



Three-Dimensional Digital Reconstruction versus Cadaveric Dissection in Anatomy Education: A Narrative Review

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Abstract

Cadaveric dissection had been the main teaching aid in anatomy, it gave students' knowledge of the morphology of the human body, variability and relationships of the tissues. Learning the complex anatomy of cross-sections can still be difficult to master, however, as conventional dissection can make it difficult to maintain a spatial sense of deep anatomical structures, two-dimensional learning materials will take a great deal of mental visualization. Three-dimensional (3D) digital reconstruction has given rise to interactive patient-specific anatomical models that allow one to explore complicated configurations from a variety of viewpoints without changing their spatial relations.

This narrative review included an analysis of the role that 3D digital reconstructions can play in educational settings related to surgical anatomy as well as their value to educational methods in comparison with cadaveric dissection. Existing reports indicate that interactive, 3D visualization helps to improve spatial cognition and interpretation of cross-sectional imaging, has a beneficial effect on extraneous

cognitive load and helps to maximize anatomical understanding, especially in anatomically challenging areas like the mediastinum, retroperitoneum and deep pelvis. The review also describes the process of image processing for the creation of individual 3D models obtained from Digital Imaging and Communications in Medicine (DICOM) databases, using a popular open-source software package called 3D Slicer, and presents recent advances in artificial intelligence-driven segmentation, extended reality technologies and 3D printing.

The creation and use of digital reconstructions have some great teaching benefits; however it cannot give the same tactile feel, handling of tissues and understanding of variation that would be experienced during cadaver dissection. Current findings thus suggest a mixed teaching model combining cadaveric dissection with interactive 3D visualization to enhance the acquisition of anatomical knowledge, spatial sense and equip future surgical professionals with the knowledge needed in current clinical practices.

Introduction

Understanding of 3-dimensional spatial relations inside the human frame is one of the most challenging problems created in the education of surgeons [1,25]. Gross anatomy education has been based on physical cadaver dissection for more than 100 years [2, 25-28]. As important and informative as dissection is, it has fundamental limitations in the teaching of cross-sectional anatomy and introduces students to the tactile nature of human tissue and the idea of individual variation in biological tissue. Complex internal anatomical spaces, such as the middle mediastinum, upper abdomen (retroperitoneal spaces), and infra pubical spaces (pelvis) are very small and closely related. There is an inherent tradeoff between destruction of the native spatial context and exposure of layers deeper in the anatomy of these areas that occur when they are physically sectioned, that is, a superficial layer must be reflected or cut away when reaching layers beneath in order to expose them [4,5].

There is, therefore, a difficulty with mentally comprehending these regions from traditional atlases, which are usually two-dimensional and unchanging illustrations. Thus, students have difficulty mentally imaging these regions from the flat, static images in conventional atlases [6]. For students, this gap is highlighted as they are expected to describe and interpret 2-D radiologic images (computed tomography [CT] or magnetic resonance imaging [MRI]) and mentally visualise these images into the dynamic surgical operative field [7,8].

In response to this need, medical informatics and anatomical education have shifted their focus to patient specific 3D digital reconstructions. Using open-source image processing tools like 3D Slicer, teachers can transform raw datasets of tomographic images (DICOM) into interactive, very precise 3D surface meshes [10]. The ability to manipulate or isolate, to make transparent, or virtually bisect the models in almost any anatomical plane allows for an infinite learning process without degradation of tissue [11,12]. This review examines quantitative and qualitative results of using 3D digital virtualization to integrate pre-surgical anatomy training. The purpose of this paper is to compare direct digital reconstruction with the conventional cadaver dissection and propose what impact digital morphology has in enhancing spatial awareness, retention of knowledge, and overall surgical preparedness of future surgical practitioners.

Review Methodology

This study aimed to examine the current evidence of using 3-dimensional (3D) digital reconstructions for the teaching and learning of surgical anatomy, and to make a comprehensive overview of their use. The current study was performed as a "narrative review" in the aim of providing a comprehensive overview of the present situation of this using 3D-DRs versus cadaveric dissection in the teaching and learning of surgical anatomy.

Four electronic databases (PubMed, Scopus, Web of Science and Google Scholar) were used in the literature search. The search started with articles from the period January 2015 – June 2025 and also included ELANDMARK articles before this date if required for historical context. Articles appearing in the English language were taken into account.

Medical Subject Descriptor (MeSH) terms and keywords were used with Boolean operators in the search strategy. The keywords were: "3D reconstruction", "three-dimensional reconstruction", "3D Slicer", "cadaveric dissection", "anatomy education", "surgical anatomy", "medical imaging", "virtual reality", "augmented reality", "cross-sectional anatomy", "surgical education", with both the AND and OR

operator applied to maximize the number of relevant studies retrieved. Selected articles were also selected and their reference lists manually screened for additional potentially eligible studies.

The selection of articles was done based on the inclusion criteria: peer-reviewed original research articles, systematic reviews, meta-analysis and official review articles that examined the use of 3D digital reconstruction, virtual anatomy technologies or cadaveric dissection in anatomy or surgical education. Studies focusing on learning outcomes including anatomical knowledge acquisition, spatial understanding, interpretation, radiological, cognitive load, surgical planning and satisfaction were prioritized.

Studies lacking full text in conference abstracts, editorials, letters to the editor, studies without educational relevance related to the anatomy of surgery, duplicates, and studies not published in English were excluded along with studies not related to anatomy education or surgical training.

Articles were initially screened for title/abstract relevance, and subsequently, full text was read for potentially relevant articles. Study objectives, educational technologies evaluated, study design, anatomical region, participant characteristics, principal findings, advantages and limitations reported. Due to the narrative format of this review and the difference between studies, a formal quantitative meta-analysis was not conducted. Similarly, a quantitative evaluation tool of any kind, which could be used to numerically assess the quality of published studies, did not exist, reflecting instead the efforts that were made to synthesize existing evidence in high quality, peer-reviewed publications, and important studies, to provide a balanced and comprehensive overview of existing evidence.

The literature retrieved was synthesized by themes, discussing various aspects, such as the neurocognitive mechanisms involved in spatial learning, technical aspects for 3D reconstruction, area-specific educational applications, comparison of digital reconstruction and cadaveric dissection, concerns in implementing 3D technologies in education, and the future technological improvements, including artificial intelligence, extended reality, and 3D printing.

The Neurocognitive Mechanics of Spatial Learning

Visuospatial processing (VS) is the cognitive capacity to analyze, rotate, manipulate, and transform 3D objects [1,18] and has been shown to be important for understanding human anatomy. In a traditional 2D cross-sectional representation from a CT scan or a textbook plate, the student has to do an intensive mental transposition and map this 2D representation to a 3D schema of the human body [15]. This cognitive overhead is significantly influenced by the Cognitive Load Theory (CLT) that has divided mental processing into three sub-constructs: intrinsic, extraneous and germane cognitive load [21,22].

.For instance, the retroperitoneum and deep pelvic neural plexi have a fixed **intrinsic cognitive load** because there is such a high concentration of nerves, blood vessels and fascial planes that they overlap [21]. But the method of teaching itself is a source of additional cognitive load [22]. So, real traditional instruction methods require a student to continuously switch between static 2D diagrams and descriptions and still see a more or less damaged specimen, which results in a very high extra cognitive load [6]. The mechanical, oriented capacity, and/or mental translation; free the learner's working memory, or cognitive act, leaving only a small room for the maintenance of important long-term structures, schemas and clinical mental models [22,23].

This spatial cognitive bottleneck can be directly overcome by interactive 3D digital reconstructions created directly from medical imaging using 3D Slicer [10,19]. The visuospatial buffer of the software helps a trainee to easily rotate a model, isolate certain vascular trees, or modify transparencies during simulation. This digital app created a huge cognitive friction reduction.

Based on empirical studies with eye-tracking metrics and response-latency test, there is evidence that interactions between 3D basic digital models and students' leads to significantly lesser response times to mental rotation in OSCE during objective structured clinical exams (OSCE) and higher in absolute terms structural identification accuracy [18,20]. Moreover, this cognitive advantage has been found to be most evident for "low-spatial-ability" learners, students who from an intrinsic point of view have difficulties related to mental visualization, and who are among the ones that are neglected by the traditional approach based on textbooks and cadaver. [1,18] 3D virtualization enables real-time visual feedback allowing spatial accuracy to become a reality for everyone, and for all trainees, to acquire the minimum spatial accuracy needed to enter safely into a surgical theater [19, 4]. Although the majority of studies have shown significant improvement in spatial perception or decrease in cognitive workload attributed to 3D visualisation, a few studies have found no significant difference in long term knowledge acquisition between 3D visualisation and cadaver-based instruction. The results of these findings indicate that integration of 3D technology in the learning of anatomy might be related to the baseline visuospatial abilities of the learners, the curriculum design and the approach used in the integration of 3D tools for teaching anatomy. To illustrate spatial learning concepts, technical details of patient specific spatial reconstruction are given and described as 3D digital reconstruction by technical workflow from the medical imaging dataset.

Technical Execution: The Image Processing Pipeline

The generation of anatomically accurate, patient-specific three-dimensional (3D) digital reconstructions requires a highly systematic image-processing pipeline. This methodology transitions from traditional tomographic clinical datasets to fully interactive surface models, as evaluated in landmark image computing frameworks [10]. This conversion shifts anatomy education from generic, idealized textbook configurations to high-fidelity, variable pathomorphological realities [5].

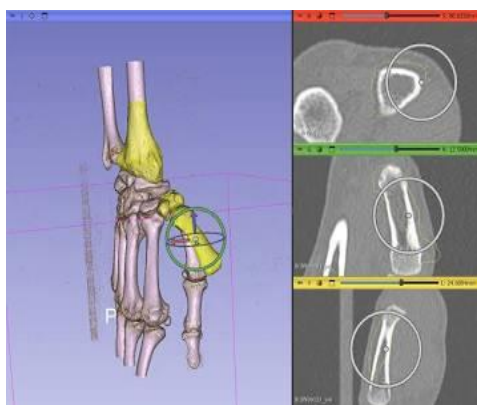


Figure 1: Multi-planar image segmentation and 3D surface reconstruction workflow in 3D Slicer. Adapted from Kitware Inc. [1]

The pipeline relies on a precise progression of data ingestion, algorithmic partitioning, and geometric optimization:

1. Data Ingestion and Volumetric Parsing

The pipeline starts by loading high-resolution Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) images, each of which is stored as an image in the DICOM standard Digital Imaging and Communications in Medicine (DICOM) format. The DICOM files include an extensive metadata header with the essential geometric information, such as the slice thickness, the pixel spacing matrix and the image orientation vectors [10,14]. High-resolution datasets (i.e. with sub-millimeter isotropic voxels) are ideal for surgical simulation (as well as undergraduate medical education). This resolution allows to avoid any geometric stepping artifacts in the clinical assessment phase that follows the analysis phase [13].

2. Multi-Planar Volumetric Segmentation

After importing the data in 2D and subsequently transferring it to an open-source software (3D Slicer), the material undergoes segmentation, which consists of breaking a digital image into a series of anatomically meaningful subsets of voxels [10]. The software synchronises the orthogonal planes as shown in Figure 1 in the multi-planar interface window:

Axial (top right)

Sagittal (middle right)

Coronal (bottom right)

This time, the mapping of selected boundaries is direct in the sense that they are brought into a common 3D workspace (left panel).

The voxels of the complex regions are separated based on the radiodensity range (in case of CT images in Hounsfield Units (HU) or signal intensity (for MRI images), respectively using automated or semi-automated thresholding techniques [14,15]. For example, the window level is locked to values above +200 HU for isolation of cortical bone structures while the window level is carefully selected with narrow window limits for contrast-enhanced vascular trees.

Users apply semi-automated region growing algorithms and manual contouring of boundaries [10] since automated thresholding is often followed by the addition of neighboring structures of similar radiodensity. In isolation, complex structural intersections are identified, like separating the osseous structures of the wrist or separating the pelvic vasculature from adjacent margins of the muscles (yellow in Figure 1).

3. Geometric Mesh Generation and Optimization

After being isolated and separated from the background, the mask(s) are restored as whole, geometric surface models with surface extraction algorithms, such as the marching cubes method [10]. The rule is that the broken-up voxel cloud is turned into a surface mesh of polygons, typically stored in Standard Tessellation Language (.stl) or Wavefront (.obj) file format [13,15].

However, the meshes that have been retrieved from the 3D model are often too high in detail to function within end-user's computer set-ups, and therefore must be processed to make them contained within a computer's processing capabilities. The extracted meshes may be too large for the end-user's computer to process, and can consist of many rough polygons. For this, the raw surface mesh is geometrically

optimized through decimation techniques that strip polygons from this surface in an aggressive manner, preserving only critical margins. At the same time, Laplacian smoothing technique is used to eliminate high-frequency noise and slice-spacing artifacts (staircasing effects).

4.Virtual Deployment and Virtual Interaction.

The resulting optimized 3D polygonal meshes are then given a colour map of the tissues to give a realistic appearance and an opacity matrix layer to give the appropriate material properties [13]. In the standard desktop environments, the assets can be modified in the standard interfaces, uploaded to web-based, cross-platform application servers, or displayed directly to a user via immersive virtual reality (VR) toolkit extensions such as SlicerVR [16,17]. The workflow allows students to interactively dissect without damaging tissues, adjust the tissues' transparency, and observe the tissue's interior anatomy while moving along custom cut planes [11,19]. After producing these anatomically accurate digital models, the educational potential depends on the region of the anatomy being examined. Their use in clinically relevant surgical areas are explored in the next sections.

Region-Specific Pedagogical Analysis

There is considerable variation in the educational effectiveness of 3D digital reconstructions by region. The role of these models becomes of great value in very deep, densely packed anatomical areas where conventional layered dissection is required to compromise the bulk, in order to visualize the deep pathology [4,5]. Overall these findings suggest that 3D reconstruction has educational value, but the majority of published research are conducted in a single institution settings, have small sample size and mix of educational interventions, making the direct comparison of educational studies difficult.

1. The Mediastinum

The mediastinum is a very dense overlapping region of respiration, blood flow and nervous tissue between the pleura, making it a very complex structure [15]. However, during standard physical dissection the anatomy of the middle and posterior mediastinum (e.g., the aortic arch, the precise branching pattern of the thoracic duct, and the tracheobronchial tree) will necessitate permanent destruction of the anterior thoracic cage and the lungs will be retracted [5].

Interactive 3D digital reconstructions are not bound by this physical limitation. The superior vena cava (SVC) and the ascending aorta (AA) can be dynamically moved to change their transparency, providing a visualization of the exact path of the recurrent laryngeal nerve or its spatial edges in the pulmonary window [13]. This capacity of awareness of overlapping structure but maintaining spatial orientation solves an important problem of traditional cadaver laboratories [11].

2. Upper abdomen and Retroperitoneum

Both the upper abdomen and the retroperitoneal space are difficult areas for future surgeons – the vessels are highly variable in both anatomical structure and space presence [1]. The number and arrangement of the branches of the celiac trunk and the hepatic artery networks, as well as the patterns of association among the renal vessels has shown to differ widely among individuals [2,14].

They have been constrained by traditional gross anatomy laboratories; one table of a dissection laboratory will teach one dissection cadaver back phenotype to the students [6]. In the case of a specimen that has a textbook appearance, students do not realize the important surgical differences that they would face in clinical practice [2].

With the help of 3D digital reconstruction, which was generated based on different patient CT angiograms, institutions can also quickly deploy large-scale digital libraries and present dozens of different vascular variations very quickly [14]. The hepatic portal system can be isolated, accessory renal arteries identified, and the retroperitoneum can be explored along any cross-sectional plane, in preparation for surgical planning workflows [10].

3. The deep pelvis and perineum

Deepness of the pelvis and the perineal spaces are among one of the most challenging ones for achieving proficiency during pre-clinical surgical training era [7,20]. Characterized by highly compact and curved osteomuscular components, facially lined areas, and deep autonomic nerve plexuses which play an important role in colorectal and urological surgeries [20].

The rigid boundaries of the bony pelvis limit the mechanical dissection of the pelvis. In order to expose the pelvic floor muscles, the internal iliac artery branches or the fascial planes of the rectum must be divided (mid-sagittally) [7]. This change in structure results in the loss of the unbroken round conformation of the pelvis.

More in contrast, when this context of circular structure is to be preserved, interactive 3D digital visualizations are of great assistance [20]. Continuous pelvic ring can be viewed from an endopelvic perspective as well as adjust the position of the pelvic ring in virtual multi-planar planes and perform virtual tracing of the internal pudendal structures under the pelvic diaphragm, without disrupting the structure [7,20].

4. Quantitative Evaluation Matrix

In order to summarize the large number of operational differences cited in modern medical publications, an analysis of pedagogic, physical, and economic parameters of both methods is given in the table below.

Table 1: Detailed Operational Matrix of Dissection vs. 3D Digital Virtualization

Evaluation Parameter	Traditional Cadaveric Dissection	Patient-Specific 3D Reconstructions (e.g., 3D Slicer)
Tactile and Haptic Reality	High; provides irreplaceable haptic feedback, realistic tissue compliance, and tactile boundaries [2,24].	Absent; currently limited to visual and multi-perspective spatial interactions [3].
Structural Integrity	Destructive; progressive layers must be permanently removed or altered to examine deep structures [4,5].	Conservative; structures can be hidden, isolated, or rendered translucent infinitely [10,13].
Anatomical and Pathological Scope	Constrained; limited to a single, typically non-pathological phenotype per specimen block [6].	Unlimited; allows rapid deployment of extensive databases showing complex anomalies and rare tumor margins [14].
Cognitive Resource Allocation	High extraneous load; students expend excessive mental energy managing physical orientation and tissue state [21,22].	Low extraneous load; rapid manipulation and orientation accelerate internal schema generation [19,23].
Repeatability and Accessibility	Finite; specimens degrade over time, and learning is bound to scheduled wet-lab hours [6,12].	Infinite digital files are non-degradable and accessible across multiple personal devices [11,16].
Economic and Institutional Burden	High; demands specialized ventilation, strict biohazard compliance, chemical preservation, and constant specimen sourcing [2,6].	Low marginal cost; relies on open-source platforms and standard institutional computer hardware [1,10].

However, there are also some significant pedagogical, technical and practical aspects to be taken into account before introducing 3D digital reconstruction in significant scale, given the many educational benefits proved by digital 3D reconstruction.

Critical Evaluation: Structural Limitations and Implementation Challenges

Patient specific 3D digital reconstructions are unprecedented in terms of spatial adaptability, but they do also cause important pedagogical shortcomings thanks to their absolute dissociation from a physical framework. One of the drawbacks is the complete absence of traditional tactile (haptic) feedback [3]. While traditional cadaveric dissection exposes students to real tissue compliance, differing resistance of tissue structures and changes in mechanical density the complete absence of this haptic feedback is a distinct limitation of digital environments [2,24].

In a digital environment, the structural resistance parts of things, such as in blunting miniscule scalpel edges, or the different elasticity properties of a collapsed venous channel in comparison to a thick arterial wall, are completely removed [3]. This "haptic deficit" may cause loss of understanding of the surgical anatomy and end up with an incomplete training experience for the student where the sense of touch will not be what they were prepared for in the surgical situation they encounter in the operating room [6,24]. Besides, digital models can be subject to structural hyper-idealization [11]. In open-source software pipelines, segmentation, triangle reduction and surface smoothing will filter out noise and pixelation at high frequencies [10,15]. But this optimization might also wash out fine biological irregularities, "fascial adhesions" and different consistencies of fatty tissue.

The student who has been drilled to the correct terminology, procedures, and logic of clear, colour-coded and transparent digital models could have a massive cognitive jump to the chaos, confusion and red-blooded environments of an operating room [6]. In an operative field, it is difficult to define the anatomic barriers, and the normal morphology may not be apparent due to disease or fat [2,14].

Finally, digitally implementing these tools poses considerable infrastructural challenges [12]. While open source, the cost of time and manpower to integrate software such as 3D Slicer into an existing medical curriculum is significant [10]. Faculty need large amounts of technical training, as they need to be proficient in multi-planar segmentation workflows and basic anatomy [5].

The first one takes up significant processing capability because in order to draw complex meshes with lots of polygons on the screen in a smooth manner, very powerful graphic cards (GPUs) and high-resolution displays are necessary [1,16]. If the investment in teaching and technical equipment means infrastructure and teaching staff is not put in place, the digital virtualization tools may be seen as unnecessary asides, not as the main agents and may therefore remain unused during their teaching process.

The teaching value of three-dimensional digital reconstruction is supported by the current literature, but there is some variation in the quality of evidence. There are many published studies so far, but they are based in a single center and comprise only a small group of undergraduate medical students, and therefore are less generalizable. There is also significant lack of comparability between studies due to variations in study design, outcome measures, educational interventions, and assessment methods. In addition many investigations only measure short term gains in anatomical knowledge or spatial ability and not in long term knowledge retention, clinical competency or surgical performance. The methodological limitations may be a source of selection bias, performance bias and the strength of the evidence is limited. In light of this, 3D digital reconstruction should be considered as a successful supplement to the education of anatomy, but more multicenter randomized controlled trials (RCTs) with a standardized educational goal are necessary to describe how this method, among all possibilities, is effective in the long term and to determine the best way to calculate its incorporation into the anatomy curriculum.

Synthesis of Findings

The reviewed literature consistently shows the effectiveness of 3D digital reconstruction as a complement to modern anatomy lectures in terms of enhancing the visuospatial perception of, and understanding of, cross section anatomy [1,17,19]. Three-dimensional models with interactive control have the advantage of allowing learners to control anatomical components several times from different angles, which minimizes the extraneous cognitive load and allows mental models to be formed by different complex

anatomical relationships [10,18]. These benefits are especially relevant for the students who start with less than optimal visuospatial skills, as these students may have more trouble using conventional two-dimensional anatomical resources [1]. The utility and educational benefit of 3D digital reconstruction is most prominent in anatomically challenging locations, where maintaining the 3D relationships between anatomical structures is critical for anatomical understanding and surgical planning—the mediastinum, retroperitoneum and deep pelvis [7,13]. Patient-specific models created from computed tomography (CT) or magnetic resonance imaging (MRI) are useful to explore anatomical variations, vascular branching and intricate neurovascular structures, which may not be fully understood with cadaver dissection and standard anatomical atlases alone [10,14].

However, throughout all the evidence reviewed, it was found that digital reconstruction is a valuable educational tool that should be used alongside cadaveric dissection, but not in lieu of it [2,5]. Cadaver-based learning also offers the most tactile pleasant learning experiences, reveals nature's anatomic variation and allows students to practice practical dissection that is essential to surgical learning [2,3]. Moreover, digital models could be less than fully realistic as there are known limitations with image segmentation and surface smoothing that can result in the loss of subtle anatomical detail [10,15] that may be encountered in the real surgical environment.

While the majority of studies found positive education outcomes of 3D visualization technologies [19], there was great variability in study design, educational intervention, sample population, and results reported variables [5,12]. Therefore direct comparisons between studies are difficult, and there is still a limited amount of evidence on the longer-term retention of knowledge, and the transfer of knowledge to clinical competence [12]. The results indicate that the integration of students into the curriculum, teachers' skills in using these teaching tools and the learners' characteristics will affect the educational effectiveness of the 3D image [5,17].

Cadaver surgery and interactive 3-D digital reconstruction appear to be a viable teaching method [5]. This method integrates the exciting hands-on and feel properties of cadaver-based training, with the better form of visualization, access, repeatability and patient-specific knowledge that digital technologies provide [10,17]. Therefore, it is likely that this complementary approach will provide the best context for the teaching of modern anatomy and the practice of surgery with the aid of images [5,24].

Research Gaps

Although there is accumulating support for the use of 3-dimensional (3D) digital reconstruction (2DR) in anatomical teaching, there are several issues of knowledge. Numerous of these published studies have been conducted in single institutions with small numbers of participants, and results have not been generalizable to other educational settings and health systems [5,12]. Additionally, there is a wide range of study designs, educational interventions, outcome measures, and assessment tools, and results from one study across multiple comparisons are not always comparable due to lack of consistency across the literature [5,17].

Another limitation is the focus on short-term educational gains. The majority of studies so far focus on the short-term benefits in acquiring anatomical knowledge, spatial ability and satisfaction by the learner after experiencing 3D visualization technology [1,17,19]. Only a few studies have dealt with the retention

of knowledge over time, with clinical decision making, learning of surgical skills or transferring anatomical knowledge to real clinical practice [12,24]. Therefore, the duration of the educational effect derived from 3D digital reconstruction is not well understood.

Existing knowledge-base research on the best practice and methods for the integration of digital reconstruction into anatomy programs is also currently limited. Many studies have indicated that digital visualization is an effective complementary method to cadaver dissection, and that both methods are equally effective, but the best timing, length and balance of digital visualization and cadaver dissection in the undergraduate and postgraduate medical education has not been determined [2,5,12]. Likewise, the comparison of various digital platforms such as desktop applications, virtual reality, augmented reality, and mixed reality platforms in medical education is still limited, even for platforms with growing use in medical education [16,17].

Another gap is the geographical and institutional coverage in the literature. The majority of the available data comes from high-income nations that have adequate technological development whereas there is not yet a substantial body of knowledge in low- and middle-income countries [6]. Factors such as the availability of resources, faculty skills, and institutional expenditures can greatly affect the use and impact of 3D tools, but to date, these have been comparatively poorly studied [6,12].

Such studies, using large multicenter trials, standardized assessment of teaching outcomes, and long-term patient follow-up will better solidify the evidence base and provide guidelines for the best practice of 3D digital reconstruction in anatomy and surgical education, which will fill these gaps [5,12,17].

Future Trajectories: Next-Generation Integration

To overcome these constraints, the medical visualization industry is undergoing a paradigm shift and moving forward from the traditional desktop render with increasingly life-like 3D images. Three areas of anatomy education are set to converge in the immediate future: automated segmentation, immersive cross-reality platforms and biomimetic physical printing.

1. Artificial Intelligence and Automated Segmentation

In the modern segmentation pipeline, the boundaries in hundreds of successive tomographic slices were to be traced manually, which was very laborious [10]. To overcome this bottleneck, deep learning architectures, in particular those based on 3D Convolutional Neural Networks (CNNs), are used to train these imaging registries which are large and carefully curated. Major organs, complex vascular networks and musculoskeletal margins can be automatically segmented in this type of network with sub-millimeter precision and in seconds [14]. Medical institutions can base the computed tomography (CT) or magnetic resonance imaging (MRI) of a new patient and in a matter of seconds can generate a dynamic educational model, putting the content of the curriculum in the medical institute in an active clinical case in motion, instead of a passively held archive of information [13].

2. Extended Reality (XR) Integration

The need for visuospatial interaction with a virtual, augmented, and mixed reality environment inherently requires surgical education to directly tackle the visuospatial requirement of a translation from a flat 2D monitor to a 3D environment [4,17]. Students can use patient-specific tools such as SlicerVR to enter a life-size virtual patient's thoracic cavity or pelvic basin, for example [16].

Additionally, during dissection, a segmented vascular segmentation or tumor margin can be overlaid on a physical model or cadaver specimen using augmented reality (AR) headsets [17,25]. The aim is to present the digital model in a multi-perspective way, which positions the virtual model into a physical, geometric dimension, offering spatial flexibility but also some physical reality [4].

3. Biomimetic 3D Printing

In order to fill this haptic void, multi-material 3D bio-printing is now becoming more popular in medical centers and has been paired with digital segmentation [24]. The optimized surface meshes do not have to be kept on a monitor, instead they can be printed on specialized polymers which have physical properties close to the ones of human tissues [13].

Custom Organs with realistic tactile liver tissue, hard osseous landmarks and soft vascular walls can be printed for surgeons to use and can be patient specific. This procedure enables physicians in the future to practically perform special anal access, special cutting/suture skills and perform a surgical procedure on a true replica of a patient's body anatomy before going into the operating room [6,13].

Multicenter prospective studies with comparable measures of educational outcomes and different digital learning platforms (DLPs) should take precedence in research to be conducted in the future. The validated educational resources and evidence-based guidelines development to integrate digital technologies into anatomy curricula will require the collaboration of all these personnel: anatomists, surgeons, radiologists, engineers and computer scientists. Moreover, efforts should be made in terms of faculty development and digital infrastructure in educational institutions and policy makers to ensure equitable use of these new technologies.

Conclusion

A patient specific, interactive 3D visualization of complex anatomical structures, such as three-dimensional digital reconstruction, has emerged as an important innovation in surgical anatomy education. These models are shown to be superior to traditional two-dimensional learning materials both from the angle of spatial understanding and regarding the interpretation of a cross-sectional image as well as reducing unnecessary cognitive load. This is especially noticeable in the mediastinum, retroperitoneum and deep pelvis where maintaining spatial relationships is crucial to understanding the anatomy and surgical planning in an anatomically complex area.

Although all these benefits exist, digital visualization is by no means a substitute for cadaveric dissection. Tactile learning is still valuable in a cadaver-based setting because students gain appreciation for anatomical variations, feedback from tactile learning, skill development in making practical dissections, and inherit the fundamental skills of dissection still necessary for surgical training. Cadaveric dissection and 3D digital reconstruction are not mutually exclusive methods, but rather can supplement each other in their role in anatomical education. The use of both modalities as methods to integrate into contemporary

anatomy curricula is supported by the evidence reviewed in this article. A blended teaching approach using a cadaver demonstration and interactive 3-D digital images provides a "holistic" training solution that enhances spatial thinking skills, promotes radiological-anatomic correlation training and better prepares students for image-directed surgical procedures. In the coming years, the evolution of artificial-intelligence-driven segmentation and extended-reality technologies and the emergence of biomimetic 3-D printing will further complement teaching of anatomy with increasingly realistic, patient-specific learning environments. Given the ongoing advancements in digital visualization technology, their judicious use with cadaveric dissection holds the promise of significantly reshaping anatomy teaching and learning, creating a more thorough, clinically viable, and student-centric experience that serves the needs of tomorrow's healthcare practitioners and professionals.

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