From Models to Metaverse AI in Anatomy Education

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ABSTRACT:
Anatomy is the backbone of pharmacy and healthcare education, yet traditional cadaver-based dissection often comes with barriers-limited resources, ethical concerns, and restricted accessibility. In today's digital era, Artificial Intelligence (AI) is transforming this landscape through virtual dissection and interactive anatomy learning platforms. These tools replace static textbooks and one-time dissections with immersive 3D models, augmented and virtual reality, and AI-powered tutors that adapt to each learner's pace. For pharmacy students, this means not only a deeper understanding of human anatomy but also the ability to repeatedly explore, visualize, and practice without limitations.

AI-driven systems bring anatomy to life-highlighting structures, simulating physiological processes, and offering real-time feedback that strengthens comprehension. They reduce dependency on cadavers, make learning more sustainable, and align with the evolving digital preferences of today's learners. At the same time, challenges such as cost, accessibility, and the need for digital literacy cannot be ignored.

This review explores the shift from conventional to AI-enabled anatomy education, highlighting its potential to create more engaging, personalized, and future-ready pharmacists. By bridging theory with practice, AI-driven virtual dissection is not just a teaching tool-it is a gateway to reimagining pharmacy education for the next generation.

KEYWORDS: Artificial Intelligence, Anatomy education, Interactive learning, Virtual reality, Digital anatomy, Innovation in Medical teaching.

INTRODUCTION:

Anatomy has long been the cornerstone of medical education, serving as the essential starting point of every doctor's journey into the complex mysteries of the human body. Long before modern imaging technologies allowed clinicians to peer inside the body without a scalpel, anatomy was pursued with a blend of curiosity, courage, and often considerable personal risk. Among the many methods of studying the human body, human cadaveric dissection (CD) emerged as the most profound, offering students an unparalleled opportunity to directly explore the intricate landscapes of life itself. Cadaveric dissection is not merely a mechanical or observational exercise; it is a deeply immersive educational practice that engages the mind, hands, and heart. It bridges the gap between theoretical knowledge and practical skill, providing the essential foundation for all clinical training that follows. Beyond the acquisition of anatomical knowledge, cadaveric dissection is a profound exercise in ethical awareness and humanism, offering lessons that no textbook, model, or virtual simulation can fully replicate.

For generations of medical students, cadaveric dissection has functioned as much more than a technical exercise; it has been a rite of passage, a first, humbling encounter with human mortality. The silent presence of a donor on the dissection table conveys lessons that no textbook or lecture can capture: the fragility of life, the dignity inherent in death, and the immense responsibility carried by those who choose the profession of healing. In this sense, the cadaver is often referred to as the "first patient," guiding students not only in the anatomy of the human body but also in compassion, respect, and the broader humanistic values integral to medicine. Numerous studies in medical education underscore the profound emotional and professional impact of cadaveric learning. Students who participate in dissection frequently report increased empathy, ethical sensitivity, and an enhanced awareness of patient dignity, indicating that cadaveric experience is as critical for forming professional identity as it is for building anatomical knowledge. Qualitative research further reveals that encounters with cadavers evoke a complex range of emotions-curiosity, anxiety, awe, and even reverence-which collectively serve as early lessons in the emotional maturity required of a physician. Structured reflection, memorial ceremonies, and debriefing sessions amplify these outcomes, allowing students to process their experiences constructively and carry forward a deep sense of responsibility and gratitude for their donors.

The story of cadaveric dissection begins in the ancient world, where early insights into human anatomy were gained largely through indirect observation. Egyptian embalmers, for example, developed rudimentary anatomical knowledge through the meticulous art of mummification, learning about organ systems, vascular pathways, and techniques for tissue preservation. Despite their advancements, strict cultural and religious beliefs limited the exploration of anatomy through direct dissection, meaning that much understanding was theoretical or derived from the examination of embalmed bodies rather than through empirical dissection. A major leap occurred in ancient Greece, around the third century B.C., in the intellectual hub of Alexandria. Herophilus of Chalcedon and Erasistratus of Ceos became pioneers of systematic human dissections. Their work marked a radical departure from previous methods: the human body was no longer merely an object of philosophical speculation but a subject of empirical study. They meticulously documented anatomical structures, including the nervous system, musculature, and vascular pathways, establishing the foundation for centuries of anatomical knowledge. Unfortunately, the majority of their work was lost over time, and their methods were not widely disseminated, largely due to societal and religious constraints that soon rendered human dissection taboo.

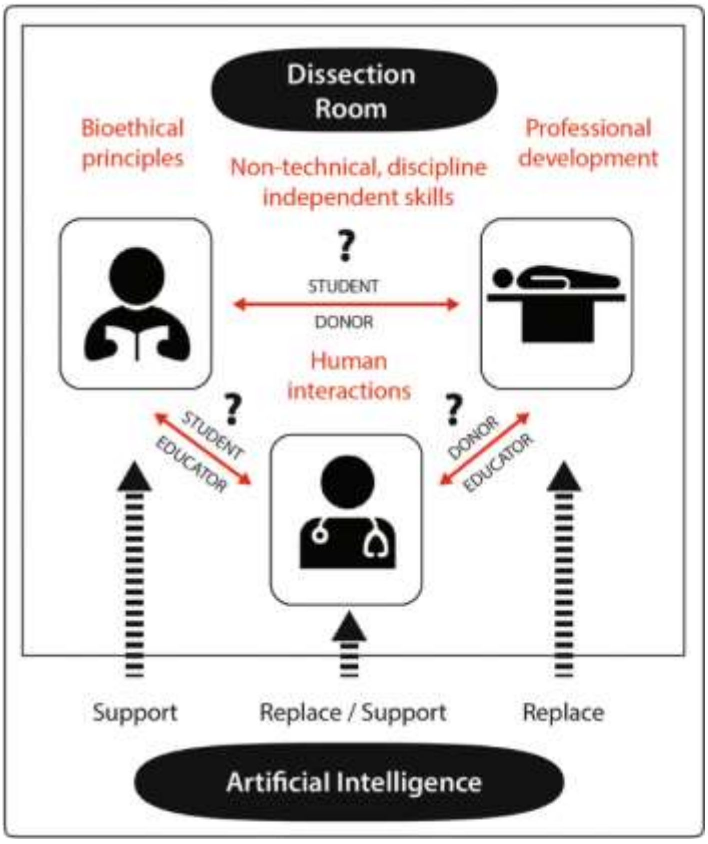

Fig 1: AI's impact on Anatomy Education with Donor Replacement
[Source: Research gate]

Following the deaths of these early anatomists, shifting cultural and religious beliefs branded human dissection as sacrilegious. For nearly seventeen centuries, human anatomy receded into silence. Medical education relied heavily on animal dissections, written texts, and speculative theories. This long hiatus had profound consequences: progress in anatomical knowledge slowed, and generations of physicians were compelled to learn without direct contact with the human body. During this period, anatomical understanding was often secondhand, reconstructed from animal models or inherited classical texts, most notably the works of Galen, whose observations on animal anatomy were extrapolated to humans. While influential, these texts contained inaccuracies and limitations that persisted for centuries, hindering medical progress and occasionally leading to flawed clinical practice.

The silence surrounding human dissection finally began to break in medieval Europe. In 1231, Holy Roman Emperor Frederick II issued a groundbreaking decree mandating that human bodies be dissected at least once every five years for medical instruction. By the 14^{th} century, universities in Bologna, Italy, had begun to reintroduce dissection as part of formal medical education. Mondino de Luzzi, often called the "Restorer of Anatomy," authored Anathomia, a manual that guided students through dissection for centuries. This period marked the emergence of formalized anatomy curricula within higher education, in which human dissection became not merely tolerated but actively required. Public dissections, conducted in large auditoriums, were attended by students, professors, and occasionally curious townspeople. These events represented a cultural shift: dissection was no longer hidden but embraced as a legitimate pursuit of knowledge, merging empirical observation with pedagogical instruction. The combination of structured manuals, public demonstration, and hands-on learning laid the foundation for modern anatomical education, emphasizing accuracy, systematic study, and ethical engagement.

The Renaissance marked a pivotal turning point, where science, art, and anatomy converged in transformative ways. Artists like Leonardo da Vinci and Michelangelo dissected human bodies not only to perfect their art but also to capture the breathtaking complexity of the human form. Leonardo's sketches-depicting veins, muscles, and internal organs-remain unmatched in their precision and aesthetic beauty, contributing substantially to anatomical knowledge by visualizing structures in unprecedented detail. The true revolution, however, was spearheaded by Andreas Vesalius. His monumental work, De humani corporis fabrica (1543), shattered centuries of reliance on Galen's animal-based teachings. Vesalius insisted that anatomy must be learned by seeing and touching the human body itself, establishing the radical principle that students must be active witnesses rather than passive recipients of anatomical truth. He emphasized direct observation, systematic dissection, and meticulous recording of individual anatomical variations, thereby formalizing empirical study and challenging centuries of unquestioned authority. With Vesalius, cadaveric dissection became not just an educational tool but the very foundation of scientific medicine. The Renaissance thus granted dissection its rightful place at the core of medical education, marrying empirical science with ethical respect and an artistic appreciation of human form.

As anatomical education evolved, cadaveric dissection diversified into multiple approaches to meet specific pedagogical and clinical needs. Systematic dissection, performed step by step from superficial to deep structures, provided students with comprehensive exposure to the human body. Regional dissection focused on specific anatomical areas-head and neck, thorax, abdomen, or limbs-allowing learners to master the structures most relevant to clinical practice. Topographical dissection emphasized spatial relationships between structures, a methodology particularly valuable in surgical training. When human cadavers were scarce, comparative dissections of animals supplemented learning, although these were never true substitutes for the human form. Demonstrative dissections, conducted in lecture halls, enabled large groups to witness the human body being studied in real time. Research dissections advanced medical knowledge by exploring the causes of disease, refining surgical techniques, and providing valuable data for anatomical and clinical research. Modern anatomical curricula often combine these approaches with advanced embalming techniques, digital supplements, and skill-based exercises, maximizing both knowledge retention and professional formation.

Despite these varied methodologies, the enduring value of cadaveric dissection lies in the holistic experience it offers. Cadavers provide realism unmatched by any model, virtual screen, or simulation. Students experience the true textures, densities, and three-dimensional arrangements of the body, developing spatial awareness that enhances memory retention and practical proficiency. Each cadaver also presents unique anatomical variations, preparing students for thediversity they will encounter in real patients. Dissection bridges the gap between theory and practice, transforming static textbook knowledge into dynamic, hands-on understanding. Simultaneously, it cultivates professionalism: the act of working with a donated body fosters humility, discipline, and a profound sense of responsibility. Dissection sharpens manual dexterity, precision, and observational skills, qualities essential for future clinicians and surgeons. Above all, it nurtures ethical awareness, reminding students of the extraordinary generosity of body donors and the societal trust invested in medical professionals. Structured studies have consistently demonstrated that students who engage in cadaveric dissection exhibit stronger retention of anatomical knowledge, superior tactile and visual-spatial skills, and heightened awareness of medical ethics and professional conduct compared to students relying solely on digital or virtual alternatives.

The emotional impact of cadaveric dissection cannot be overstated. Many physicians vividly recall their first day in the dissection hall-the sterile smell, the silence, and the initial encounter with the cadaver leave an indelible impression. For some, the experience is unsettling; for others, profoundly moving. Yet for nearly all, it is transformative. The cadaver becomes a silent teacher-one who commands respect but imparts knowledge generously. Students learn resilience in the face of discomfort, reverence for life's fragility, and gratitude for the opportunity to learn. This emotional dimension underlies why cadaveric dissection is often described as a rite of passage. It is not merely a means of learning anatomy; it is a formative experience that shapes a student into a physician in the fullest sense. Evidence indicates that exposure to dissection enhances emotional maturity, ethical reasoning, and reflective practice, qualities that extend into clinical care and patient interactions throughout a physician's career.

In contemporary times, debates occasionally arise regarding whether cadaveric dissection should remain central in medical education. Critics cite ethical dilemmas, financial costs, and the advent of sophisticated alternatives such as virtual reality (VR), augmented reality (AR), or digital 3D models. While these technologies provide valuable supplemental learning, research consistently demonstrates that they cannot fully replace the authenticity, tactile engagement, and professional formation derived from cadaveric study. Consequently, many medical schools now employ blended curricula, integrating hands-on dissection with VR/AR tools. This combination reinforces spatial learning, preparation, and repeated practice while preserving the humanistic lessons of working with real human tissue. Most importantly, cadaveric dissection preserves the human connection at the heart of medicine. Each donor is not merely a specimen but a life once lived-a final act of teaching and generosity that future doctors carry with them throughout their professional journey.

The broader societal and ethical dimensions of cadaveric dissection also merit consideration. Modern anatomy programs emphasize respect for donors, including formal ceremonies, memorials, and reflective exercises designed to instill a sense of gratitude and ethical responsibility. The ethical framework surrounding dissection today is far more structured than in past centuries, guided by principles of informed consent, respect for the deceased, and confidentiality. Medical students learn to approach the cadaver with both scientific curiosity and moral responsibility, ensuring that education and research are conducted with integrity. This approach cultivates a professional mindset that extends beyond the anatomy lab, informing attitudes toward patients, colleagues, and society at large.

Technological advancements have further enriched the study of anatomy while complementing cadaveric dissection. High-resolution imaging modalities, such as MRI, CT, and ultrasound, provide dynamic visualization of living anatomy, allowing students to correlate findings with the static structures observed during dissection. Three-dimensional printing, virtual simulations, and interactive digital platforms enable repeated practice and detailed exploration of complex structures. Yet even with these innovations, the consensus remains that nothing replicates the sensory, cognitive, and emotional learning fostered by direct engagement with the human body. Tactile feedback, spatial orientation, and the nuanced understanding of tissue consistency and variation are experiences that digital models alone cannot provide.

From the daring dissections of Herophilus in ancient Alexandria to the artistry of Leonardo da Vinci, from Vesalius's revolutionary empirical teachings to the modern integration of digital technologies in medical classrooms, cadaveric dissection has endured across centuries. It has faced societal bans, religious taboos, and practical shortages, yet it remains the gold standard for anatomical learning. Its unique characteristics-realism, variability, integration with clinical practice, development of manual skills, and ethical grounding-make it irreplaceable. Beyond instruction, cadaveric dissection humanizes medicine itself, forging a bridge between scientific understanding and compassionate patient care. As long as physicians are trained and patients are healed, cadaveric dissection will retain its central place in medical education. It is more than an anatomical study; it is a tradition that shapes the values, skills, and humanity of those who will carry the responsibility of healing. Ultimately, the cadaver is not merely a body; it is a teacher, a guide, and a reminder of the profound connection between knowledge, compassion, and the human experience. It embodies the continuity of medical knowledge, the integration of science with ethics, and the unbroken lineage of doctors who, across centuries, have dedicated themselves to understanding and serving the human body. [1, 2]

IMPORTANCE:

Anatomy has always been a cornerstone of medical and health professional education, providing the foundation upon which clinical skills are built. A deep understanding of the structure, organization, and relationships of the human body equips future doctors, pharmacists, nurses, and allied health professionals with the knowledge they need to make sound clinical decisions. Without this knowledge, the ability to understand diseases, interpret symptoms, and apply therapeutic interventions would be compromised.

In the early 20th century, anatomy dominated medical curricula, often comprising hundreds of hours of dedicated instruction. Although the number of hours has been reduced over time, the importance of anatomy remains undiminished. The study of anatomy helps bridge the gap between theory and practice, enabling students to visualize and comprehend the human body beyond textbooks. Whether through cadaveric dissection, prosections, or clinical case-based learning, students gain not only factual knowledge but also the ability to integrate structure with function, which is essential for patient care.

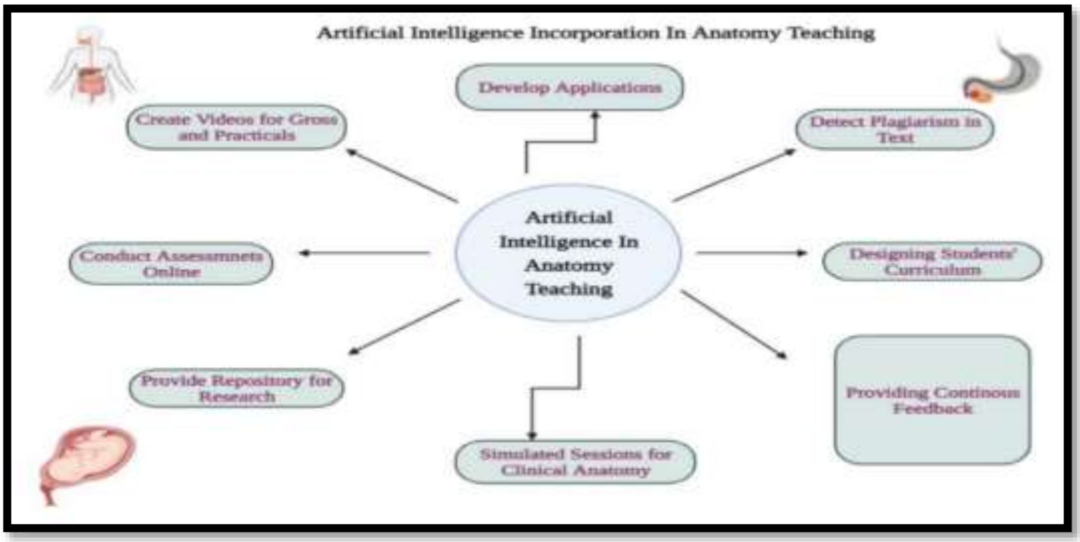

Fig.2: AI in Anatomy Teaching

[Source: MDPI]

For pharmacy students, anatomy plays a less direct but equally important role. Pharmacists today are not only dispensers of medicines but also frontline healthcare providers engaged in patient monitoring, clinical assessment, and therapeutic decision-making. Understanding where organs are located, how systems interact, and how diseases alter the body allows pharmacists to recognize adverse drug reactions, counsel patients more effectively, and collaborate with other healthcare professionals in multidisciplinary settings. For example, recognizing the anatomical basis of hypertension or diabetes complications helps pharmacists understand why specific medicines are chosen and how they impact the body.

Some of the major reasons why anatomy is vital for health professional education include:

1. **Foundation for Clinical Knowledge** – Anatomy is the basis for subjects like physiology, pathology, and pharmacology.
2. **Clinical Safety** – Prevents errors in procedures such as injections, surgeries, and medical imaging.
3. **Professionalism and Empathy** – Encounters with cadavers instill respect for the human body and sensitivity in patient care.
4. **Teamwork Development** – Dissection sessions promote collaboration, communication, and peer learning.
5. Interdisciplinary Language–Provides a common ground for doctors, nurses, and pharmacists to work together effectively.
6. **Understanding Anatomical Variations**–Exposure to cadavers highlights natural differences in human bodies, preparing students for real-world patient diversity.
7. **Emotional Resilience** – Coping with death and mortality in anatomy labs strengthens students emotionally for clinical practice.

The integration of anatomy into undergraduate curricula also helps students develop a professional identity. Encounters with cadaveric specimens, in particular, foster respect for the human body and cultivate empathy and professionalism. These experiences can shape how future health professionals approach patient care, emphasizing dignity, compassion, and sensitivity in clinical practice. Anatomy education, therefore, is not only about learning structures but also about shaping attitudes and values central to healthcare.

Dissection-based teaching continues to hold a unique place in anatomy education. Unlike virtual models, dissection offers an irreplaceable three-dimensional understanding of body structures, their textures, and spatial relationships. It also exposes students to the natural variation among human bodies, preparing them for the reality that no two patients are identical. While it may be resource-intensive, many institutions still value it for the unparalleled depth of learning it provides. Moreover, group dissections foster teamwork, communication, and collaborative problem-solving-skills that are vital in professional practice.

Beyond technical skills, anatomy prepares students emotionally. Students often report that their first encounters with human cadavers teach them coping mechanisms for dealing with death and mortality, which are inevitable aspects of healthcare. This emotional resilience is crucial in shaping well-rounded professionals capable of supporting patients and families during vulnerable times. Thus, anatomy teaching also serves as a form of professional socialization into the healthcare field.

To summarize, anatomy remains an essential pillar of undergraduate education for health professionals. It provides the structural framework for understanding disease, supports the development of clinical reasoning, and fosters professional values. For pharmacists and other health professionals, anatomy ensures that their contributions to patient care are informed, accurate, and collaborative. Despite evolving teaching methods and changing curricula, the importance of anatomy cannot be overstated-it is the language of medicine and the foundation of all healthcare practice.[3,4]

CONVENTIONAL METHODS:

Anatomy has always been a cornerstone of healthcare education, including pharmacy, because it helps students understand how drugs interact with the body and supports clinical decision-making. Over time, anatomy teaching has shifted from traditional methods to advanced, AI-powered approaches that make learning more interactive, personalized, and accessible.

Traditionally, pharmacy students have relied on well-established tools and classroom techniques to learn anatomy:

- **Textbooks and Atlases:** Standard resources such as Gray's Anatomy and anatomy atlases provide detailed diagrams and descriptions of organs and systems. While informative, these are static and require students to imagine 3D structures.
- **Charts and Models:** Wall charts, skeletons, and plastic models are widely used for demonstrations. They help in visualizing organs but lack interactivity and dynamic features.
- **Classroom Teaching:** Lectures supported by blackboards or PowerPoint slides form the backbone of anatomy teaching. This method, though effective for theoretical understanding, can be passive and less engaging.
- **Microscopy and Histology Slides:** Tissue and cell structures are studied under microscopes, offering a closer look at the microscopic anatomy relevant to pharmacy and pathology.
- **Dissection:** Students explore real cadavers by dissecting tissues and organs. This hands-on method, practiced for centuries, builds deep understanding but faces challenges such as cadaver availability, cost, time, and ethical concerns.
- **Prosection:** Pre-dissected cadavers prepared by experts, allowing students to observe structures without performing the dissection themselves. This saves time and resources.
- **Plastination:** A technique where real body tissues are preserved with chemical materials to create durable, odorless, and reusable anatomical specimens.
- **Anatomical Models & Charts:** 2D charts, posters, and plastic/resin 3D models that visually represent organs and systems.
- **Surface Anatomy & Radiological Imaging:** Observing external body landmarks and studying X-rays, CT scans, or MRIs to understand internal structures.

While these methods are reliable and foundational, they are often passive and limited in terms of interactivity and scalability.

MODERN METHODS: [7-8]

With the advancement of technology, new methods have been integrated alongside conventional ones:

1. **<u>3D Interactive Anatomy Tools</u>:** Computer-based programs offering interactive, rotatable models of human anatomy for better spatial understanding.
2. **<u>Digital Dissection Platforms:</u>** "Virtual cadavers" displayed on digital tables or software allow students to dissect layer by layer without the need for real bodies.
3. **<u>3D Printing Technology:</u>** Produces accurate anatomical replicas for tactile learning, supporting both teaching and research.

4. **Online Learning Resources:** Recorded video dissections, digital atlases, and virtual anatomy labs have made anatomy education more accessible.

AI-Driven Virtual Dissection and Anatomy Learning:

Artificial Intelligence (AI) is now revolutionizing anatomy learning in pharmacy education by providing personalized, immersive, and adaptive experiences:

- **Virtual & Augmented Reality (VR/AR):**Virtual Reality (VR): Immerses students in a fully simulated 3D environment where they can explore the human body layer by layer.
- **Augmented Reality (AR):** Projects 3D anatomical models into real-world settings using tools like Microsoft HoloLens, enabling interactive exploration.
- **AI-Powered Learning Platforms:**
- Adaptive Learning Systems – Platforms like Smart Sparrow tailor lessons to individual learning speeds and preferences.
- AI Tutors &Chabot's–Virtual assistants (e.g., AnatomyGPT) answer questions, explain concepts, and provide real-time feedback.
- **Immersive and Gamified Learning:**
- Anatomy Detective Games simulate clinical cases where students apply anatomical knowledge
- AI-driven Quizzes & Assessments (e.g. Kahoot) promote active recall and engagement.
- 3D Printing with AI Support: Personalized anatomical models can be designed and printed based on learning requirements, making spatial learning more effective.
- **Role of AI in Assessment & Curriculum Design:**
- Detecting plagiarism in assignments.
- Designing adaptive curricula based on performance.
- Providing continuous feedback.
- Simulating clinical sessions for practice.

Benefits of AI-Driven Approaches:

- **Personalized Learning:** Tailors teaching methods to each student's pace and style.
- **Enhanced Engagement:** VR/AR and gamification make learning interactive and enjoyable.
- **Improved Understanding**: 3D visualization clarifies complex anatomical relationships.
- **Accessibility:** Digital and AI-based tools overcome limitations of cadaver availability, cost, and ethics.
- **Integration with Pharmacy Education:** Helps pharmacy students link drug action sites with specific anatomical structures for better therapeutic understanding.

Conventional anatomy teaching methods-such as dissection, prosection, plastination, and anatomical models-have laid the foundation for generations of healthcare professionals. However, with the rise of modern technology and AI-driven innovations, anatomy learning in pharmacy education is becoming more immersive, interactive, and student-centered. By combining the reliability of traditional methods with the power of AI-driven virtual dissection and learning platforms, pharmacy students can gain deeper insights, stronger clinical relevance, and enhanced readiness for patient care in the future.[5,6]

INNOVATIVE APPLICATIONS:

Anatomy education today faces several challenges, including reduced curricular time and ethical concerns around cadaver use. To address these issues, educators are turning to innovative teaching methods that blend traditional practices with modern technology.

Digital tools like 3D models, virtual reality (VR), and augmented reality (AR) allow students to interactively explore the human body. These resources help learners visualize complex structures more clearly and improve their spatial understanding. When combined with traditional approaches, they create a richer, more well-rounded learning experience. At the same time, understanding how students respond to these technologies is vital to ensure they are used effectively.

The COVID-19 pandemic accelerated this shift by pushing medical schools to adopt hybrid learning models. Multimedia resources and digital platforms helped maintain continuity of education, even when in-person teaching was limited. Alongside these tools, teaching strategies such as flipped classrooms, problem-based learning, and team-based exercises have gained popularity, making anatomy classes more engaging and participatory.

Artificial intelligence (AI) is also playing an increasingly important role. By offering adaptive learning pathways, real-time feedback, and even virtual tutoring, AI tools can personalize the learning experience. However, there are concerns about depending too much on algorithms, which may not capture the deeper, human aspects of observation and understanding.

Despite the promise of digital and AI tools, cadaveric dissection remains irreplaceable. The hands-on experience not only strengthens knowledge but also shapes students' professional identity and fosters empathy, offering lessons in humanity that digital tools alone cannot provide.

Ultimately, the best approach is a balanced, integrated model-one that combines the depth of hands-on dissection with the flexibility and innovation of modern technologies. This ensures that students receive both the scientific knowledge and the humanistic perspective needed in medical practice.

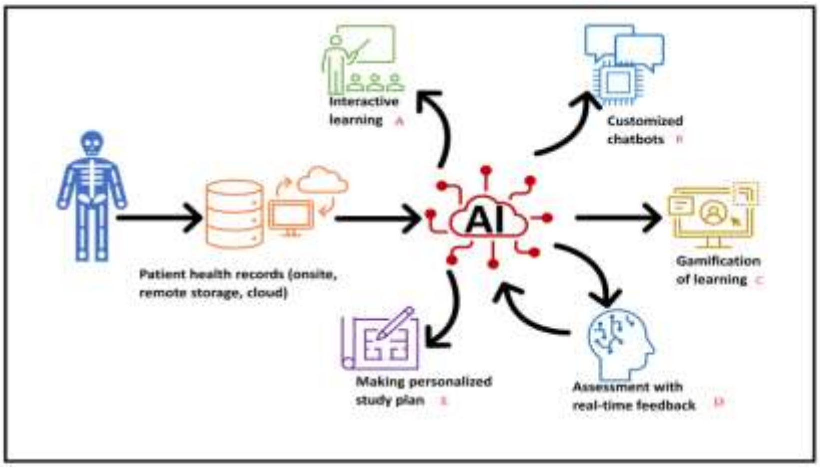

Fig.3: Applications of AI

[Source: MDPI]

1. **AI-Powered Virtual Reality (VR) Dissection with Chatbot Assistance**

- **How it works:**Modern VR platforms such as Oculus Rift, HTC Vive, or Medical Holodeck's Dissection Master XR create lifelike 3D anatomical models from CT and MRI scans. AI algorithms enhance the accuracy and realism of tissues, while embedded chatbots use natural language processing to answer students' questions in real-time. For example, a student can ask: "What does the hepatic portal vein do in drug metabolism?" The chatbot will highlight the vein in VR and explain its role in first-pass metabolism.

- **Pharmacy connection:**These simulations go beyond anatomy-they allow pharmacy students to trace drug pathways, visualize how beta-blockers act on the heart, or explore NSAID effects on the stomach lining. A 2024 study even found a 28% improvement in pharmacy students' ability to connect vascular anatomy to intravenous drug use when VR with AI was compared to textbook learning.
- **Pros:**

a) Enhances 3D spatial reasoning and integrates anatomy with pharmacology
b) Supports remote and hybrid learning, reducing ethical reliance on cadavers

- **Cons:**

a) Requires VR headsets and strong computing power
b) 10–15% of student's experience motion sickness during prolonged sessions

2. AI-Enhanced 3D Anatomical Models and Smart Dissection Tables

- **How it works:**Smart tables such as the Anatomage Table provide large, touch-sensitive displays of AI-generated anatomical models. Students can "virtually dissect" with gestures, while AI automatically labels structures and predicts common errors.
- **Pharmacy connection:**Drug-specific overlays link anatomy to pharmacology-for example, showing receptor sites for antipsychotics in the brain or drug clearance issues in patients with renal artery stenosis. At Drake University, these tools are used to connect pharmacokinetics with anatomy in real-time, letting students see how conditions like liver cirrhosis alter drug metabolism.
- **Pros:**

a) Reduces cadaver lab costs by 50–70%
b) Students report higher confidence applying anatomy to drug therapy

- **Cons:**

a) Smart tables are expensive ($70,000–$100,000)
b) Lack of tactile feedback compared to real dissection

3. Gamified AI Mobile Apps

- **How it works:**Mobile apps such as Complete Anatomy or Anatbuddy use gamification and adaptive AI. Students earn points by solving puzzles, identifying structures, or tracing drug pathways. AI adjusts difficulty based on performance, keeping learners motivated.
- **Pharmacy connection:**Apps allow students to visualize drug absorption (e.g., patches across skin layers) or understand antibiotic penetration into tissues. A 2023 pilot study showed a 30% improvement in retention when pharmacy students used gamified anatomy apps.
- **Pros:**

a) Affordable and accessible ($10–$50/year)
b) Highly engaging and ideal for self-paced learning

- **Cons:**

a) Less immersive than VR or smart tables
b) Dependent on reliable internet access

4. AI-Driven Personalized Assessment and Predictive Analytics

- **How it works:**AI assessment tools analyze students' learning patterns-such as time spent on tasks or frequent mistakes-and generate personalized quizzes or VR scenarios. For instance, a student struggling with injection site anatomy may be given extra insulin administration exercises.
- **Pharmacy connection:**This approach is invaluable for precision medicine education, helping students understand how anatomical differences influence drug dosing, metabolism, or side effects. At the University of Michigan, such AI tools are even used to predict pharmacy students' readiness for clinical rotations.
- **Pros:**

a) Boosts learning outcomes by 20–35%
b) Encourages targeted remediation and confidence

- **Cons:**

a) Raises data privacy concerns
b) Faculty require training to interpret AI analytics

Challenges and Considerations

- **Cost:** While VR and smart tables are expensive, cloud-based or mobile apps provide affordable entry points.
- **Faculty training:** Instructors need support to integrate AI effectively.
- **Student adaptation:** While most students welcome AI tools, some prefer traditional methods.
- **Ethical aspects**: Virtual dissection lacks the emotional and humanistic weight of cadaver labs—hence hybrid models are recommended.

Future Directions

- **Pharmacogenomics**: AI may soon simulate anatomy based on genetic profiles, showing how variations affect drug metabolism.
- **Augmented Reality (AR):** AR glasses could project drug pathways directly onto physical models or patients.
- **Haptics:** AI-powered gloves may soon simulate tissue resistance, bringing back the tactile feel of real dissections.
- **Global accessibility**: Open-source AI anatomy platforms could democratize pharmacy education worldwide.

Implementation Roadmap for Pharmacy Programs

- **Year 1:** Introduce mobile apps and cloud platforms (budget: $5,000–$10,000).
- **Year 2:** Add VR dissection modules in pharmacotherapy courses (budget: $20,000–$50,000).
- **Year 3:** Invest in a shared smart dissection table (budget: $70,000–$100,000).
- **Ongoing:** Provide faculty training, monitor outcomes, and expand into AR and pharmacogenomics as costs fall.

AI-driven technologies are reshaping anatomy education for pharmacy students by making learning interactive, clinically relevant, and accessible. From VR dissections to mobile gamified apps, these innovations enhance spatial understanding and bridge anatomy with pharmacology. While cost and training remain barriers, hybrid approach-combining traditional cadaveric experiences with AI-powered tools-offers the best of both worlds. For pharmacy programs, adopting these technologies step by step ensures students are prepared for the future of precision medicine and patient care. [9-11]

ADVANTAGES/IMPACT OF AI:

- Students studying with virtual dissection tools including the Anatomage table are more excited before and after laboratory sections and tend to have a greater degree of learning evidenced by significantly higher mean scores in anatomy assessments
- One of the most significant advantages of artificial intelligence in education is the ability to provide personalized learning experiences through data-driven insights. AI algorithms can analyze individual student data, including learning pace, strengths, and weaknesses, to tailor educational content and activities.
- The Integration of AI in anatomy teaching is diverting the teaching process into more interactive and adaptive methodologies. It enhances the learning experience by providing learners with advanced tools that include the subfields of AI, such as ML, DL, and natural language processing (NLP).
- Virtual dissection bypasses the ethical concerns and logistical difficulties of using human cadavers, making anatomical education more broadly available and ethically sound.
- The Integration of AI in recent decades has revolutionized this process, offering unprecedented capabilities to analyze complex clinical data. Tools such as machine learning algorithms and predictive systems have enhanced diagnostic precision, allowing for the identification of previously unnoticed patterns.
- This data-driven approach strengthens physicians' ability to correlate clinical symptoms and signs with specific pathological entities. However, the incorporation of AI presents challenges in medical education. Future physicians must combine learning traditional clinical foundations with mastering advanced technologies, all while maintaining an ethical and patient-centered approach
- Anatomy education has long served as a cornerstone of medical training, equipping healthcare professionals with the foundational knowledge necessary for clinical practice. However, the discipline has undergone significant transformations in response to evolving curricula, ethical considerations, and technological advancements.
- The virtual dissection Is operated by touch or styluses and provides life-size digital cadavers of male and female bodies, which can be rotated, magnified, labeled, and dissected with virtual scalpels.
- Students can isolate structures in three-dimensional form, dissect, reconstruct, magnify, and transect regions and structures to appreciate anatomical form and relationships. The ability to reconstruct and save dissections is a unique feature that provides visualization and personalization to students.
- Unlike cadaveric dissection, virtual dissection allows the same structure or region to be dissected repeatedly and customized to the students' specific needs. Structures are indestructible and safe from inexperienced dissection.
- Students can perform virtual dissections with greater time-efficiency and more seamless than cadaveric dissections.
- Students can explore detailed, high-resolution 3D models of anatomical structures that can be rotated, magnified, and dissected in real-time
- Tools allow for the removal of layers to isolate specific organs, enhancing comprehension of complex relationships and structures
- AI can analyze individual student performance, providing tailored feedback and recommendations to support their learning pace and needs

- Dissections can be customized and repeated, allowing for deeper mastery of challenging areas without damaging or depleting physical resources.
- Unlike cadaveric dissection, virtual dissections are indestructible, allowing for repeated practice without safety concerns or resource limitations.
- This risk-free environment also reduces the fear and discomfort some students may feel when first encountering human specimens etc.
- Moreover, AI's integration into anatomy education extends beyond visualizing anatomical structures in a digital environment. It offers dynamic, personalized learning experiences by analyzing individual student performance to deliver tailored feedback and recommendations, enabling a deeper, more adaptive understanding of the student and their mastery of anatomy. This transformative shift is driven by advancements in machine learning, enhanced graphics processing, and the availability of large, annotated datasets, which allow AI systems to generalize, reason, and learn from experience.
- Artificial intelligence can be used to teach anatomy in conjunction with cadavers or even as a stand-alone technology. It provides an opportunity to understand anatomy and demonstrates the specifics of various anatomical structures. To pique the curiosity of the students, different layers of the cadavers might be cut away or removed. By removing the associated components, students can also separate a single organ. Virtual dissectors can also be used for conducting practical's and discussion as well.

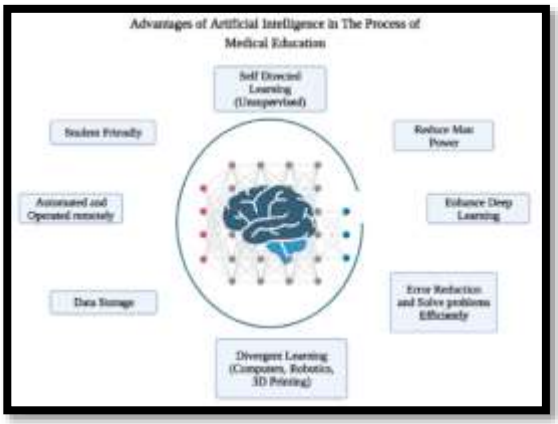

Fig.4: Advantages of AI in Medical Education
[Source: MDPI]

- Medical pupils can modify and learn about a detailed, interactive, 3D digital depiction of the human anatomy using a high-tech tool called a virtual dissection table, which incorporates modern imaging technology. Due to their many advantages over conventional approaches, virtual dissection tables have become an essential part of contemporary medical education. In contrast to conventional dissection techniques, it has a number of advantages.
- The key benefit Is that it does away with the necessity for actual cadavers, which may be expensive, challenging to obtain, and dangerous for students' health.
- Students can use a computer and specialized software to alter and dissect virtual 3D representations of the human body.
- The ability for these technologies to operate at levels and pace thatare not ordinarily feasible by human instructors is one of the alluring prospects and advantages of artificial intelligence-infused anatomical education.

- This technology gives students a learning experience that closely resembles the actual dissection procedure while being realistic, engaging, and dynamic. Students have the option to see various bodily layers, spin and focus in on particular components, and even do simulated dissections.
- It encourages students to learn anatomy at their own rate, go over difficult ideas several times, and practice skills without worrying about harming the specimen being studied.
- The Artificial Intelligence provides virtual anatomy for both men and women, with accurate representations of the muscles, bones, nerves, and internal organs.
- Students can utilize the labelled structures and remarks for self-evaluation or self-review.[12,13]

DISADVANTAGES/ETHICAL ISSUES OF AI:

- With no manipulation of human tissues, virtual dissection prevents students from appreciating the feel and texture of specific anatomic organs, such as muscles, tendons, bones, heart, and lungs, which limits the tactile form of learning.
- Smooth and effective integration of technology into the classroom can be challenging. Faculty must be adequately trained related to using the technology and incorporating technology into pedagogy, and if faculty are not provided this training, they will not be capable of using it to its full potential.
- With the ongoing advancement and upgrades related virtual cadavers, this training needs to be ongoing.
- It's crucial that anatomy educators gain a critical knowledge of the larger implications of using artificial intelligence in addition to developing a clear understanding of what could be accomplished practically with AI technologies.
- Virtual dissection inhibits the tactile form of learning by preventing students from enjoying the feel and texture of specific organ of the human body, such as muscles, tendons, bones, hearts, and lungs, without interacting with human tissues.
- It can be difficult to Integrate technology into the classroom in an efficient and effective way.
- If faculty are not given this training, they will not be able to use the technology to its maximum potential. Faculty must receive proper training linked to using the technology and integrating it into teaching.
- The setting up of virtual dissector table and system is expensive so every institute cannot afford it.
- There is a risk that too prescriptive AI diagnostics would reduce students' ability to tolerate uncertainty, dulling their perception of the inherent nuances and uncertainties in human anatomy. The design of anatomy education curricula that challenges students to understand the human form as individually variable and the clinical implications of anatomy as complicated is a recent trend, thus it is crucial that AI-driven teaching tools reflect this model.
- Despite its benefits, AI integration raises concerns about over-reliance on technology, biases, and diminished human interaction in training. This review examines AI's transformative potential in anatomy education while emphasizing the need for balanced implementation and ethical oversight. A systematic review following PRISMA guidelines was conducted, utilizing PubMed and backward citation searches. The search yielded 56 studies, with 47 additional articles from citations, resulting in 61 included studies. These explored AI applications such as virtual dissection simulations, machine learning algorithms for adaptive feedback, and gamified learning experiences, which were shown to enhance engagement, personalize learning, and improve anatomical understanding.

Concerns about over-reliance on AI and the loss of human interaction were also raised. AI has the potential to enhance anatomy education, but careful consideration of ethical and practical implications is essential. A balanced approach combining traditional methods with AI and robust oversight is crucial for effective integration.

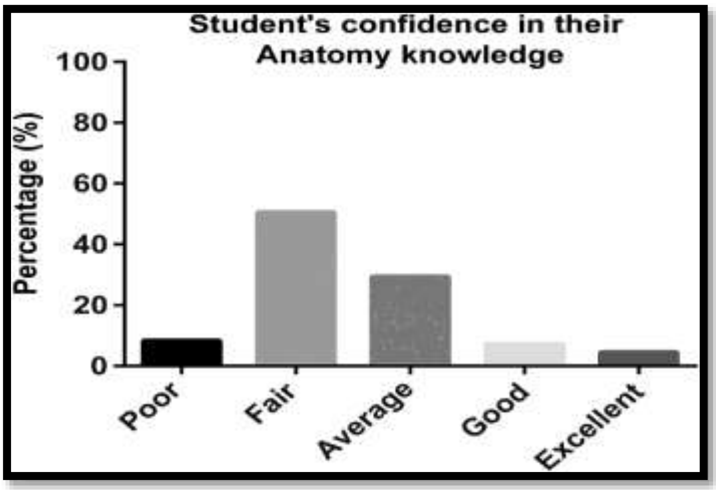

Fig.5: Graph Percentile vs confidence in Anatomy Knowledge

[Source: Sage Journal]

- A significant limitation of AI in anatomy education is its potential for inaccuracies and inconsistencies in generated content (AI hallucinations). While AI-powered tools such as ChatGPT and AnatomyGPT have demonstrated high accuracy rates in anatomy assessments studies have shown that AI models can still produce incorrect or misleading information, mainly when dealing with complex anatomical structures or nuanced medical concepts highlights that AI tools like ChatGPT struggle with tasks requiring high visual comprehension, which is crucial in anatomy education, where understanding spatial relationships between structures is essential.
- Before integrating AI-generated educational content into medical curricula, expert review, continuous refinement, and validation are necessary to ensure accuracy and reliability (Collins et al. 2024; Masters 2023). Educators should complement AI tools with traditional learning approaches to ensure accuracy, depth, and clinical applicability in anatomy education. Future advancements should focus on developing more reliable AI systems with enhanced visual learning capabilities and built-in quality control mechanisms (Bankar et al. 2024). A balanced approach to blending AI innovations with human oversight remains essential to preserving the integrity and effectiveness of anatomy education.
- Virtual dissection removes the essential element of touching and feeling the textures of actual human tissues, bones, muscles, and organs, which is crucial for developing a comprehensive understanding of anatomy.
- The absence of physical interaction with a cadaver can hinder the development of an emotional connection to the subject matter, a factor important in medical education
- The use of student data for training AI models raises significant concerns regarding privacy and security, which are critical in a healthcare education setting.
- AI systems trained on biased datasets can perpetuate and even amplify discriminatory biases, potentially influencing how anatomy is presented and understood

- Setting up the required hardware and software for virtual dissection platforms is expensive, making it inaccessible for some institutions.
- Requires reliable technology infrastructure, and there's a risk of hardware or software problems limiting practical application, especially in regions with limited resources
- There's a current scarcity of anatomically accurate and high-quality content specifically for AI and virtual reality platforms, which can restrict the effectiveness of the learning tools
- Students may become overly dependent on the AI, potentially leading to "automation bias" where they trust the machine's output over their own critical judgment and inspection
- Educators require proper training to effectively use AI technologies and integrate them into their teaching, which is a significant logistical hurdle
- Prescriptive AI diagnostics could dull students' ability to tolerate the natural uncertainties and nuances present in real human anatomy, which is vital for clinical pharmacy practice
- Lack of tactile and sensory experience from human tissues, the high cost and need for robust infrastructure, potential for over-reliance on technology, risk etc. [14,15]

FUTURE SCOPE:

Artificial Intelligence (AI) is set to play a transformative role in the future of anatomy and medical education. Anatomy has always been one of the most challenging subjects for students, largely because of its complexity and the vast amount of information it carries. In this context, AI can act as a powerful companion, simplifying difficult concepts and creating new ways of teaching, learning, and practicing medicine.

One promising area is the use of virtual and augmented reality powered by AI. Instead of merely reading about embryological changes or memorizing neural pathways, students could "step inside" a dynamic 3D model and watch these processes unfold. Complex regions, such as the basal ganglia or the pterygopalatine fossa, could be visualized in motion, making them easier to grasp than static textbook diagrams. This immersive approach would also make anatomy more engaging and memorable.

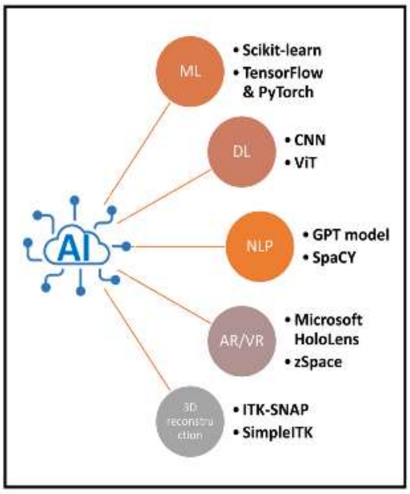

Fig.6: AI Tools used in Anatomy & Dissection

[Source: Research Gate]

AI also has the potential to organize and present vast pools of anatomical data in ways humans often struggle with. Imagine a smart tool that not only stores developmental sequences but also highlights key patterns, such as how tissues differentiate or how molecular signals regulate growth. Such systems could break down overwhelming topics into smaller, digestible parts or provide a clear overview when needed. For learners, this would mean moving from rote memorization to deeper understanding.

In addition, combining AI with 3D imaging and printing could bring anatomy to life in unprecedented ways. Realistic models of intricate structures, like the inner ear or the blood supply of the brain, could be printed for hands-on learning. These tools would complement traditional cadaveric dissection, especially in situations where access to human specimens is limited.

Assessment and self-learning are other areas where AI shows promise. Interactive platforms could generate problem-based scenarios, self-testing modules, and instant feedback, helping students track their progress and build confidence. At the same time, educators could benefit from AI's ability to analyze large sets of student data, ensuring fair evaluation and identifying areas where learners need extra support.

Looking further ahead, AI could reshape clinical training. Intelligent simulators and robotic patients could mimic medical conditions and respond to treatments, allowing students to practice diagnostic and problem-solving skills in a safe yet realistic environment. This would prepare future doctors to deal with emergencies more confidently before facing real-life situations.

Beyond education, AI will also influence healthcare practice. Its integration into telemedicine, wearable devices, and virtual platforms may expand healthcare access in underserved regions. Patients could also become active participants in their care through immersive tools that explain conditions and treatment options in simple, visual ways. Mental health may benefit too, through virtual platforms designed for counseling and therapy.

While the opportunities are vast, one important consideration remains: AI should support, not replace, the human essence of teaching and healing. Educators and clinicians will need training to interpret AI-based insights responsibly. When used thoughtfully, AI can act as a bridge-enhancing clarity, improving efficiency, and making anatomy education and healthcare delivery more effective and compassionate.[16-19]

CONCLUSION:

Artificial Intelligence is no longer just a futuristic concept-it is actively reshaping how pharmacy students learn and experience anatomy. By replacing the limitations of cadaver-based dissection with virtual, AI-powered platforms, pharmacy education gains a new dimension: accessible, repeatable, interactive, and tailored to every learner's needs. These tools do more than display body structures; they allow students to explore, visualize, and interact with anatomy in ways that traditional methods cannot.

For pharmacy students, this means building stronger foundations in human anatomy, which directly enhances their ability to understand drug action, interactions, and patient care. The blend of 3D visualization, virtual reality, and adaptive AI feedback creates a learning environment that is not only efficient but also exciting and engaging.

However, the journey is not without challenges-issues of affordability, technological infrastructure, and digital literacy must be addressed to ensure equal access for all learners. With the right strategies, collaborations, and investments, AI-driven anatomy learning has the potential to move from being an "add-on" to becoming an essential part of pharmacy education worldwide.

In essence, AI-driven virtual dissection is more than a technological upgrade -it is a transformative shift that bridges the gap between theory and practice, nurtures curiosity, and prepares the next generation of pharmacists to thrive in a digitally evolving healthcare landscape.

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