudhary *et al.*, 2023; 2025).

Integration into learning management systems (LMS): Digital animal anatomical models and simulations are being embedded into LMS like Moodle, Canvas, and Blackboard, allowing seamless access to 3D models, embedded quizzes and annotations, and integration with lecture content and student portfolios (Durrani *et al.*, 2024). For example, a bovine thoracic anatomy model embedded in a Moodle course may allow veterinary students to complete an interactive quiz on rib numbering, lung lobes, or heart positioning directly within the platform (Johnson *et al.*, 2011; García-Robles *et al.*, 2024).

Simulation-based learning and haptic feedback: Advanced simulation tools incorporate haptic technology to simulate tactile feedback, which is crucial for training in procedures like palpation, auscultation, catheter placement, or surgical incisions (Azuaga Filho *et al.*, 2023). Simulators like the Bovine Breeder or Equine Colic Trainer utilize both physical models and sensors to replicate the tactile experience of reproductive exams or abdominal exploration (Scalese and Issenberg, 2005; Azuaga Filho *et al.*, 2023). Force-feedback devices integrated with VR models train veterinary students in applying the appropriate amount of pressure during diagnostic procedures in veterinary clinical practice. Simulation-based anatomical training not only builds anatomical knowledge but also enhances psychomotor skills and confidence of the students before working with live animals (Choudhary *et al.*, 2024, 2025) (Fig. 15).

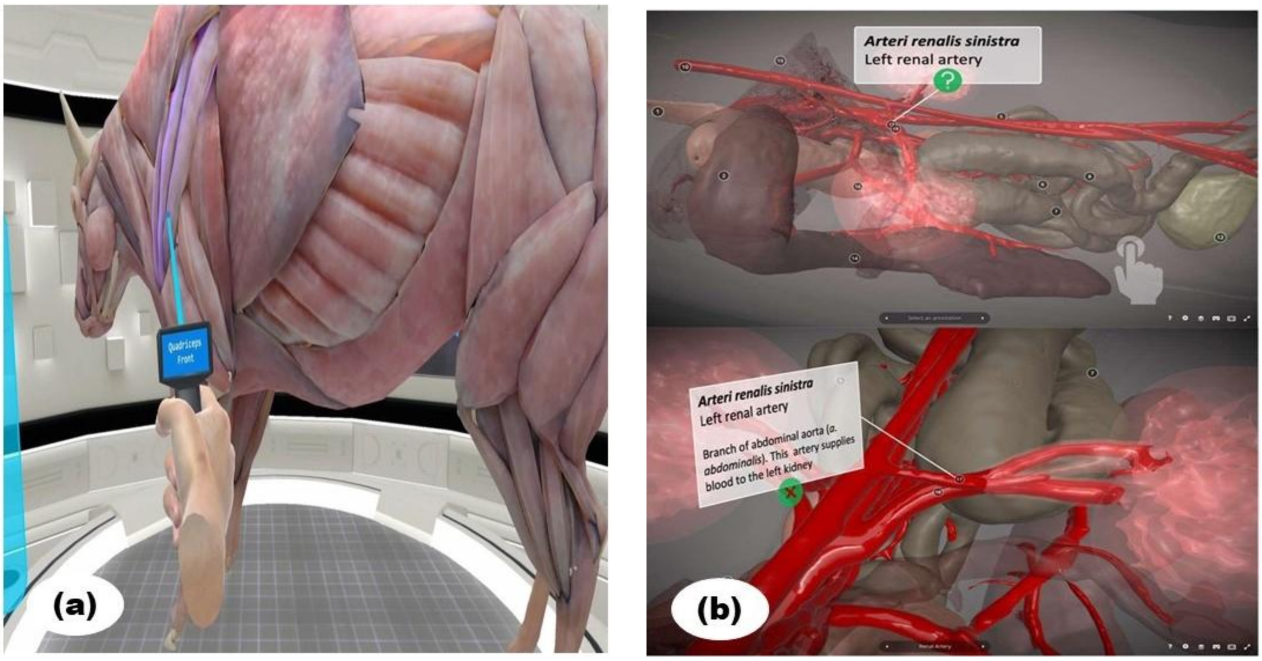

Fig. 14: (a) Illustrates a VR anatomy laboratory provided by ALTLAB™, one of VTK's modern applications, which allows users to learn animal anatomy by exploration of animal viscera with multi-layered digital representations of the same animal structures (https://www.altlabvr.com) (Altaey *et al.*, 2024). (b) Illustration of VR-based animal anatomy learning system (Cahyadi *et al.* 2022).

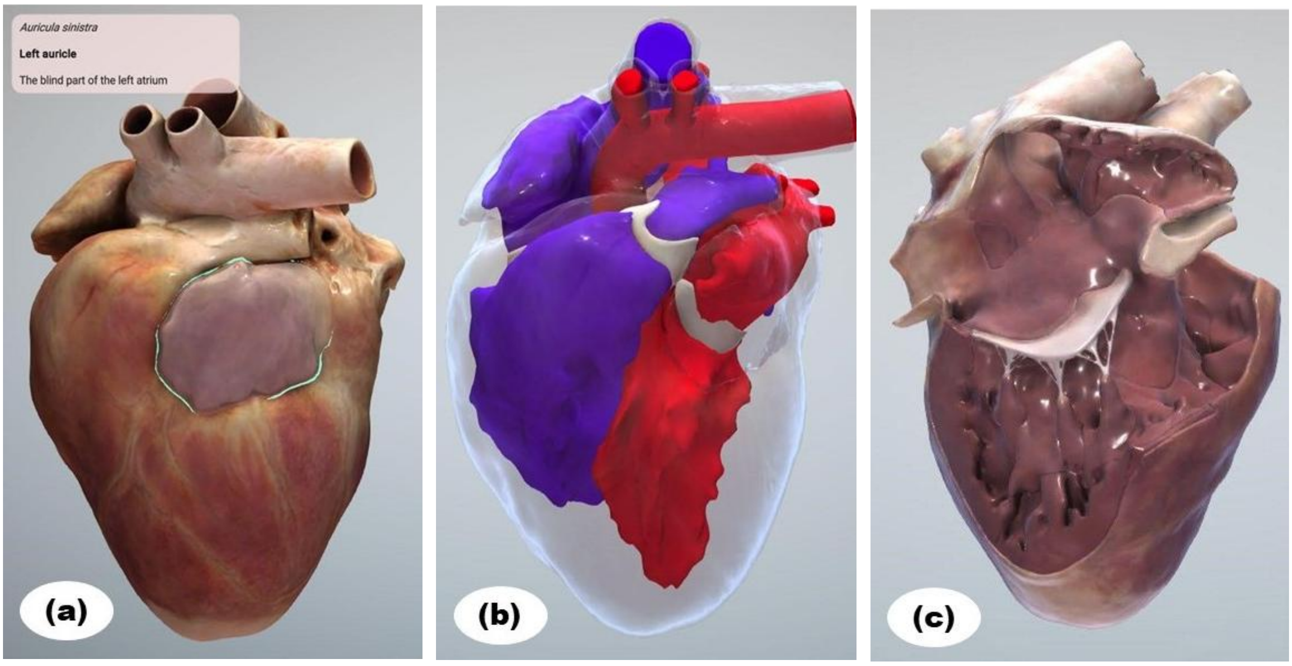

Fig. 15: (a) Exterior topography with identification highlighting the left auricle. (b) heart chambers and large vessels. (C) right marginal walls removed, illustrating interior features (Little *et al.*, 2021).

Cloud collaboration and global access: Cloud-based storage and collaborative platforms now allow the sharing of 3D anatomical model files across institutions, enabling students and faculty to work together regardless of their location. These platforms support a real-time collaborative model annotation, allowing students and faculty to add notes, highlight structures, and discuss findings interactively with each other. They also enable a global virtual anatomy laboratory, where veterinary students from different regions can collaborate on digital specimens (Neyem *et al.*, 2025). This supports equity in veterinary anatomy education, particularly for institutions in low- and middle-income countries that may lack physical resources but have access to the internet and basic computer facilities (Choudhary *et al.*, 2024, 2025).

Challenges and considerations: While technological innovations bring numerous benefits, challenges remain. Infrastructure requirements, such as reliable internet, powerful computers, and skilled technical staff members, are essential for successful implementation (Huang, 2021). Training is another key factor, as faculty and students require proper onboarding to use AR/VR and AI tools effectively. Cost continues to pose a barrier—despite falling hardware prices, some tools remain unaffordable for institutions with limited resources

(Choudhary *et al.*, 2024, 2025). Validation is equally important, with a continuous need to assess whether digital tools genuinely improve learning outcomes for veterinary anatomy education (Cook and Hatala, 2016). Sustainability must also be considered, ensuring that digital models remain updated, supported, and integrated with evolving veterinary curricula. These challenges must be addressed through institutional planning, funding strategies, and collaborative partnerships between institutions/ universities, ed-tech companies, and policymakers (Cook and Hatala, 2016; Huang, 2021).

Ethical considerations and the 3Rs (Replacement, Reduction, Refinement): The use of anatomical models in veterinary education is not only a pedagogical innovation but also a response to pressing ethical concerns regarding the use of animals for educational purposes. As veterinary programs face increasing scrutiny over the use of live animals in dissection and clinical training, models have become a critical tool in fulfilling ethical and educational mandates (Marcos *et al.*, 2023). The principles of the 3Rs (Replacement, Reduction, and Refinement), which aim to minimize animal suffering while advancing scientific knowledge, are central to the discussion on the ethical use of anatomical models (Hubrecht and Carter, 2019; Marcos *et al.*, 2023; Choudhary, 2025). This section examines the ethical implications of utilizing anatomical models in veterinary education, with a focus on how they align with the 3Rs and contribute to the ethical evolution of veterinary curricula (Hubrecht and Carter, 2019; Choudhary, 2025).

The 3Rs framework: An overview: The 3Rs framework, developed by Russell and Burch in 1959, provides a set of ethical guidelines for the use of animals in research and education (Tannenbaum and Bennett, 2015; Choudhary, 2025). These principles are designed to ensure that animal use is justified, humane, and scientifically valid. Replacement emphasizes the use of alternative methods to replace animal models whenever possible. Reduction focuses on minimizing the number of animals used in education and research, ensuring that each use contributes maximally to the learning or research objective (Tannenbaum and Bennett, 2015; Choudhary, 2025). Refinement involves improving animal handling, care, and procedures to reduce harm, distress, and suffering. In veterinary education, the application of the 3Rs has become a critical consideration, especially as the demand for ethical training practices grows. Anatomical models, which replicate real animal anatomy without the need for live dissection or cadaver use, have become a cornerstone of ethical curriculum redesign (Grimm *et al.*, 2023; Lauwereyns *et al.*, 2024).

Replacement: Moving beyond live animal use: One of the most significant ethical advances in veterinary education has been the replacement of live animals with anatomical models. Traditional practices often involved the dissection of animals, ranging from dogs and cats to cattle and pigs, for educational purposes. While dissection provided first-hand experience in anatomy, it also raised significant ethical concerns, particularly regarding the killing of animals for educational purposes. The replacement principle advocates for using alternatives such as anatomical models (e.g., plastic, silicone, or 3D-printed models), virtual dissections through software and AR/VR platforms, and plastinated specimens that preserve animal tissue without the need for continuous cadaver use.

Replacement brings several benefits. One is the reduction in animal suffering: by using models or digital tools, veterinary schools can provide comprehensive anatomy education without subjecting animals to dissection or killing. Another is ethical alignment: the use of models aligns veterinary education with the ethical values that students are expected to uphold in their future practice. They learn to respect animal life and the intrinsic value of animals, promoting compassion and humane treatment in clinical practice. Additionally, there is increased accessibility: models and digital tools are accessible to all students, irrespective of the availability of cadavers, especially in regions with limited resources or where cadaver procurement is ethically or legally restricted. Many veterinary institutions worldwide have already adopted models in place of animal dissections. For instance, the Royal Veterinary College (UK) has transitioned to using digital and physical models for anatomy education, significantly reducing animal use.

Reduction: Minimizing the use of animal models: While complete replacement of animals in veterinary education is a critical goal, the principle of reduction also plays a vital role. Even when animal models are used, the goal is to reduce the number of animals needed to achieve the educational objectives.

Strategies for reducing the use of animals in veterinary education include focused dissections, where dissection is necessary but fewer cadavers are used by concentrating on critical anatomical systems rather than full-body dissections, thereby reducing the number of animals required (Lairmore and Ilkiw, 2015). Simulated or virtual learning also supports this goal; the use of anatomical models in virtual dissection programs or as supplementary learning tools reduces reliance on cadavers. For instance, students can practice with models of the equine digestive system or the canine respiratory tract repeatedly without the need for multiple animals. Additionally, 3D printing and custom models-particularly those created through CT or MRI scans- can be tailored to highlight specific anatomical features or pathologies, further reducing the need for multiple animal specimens (AbouHashem *et al.*, 2015; Hadžiomerović *et al.*, 2025). Multi-species models offer another practical approach; comprehensive models of organs or body systems, such as cross-species anatomical models of the heart, brain, or reproductive organs, can serve as templates for multiple species, significantly reducing the need for different cadavers for comparative anatomy. The benefits of reduction are clear. Ethical compliance is strengthened by ensuring that only the most essential dissection practices are performed, aligning veterinary schools with modern ethical standards. Reduction also brings cost efficiency, as less reliance on cadavers and live animals decreases the costs associated with animal procurement, transportation, and disposal. Moreover, it promotes environmental sustainability, as using fewer animals in education reduces the environmental impact by minimizing the logistics of animal procurement and transportation (Lairmore and Ilkiw, 2015). Many institutions have now adopted hybrid teaching methods that blend digital simulations with minimal cadaver use, allowing for an effective reduction in animal use without sacrificing the quality of anatomical education (Hadžiomerović *et al.*, 2025).

Refinement: Enhancing humane treatment and minimizing suffering: The principle of refinement involves improving the care, treatment, and use of animals to reduce distress and suffering. In the context of veterinary anatomy education, this principle emphasizes the better handling of animals used in dissection and the adoption of more humane practices in learning. Where dissection is unavoidable, using plastinated specimens or preserved anatomical models can ensure that animals are treated with dignity. Plastination preserves anatomical structures in a lifelike state without the need for continuous use of fresh animals. Veterinary schools increasingly seek cadavers from ethical sources, such as animals that have died due to natural causes or were euthanized for medical reasons (Riederer, 2014). This ensures that no animal is killed specifically for educational purposes. Equally important is ensuring that students understand and adhere to ethical guidelines in dissection practices, including proper handling, respectful treatment of cadavers, and the use of specimens only when necessary (Flecknell, 1994).

Advances in VR, AR, and haptic feedback technologies allow students to practice and refine their skills without interacting with real tissues. For example, haptic feedback devices in VR can simulate the sensation of palpation or surgical incision, creating a realistic training environment without the need for animal models (Sanfilippo *et al.*, 2022). Silicone, soft-tissue, and 3D-printed models that mimic the flexibility and texture of living tissue offer students a more refined experience than traditional plastic models, enabling them to understand the nuances of real animal anatomy (Lalotra and Kumar, 2024). Refinement helps maintain a respectful relationship with animals, emphasizing humane treatment throughout the educational process. Models and simulations that reduce or eliminate the need for live animals create a safer, more ethical learning environment, promoting positive attitudes toward animal welfare. Teaching students to handle anatomical specimens respectfully helps foster a sense of compassion and responsibility that is integral to veterinary practice.

Ethical challenges and future directions: While technological innovations in anatomical modeling have significantly advanced the ethical treatment of animals in veterinary education, several challenges remain. The high cost of some digital tools and 3D printing technology can limit access to these resources in low- and middle-income regions, where dissection of cadavers may still be the only feasible option. Moreover, not all institutions have the infrastructure to support immersive VR or AR-based learning (Sanfilippo *et al.*, 2022; Sambargi *et al.*, 2024). However, ongoing advancements in open-source initiatives, reduced-cost 3D printing, and cloud-based simulations are expected to democratize access to ethical anatomical learning tools. Collaboration between universities, technology companies, and policymakers will be crucial in overcoming these challenges and ensuring that all veterinary institutions can adopt ethical, cutting-edge teaching practices (Sambargi *et al.*, 2024; Choudhary *et al.*, 2025).

Challenges and future directions for anatomical models: As veterinary anatomical models continue to evolve into increasingly sophisticated teaching tools, several challenges must be addressed to ensure their effectiveness, accessibility, and integration into mainstream veterinary curricula. The development, deployment, and adoption of these models are shaped not only by technological progress but also by economic, institutional, and pedagogical considerations (Sinha and Lee, 2024). This section discusses the primary challenges encountered in implementing anatomical models and outlines promising future directions to enhance veterinary anatomy education (Sinha and Lee, 2024).

Challenges in the development and use of anatomical models

Cost and resource constraints: Despite the growing popularity of anatomical models, their development and integration often remain cost-intensive, particularly for high-resolution 3D printers and printing materials, commercially manufactured models, licensing fees for digital anatomy software, and technical support and maintenance (Khalil *et al.*, 2021; Kapoor, 2024). Institutions in low- and middle-income countries (LMICs) often struggle to afford these resources for anatomical model preparation. Even in well-funded programs, scaling up model availability to meet large student cohorts can be financially demanding (Khalil *et al.*, 2021).

Limited access to advanced technology: Adopting advanced technologies such as AR, VR, and AI-enhanced tools requires high-speed internet, high-performance computers, VR/AR headsets, and simulation labs, and technical expertise among faculty and staff in educational institutions (Xiong *et al.*, 2021). In many regions, particularly in rural or underfunded veterinary colleges, such high-tech infrastructure is lacking. This leads to a digital divide, where only a subset of students and institutions benefit from technological advancements (Xiong *et al.*, 2021; Daniels, 2025).

Anatomical accuracy and standardization: While 3D printing and digital modeling offer customization, variability in model design may result in inconsistencies in anatomical accuracy. If models are created without expert validation, there is a risk of disseminating misleading anatomical information to the veterinary students (Choudhary *et al.*, 2023). There is currently no universal regulatory body overseeing the quality of anatomical models in veterinary education. Moreover, the inclusion of species diversity in veterinary curricula complicates standardization. A canine limb model may be highly detailed and accurate, while equivalent models for bovines, felines, or avian species may be lacking or oversimplified (Tomaszewski *et al.*, 2017).

Faculty training and resistance: Veterinary educators often come from backgrounds rooted in traditional pedagogy-dissection, textbooks and cadaver-based learning. Transitioning to model-based or digital instruction requires training in software usage, such as segmentation and simulation platforms, as well as digital pedagogy and instructional design for hybrid or flipped classrooms

(Guevar, 2020). Resistance to change may stem from concerns about the loss of dissection skills, unfamiliarity with technology, or doubts about educational efficacy (Guevar, 2020).

Limited long-term validation data: While numerous studies have demonstrated short-term gains in knowledge and confidence using anatomical models, longitudinal studies showing their impact on long-term retention, clinical skills, and real-world veterinary outcomes are still limited (Gureckis and Love, 2009). This poses a challenge for institutional investment and curriculum overhaul, as hard evidence of long-term benefit is essential for systemic change.

Future directions in veterinary anatomical modelling

Despite these challenges, the future of anatomical model development is promising. Several emerging trends, technologies, and educational strategies are likely to transform veterinary anatomy education over the coming decades.

Open-access model repositories and shared platforms: Open-source initiatives that allow free sharing of 3D model files (STLs, OBJs) have already begun to democratize access to anatomical models. Examples include the Vet3D Open Library, which is a repository of dog and cat skeletal models, and AnatoVet3D in India, which shares farm animal anatomical models (Kapoor *et al.*, 2024; Oliveira Calixto *et al.*, 2025). Platforms like Thingiverse and the NIH 3D Print Exchange also host free veterinary anatomical files (Fig. 16). Future development should focus on international collaboration for comprehensive species libraries, peer-reviewed validation of shared models, and language localization with region-specific anatomical adaptations. Such repositories empower institutions in LMICs to print and use high-quality models at a fraction of the cost, fostering global equity in veterinary education (Oliveira Calixto *et al.*, 2025).

Hybrid learning and curriculum integration: The future of veterinary anatomy lies in blended learning models that combine physical models for tactile exploration, digital simulations for spatial visualization, and clinical cases for contextual relevance (Spruijt *et al.*, 2023; Li *et al.*, 2025). Curricula will need to adapt to this multimodal paradigm by aligning models with specific learning outcomes, introducing early exposure to model-based learning in preclinical years, and embedding model use in assessments such as OSPE stations and skill demonstrations (Luo, 2023). Hybrid approaches cater to diverse learning styles and bridge the gap between theory and clinical application, producing better-prepared graduates (Gómez *et al.*, 2023).

Augmented reality (AR) on mobile and wearable devices: While high-end AR devices like Microsoft HoloLens are currently expensive, future iterations are expected to be more affordable and mobile-based, thereby significantly expanding access. Predicted advancements include AR overlays on smartphones and tablets via apps, haptic gloves integrated with AR for tactile learning, and QR-code-enabled real-time model activation in textbooks and classrooms. Such innovations will decentralize AR learning, allowing students to study anytime, anywhere- an advantage particularly during global disruptions like pandemics.

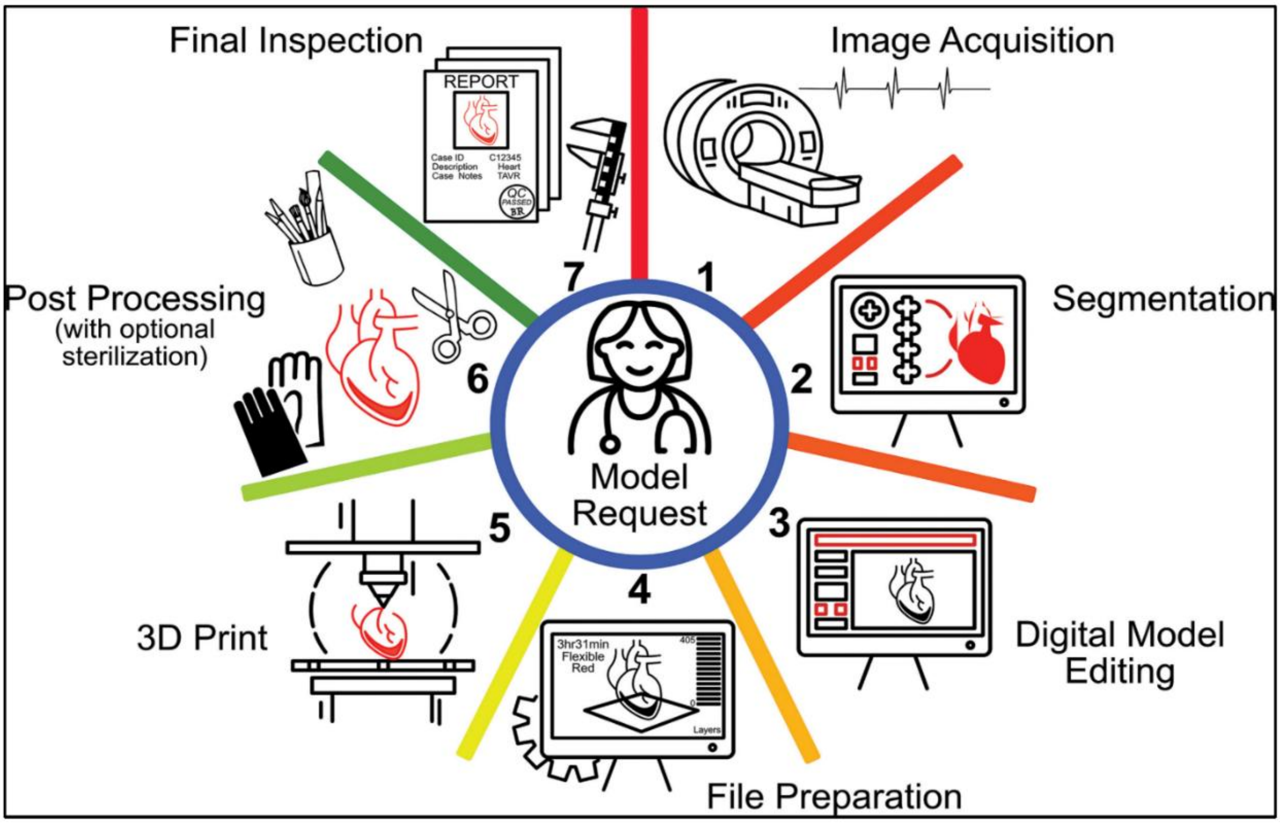

Fig. 16: Showing (a) Schematic flow steps involved in the process of 3D printing technology, i.e., from imaging to 3D modelling. (b) Illustration of current applications of 3D printing technology in veterinary medicine (Patel *et al.*, 2023).

AI-Driven personalization and feedback systems: Artificial Intelligence will play a key role in adaptive anatomy education, allowing platforms to track student progress, diagnose learning gaps, recommend tailored model interactions, and simulate clinical reasoning based on anatomical understanding. Future systems may include AI tutors that respond to student queries in real-time, offer procedural guidance during simulations, and suggest remedial learning activities- all integrated with anatomical models (Spruijt *et al.*, 2023; Narayanan *et al.*, 2023).

Sustainability and eco-conscious model development: As environmental consciousness grows, the production of anatomical models is expected to shift toward using biodegradable or recycled materials in 3D printing, as well as digital-only models, to reduce material waste and adopt energy-efficient fabrication methods. Sustainable practices will be essential for aligning veterinary education with global environmental goals and ensuring responsible resource use (Szechyńska-Hebda *et al.*, 2024).

Interprofessional and comparative anatomy applications: Anatomical models developed for veterinary education may be adapted for comparative anatomy studies across human and animal species, zoological and wildlife training and One Health curricula involving collaboration with medical, dental and public health disciplines. This interdisciplinary approach will expand the utility of anatomical models and foster collaborative understanding of disease, anatomy, and physiology across species (Bhattacharjee *et al.*, 2022).

Vision for the future: In the long term, we may see the emergence of global virtual anatomy campuses- cloud-based platforms where veterinary students can access a global repository of species-specific anatomical models, participate in remote VR dissections and simulations, and collaborate with international peers and experts in real time. Supported by AI and AR, these platforms will transform anatomy learning from a static classroom activity to an interactive, personalized, and globally connected experience (Spruijt *et al.*, 2023).

The development and implementation of anatomical models for veterinary education face several challenges-financial, technological, pedagogical, and infrastructural. However, the rapid pace of innovation, combined with increasing global collaboration and ethical imperatives, is paving the way for a more accessible, engaging, and humane anatomy curriculum. By investing in open access, faculty development, sustainability, and integration of cutting-edge technologies like AI and AR, veterinary education can not only overcome existing barriers but also set a new global standard for anatomical science. The future is one where every veterinary student, regardless of geography or institutional wealth, has access to accurate, interactive, and ethical tools to master the complexity of animal anatomy- laying the foundation for excellence in animal health, surgery, and welfare.

Conclusion and recommendations: The advancement of animal anatomical teaching models marks a pivotal shift in veterinary anatomy education, offering innovative alternatives and supplements to traditional dissection-based methods. These models- ranging from plastinated specimens and silicone replicas to 3D-printed structures and virtual simulations- enhance the clarity, accessibility, and ethical delivery of anatomical knowledge. They support active and repeatable learning, minimizing the logistical and ethical concerns associated with cadaver use, and are increasingly aligned with global educational standards. As veterinary curricula evolve, these models prove instrumental in improving student engagement, spatial understanding, and long-term retention of anatomical structures.

To fully leverage the benefits of these models, veterinary institutions should adopt a blended teaching approach that integrates both conventional and modern methods. Faculty training, curriculum redesign, and investment in infrastructure are crucial for the effective implementation of these initiatives. Collaborative research and validation studies should be prioritized to assess the educational impact and cost-effectiveness of these models. Moreover, policies should encourage ethical teaching practices and promote accessibility across institutions, especially in resource-limited settings. By embracing these innovations, veterinary education can become more humane, effective, and responsive to the changing demands of the profession.

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