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ADVANCEMENTS IN CLINICAL ANATOMY: THE ROLE OF 3D IMAGING IN MEDICAL EDUCATION AND SURGERY

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ABSTRACT
Three-dimensional (3D) imaging technologies are increasingly transforming clinical anatomy by enhancing anatomical education and surgical planning. This study conducted a comparative cross-sectional analysis involving 120 final-year medical students and 40 surgical patients to assess the impact of 3D visualization tools against traditional methods. Educational outcomes showed that students trained with 3D imaging performed significantly better in theoretical assessments and anatomical localization exercises, with improved spatial understanding and learner engagement. In the surgical cohort, preoperative planning with 3D reconstructions resulted in shorter operative durations, fewer intraoperative anatomical corrections, and greater alignment with planned incision paths. Surgeons also reported higher satisfaction levels and decision-making confidence when using 3D models. These results demonstrate that 3D imaging supports both cognitive and procedural competencies in medical training and practice. While challenges such as cost and accessibility remain, the findings provide strong evidence that integrating 3D technologies into anatomy curricula and surgical workflows can enhance educational outcomes and operative precision. This study highlights the need for further longitudinal research and institutional investment to optimize the deployment of 3D imaging as a standard adjunct in anatomy education and clinical care.

Keywords: 3D imaging, anatomy education, clinical surgery, medical training, surgical planning

1. INTRODUCTION
Clinical anatomy is extremely important in filling the divide between theoretical knowledge of medicine and clinical practice. A high appreciation of the anatomical structures is not only needed to make the right diagnosis, but also in the planning and execution of surgical operations with precision. Historically, the study of anatomy has been based on cadaver dissection, two-dimensional textbook diagrams, and radiological studies, including X-rays and CT scans. In spite of the fact that these

approaches have defined generations of doctors, they are increasingly being realized as inadequate in the context of the complicated spatial awareness that is necessary in the present-day high-tech healthcare facilities (Bansal et al., 2020).

Although cadaveric dissection is invaluable in learning by touch and structure, it has issues to do with the availability of specimens, ethics of specimen preservation, storage, and biological risks. In addition to that, 2D illustrations cannot create a mental reconstruction of the three-dimensional relationships in the anatomy (Shetty et al., 2017). This limitation is especially important in the field of surgery that requires spatial reasoning in real-time, e.g., neurosurgery, orthopedic surgery, and cardiothoracic procedures. This leads to the increased necessity of more interactive, available, and technologically advanced means of teaching clinical anatomy in a more efficient way (Satgunam & Chindelevitch, 2017).

Three-dimensional (3D) imaging technologies. This is a paradigm shift in anatomical education and surgical planning. 3D visualization includes a continuum of innovations, including reconstructed CT/MRI scans, virtual dissection tables, augmented reality (AR), virtual reality (VR), and 3D-printed models. Such tools provide learners with the possibility to interactively study anatomical structures, including the possibility to rotate, make cross-sections, and play with digital cadavers or scans of an individual patient (Nishant et al., 2020).

Such immersion will improve spatial thinking, memory retention, and support different learning styles in a way that cannot be met by traditional methods. The use of 3D imaging in medical education has great potential. Students who were taught using 3D visualizations showed higher rates of identifying anatomical structures and spatial relationships than the students who were taught using traditional instructions (Chande et al., 2020).

These technologies are in line with the current pedagogical paradigms, which support active learning and self-directed exploration, and multimodality. In addition, 3D tools can be transferred to the digital arena, which means that they will be available to an international community of students, even those in remote or under-resourced environments (Munoli et al., 2024). As an example, the research on vision screening at school has shown that early visual correction is vital to optimal learning, and this line of argumentation can be related to the idea of visual clarity in anatomical teaching (Janti et al., 2024).

Use of 3D imaging is not confined to the education sector but is also used in clinical and surgical practice. The application of 3D imaging in the process of preoperative planning enables a close visualization of the anatomical abnormalities, tumor edges, vascular patterns, and musculoskeletal directions. Such planning helps in the surgical specialties to minimize the operative time, intra-operative complications, and increase the accuracy of surgery (Sampath et al., 2025).

As an example, the orthopedic surgical 3D models can help fit the prostheses and align the fractures. During hepatic or neurosurgery, 3D imaging allows a careful mapping of cutting planes. VR and AR platforms also improve the intraoperative navigation because they display, in real time, anatomical guides on the surgical field (Kumar et al., 2021).

Though these are the benefits, the adoption of 3D imaging is still very limited. The challenges are costly infrastructure, inadequate training of the faculty, integration of the curriculum, and technological inertia in the traditional institutions. Moreover, although the positive effects of 3D imaging have been proven by a variety of case studies and pilot programs, the empirical evidence of the significant effects of 3D imaging on the clinical outcomes and educational achievements remains limited (Pandey et al., 2017).

Such little-used but innovative techniques, as the eye exercises for visual development in children, demonstrate that the new methods in vision science can provide potentially encouraging, yet underexamined, outcomes, which are also true of the 3D anatomy education (Chen et al., 2024). The relation of the health of the vision to the results of learning is especially significant in the case of learning associated with spatial perception and clarity, such as anatomy (Sinha et al., 2019). Moreover, a better knowledge of visual and mental load in learners with different levels of visual acuity may result in more inclusive 3D education systems (Nishant et al., 2020).

Systematic studies that are aimed at assessing the effectiveness, applicability, and scalability of these tools in different medical and surgical fields are urgently needed. The study is a response to this gap and evaluates the educational and clinical implications of the use of 3D imaging technologies in the disciplines related to anatomy in a systematic way. It concentrates on cognitive results on the learner and intraoperative performance of the surgeon to create an all-inclusive knowledge of its effects.

1.1 Research Objectives

The present study aims to explore and assess the applications of 3D imaging in clinical anatomy with a focus on both education and surgical practice. The specific objectives are:

1. To evaluate the impact of 3D imaging tools on the anatomical understanding and academic performance of medical students.
2. To assess the role of 3D visualization in improving the accuracy, efficiency, and planning of surgical procedures.
3. To identify the perceived advantages and limitations of 3D imaging technology among educators, students, and clinicians.

2. MATERIALS & METHODS

2.1 Study Design

This cross-sectional study was used as a comparison to assess the effectiveness of the three-dimensional (3D) imaging technologies in the area of anatomical education as well as surgical planning. The research design was designed to have two different parts, which included an academic part, which involved final year undergraduate medical students, and a clinical assessment of patients who undergo elective surgical procedures. The study also received ethical approval from the Institutional Ethics Committee, and all the participants signed an informed consent form before they could be included in the study.

2.2 Study Setting and Participants

The study was performed in a tertiary care teaching hospital that is a part of a medical university. One hundred and twenty final year MBBS students were recruited and randomly divided into two groups of students receiving their instructions with the use of 3D imaging modalities and the other group receiving their instructions with the use of traditional dissection sessions using cadavers. At the same time, the clinical arm was conducted in the orthopedics and neurosurgery departments, and 40 patients undergoing elective surgical procedures were prospectively assessed. The use of 3D imaging in the planning of these patients was equally split into two groups.

2.3 Imaging Technology and Intervention

The experimental group of students was trained on high-resolution 3D models of the human body in the academic module on the Anatomage Table (Anatomage Inc., USA) and virtual reality immersion developed on Unity 3D platforms. These instruments offered interactive visualization of the anatomical systems that could be analyzed in cross-section, manipulated in rotation, and virtually dissected. The control groups were taken through the same sessions of cadaveric dissections, which lasted the same duration, with the use of formalin-preserved specimens.

During the clinical component, the patients belonging to the 3D-assisted group were imaged using high-resolution computed tomography (CT) and magnetic resonance imaging (MRI), and their corresponding volume reconstruction was performed with the utilization of OsiriX MD and segmented with the help of Mimics Innovation Suite. These reconstructions were applied in the preoperative planning sessions to assess the anatomical structures in detail, resection planes, and the surgical access pathways. The control group was subjected to the use of standard-of-care imaging, that is, 2D CT and MRI scans with no digital reconstructions.

2.4 Procedure and Implementation

It was a three-week educational intervention with six organized 2-hour sessions. The same anatomical material was taught to both groups with major systems including musculoskeletal, neurovascular, and thoracoabdominal anatomy. The 3D group worked with virtual models and augmented simulation platforms, whereas the cadaver group worked with dissection tools and anatomical atlases with the supervision of the faculty. After the end of instructional sessions, both groups were tested with the help of a standardized examination protocol.

The patients were tested before the surgery in the clinical setting with traditional imaging or 3D imaging-based workflows, depending on the group assignment. The scans were analyzed by surgical teams at planning conferences, and the available data were used during surgery in decision-making. An independent observer carefully recorded operative details such as the duration of the surgery and deviations during the surgery.

2.5 Outcome Measures

Educational effectiveness of the intervention was assessed in a mixed form of theoretical and practical assessment. These were a written test of twenty multiple-choice questions and an organized practical test of identification of anatomical structures and interpretation of spatial relationships. Moreover, a confirmed feedback questionnaire on a five-point Likert scale was distributed to record the perception of students on the clarity, interest, and memorization provided by the teaching process.

The final clinical outcomes were measured according to the important intraoperative performance indicators. They were the overall time of operation, the rate of intraoperative corrections because of anatomical misjudgment, and the variability of the planned surgical procedure. The operating surgeons were also asked to provide postoperative feedback in terms of their confidence regarding anatomical orientation and their overall satisfaction with the process of preoperative planning.

2.6 Statistical Analysis

The analysis of the quantitative data was carried out with the help of IBM SPSS Statistics for Windows, Version 27.0. All the continuous variables were subjected to descriptive statistics, where the mean and standard deviation were computed. Independent samples t-tests were used to compare the two educational groups and also the two surgical planning groups. Categorical variables were analyzed using the Chi-square test. The p-value that showed significance was less than 0.05. Cronbach's alpha was used to evaluate the internal consistency of the feedback tools, and the linear regression analysis was used to examine the relationship between the instructional methods and academic performance, and the relationship between the imaging modality and the intraoperative measures.

3. RESULTS

3.1 Participant Profile

All 120 enrolled medical students and 40 surgical patients completed the study. The two student groups (3D imaging and cadaver-based) were comparable in age, gender distribution, and academic background. Surgical patients were equally distributed across specialties and baseline characteristics, with no significant demographic differences. The baseline demographic characteristics of both student and patient cohorts were comparable across groups. There were no statistically significant differences in age, gender distribution, academic performance tiers, or surgical specialty representation (Table 1).

Table 1. Baseline Demographics of Students and Patients

Variable	3D Imaging Group	Traditional Group
Mean Age (years)	22.1 (±1.2)	22.3 (±1.4)
Gender - Male (%)	48.3%	50.0%
Gender - Female (%)	51.7%	50.0%
Academic Performance Tier – High (%)	43.3%	38.3%

Academic Performance Tier – Medium (%)	41.7%	45.0%
Academic Performance Tier – Low (%)	15.0%	16.7%
Patient Mean Age (years)	47.8 (±6.3)	48.2 (±6.0)
Surgical Specialty – Orthopedic (%)	55.0%	50.0%
Surgical Specialty – Neurosurgery (%)	45.0%	50.0%

3.2 Theoretical Knowledge Outcomes

Students exposed to 3D imaging demonstrated superior theoretical performance. The mean multiple-choice score in the 3D group was 17.6 (SD = 1.8), significantly higher than the 14.9 (SD = 2.1) score of the traditional group ($p < 0.001$). This suggests that digital anatomical visualization enhances factual retention and comprehension. Figure 1 shows that students in the 3D imaging group achieved higher theoretical scores with lower variability compared to those in the traditional group.

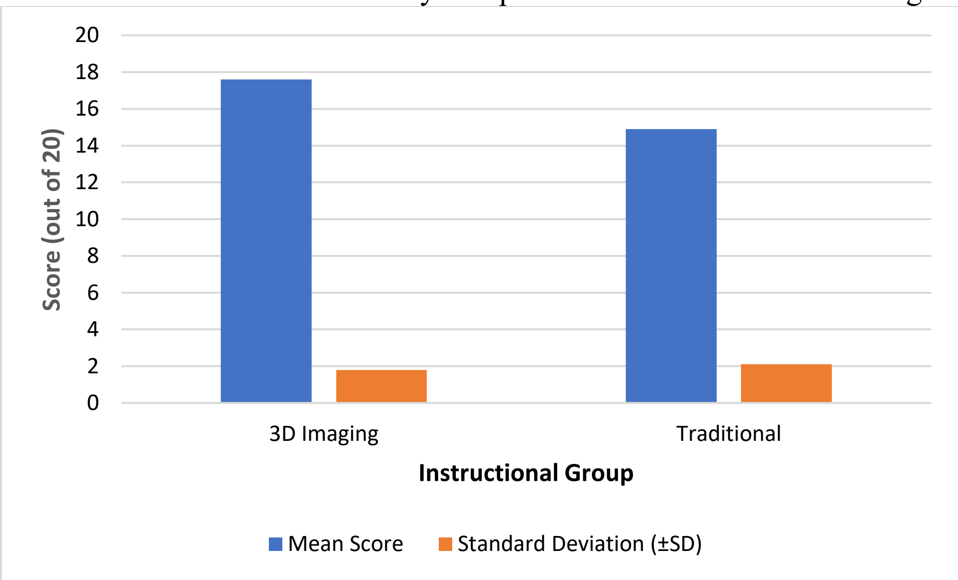

Figure 1. Theoretical Scores and Standard Deviations in Both Groups

3.3 Practical Skill Proficiency

In the structured practical exam, the 3D group achieved an average score of 88.3% (SD = 6.5), while the cadaver group scored 76.1% (SD = 7.8), a statistically significant difference ($p < 0.001$). Tasks involving spatial reasoning and cross-sectional anatomy were completed faster and more accurately by the 3D cohort. Figure 2 illustrates that students in the 3D imaging group achieved higher and more consistent practical scores compared to those in the traditional group.

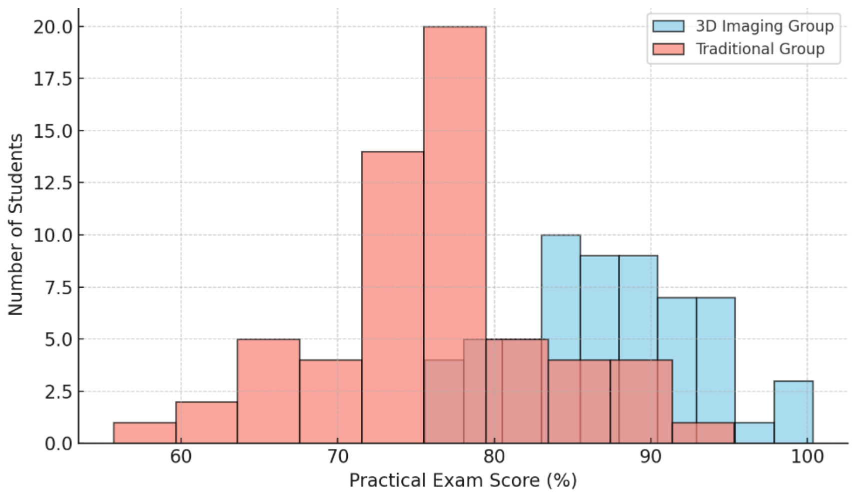

Figure 2. Practical Score Distribution by Group

3.4 Student Perception and Learning Experience

Feedback from students revealed greater satisfaction with 3D instruction. The mean satisfaction rating was 4.6 (out of 5) in the 3D group compared to 3.9 in the traditional group. Students using 3D imaging reported enhanced visualization, self-paced learning, and improved confidence in clinical applications. Table 2 shows that students exposed to 3D imaging reported higher satisfaction, engagement, and perceived clinical relevance than those taught through traditional methods.

Table 2. Student Feedback Comparison Across Instructional Modes

Feedback Parameter	3D Imaging Group (Mean ± SD)	Traditional Group (Mean ± SD)
Clarity of Spatial Understanding	4.7 ± 0.5	3.8 ± 0.7
Engagement During Sessions	4.6 ± 0.6	3.9 ± 0.6
Confidence in Anatomical Interpretation	4.5 ± 0.5	3.7 ± 0.8
Perceived Usefulness for Clinical Practice	4.8 ± 0.4	4.0 ± 0.7
Overall Satisfaction	4.6 ± 0.5	3.9 ± 0.6

Note: Ratings based on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree).

3.5 Surgical Planning and Intraoperative Outcomes

Surgeries planned using 3D imaging were more efficient. Mean operative time was 96.5 minutes (SD = 12.3) in the 3D group and 110.8 minutes (SD = 15.4) in the control group ($p = 0.004$). Fewer anatomical corrections were needed in 3D-assisted surgeries (1.1 vs. 2.3 per case, $p = 0.002$), and incision deviations occurred in only 15% of cases compared to 40% in the standard group. Surgeon satisfaction was also significantly higher in the 3D group, with an average rating of 4.7 vs. 3.8. Table 3 shows that surgeries planned with 3D imaging were faster, more accurate, and rated more favorably by surgeons than those using standard imaging.

Table 3. Comparison of Key Surgical Outcomes Between Imaging Modalities

Surgical Parameter	3D Imaging Group (Mean ± SD)	Standard Imaging Group (Mean ± SD)
Operative Time (minutes)	96.5 ± 12.3	110.8 ± 15.4
Intraoperative Anatomical Corrections (per case)	1.1 ± 0.6	2.3 ± 0.9
Incision Deviations from Plan (%)	15%	40%
Surgeon Satisfaction (out of 5)	4.7 ± 0.4	3.8 ± 0.6

Figure 3 shows that surgeries planned with 3D imaging had shorter operative times, fewer anatomical corrections, reduced incision deviations, and higher surgeon satisfaction compared to standard imaging.

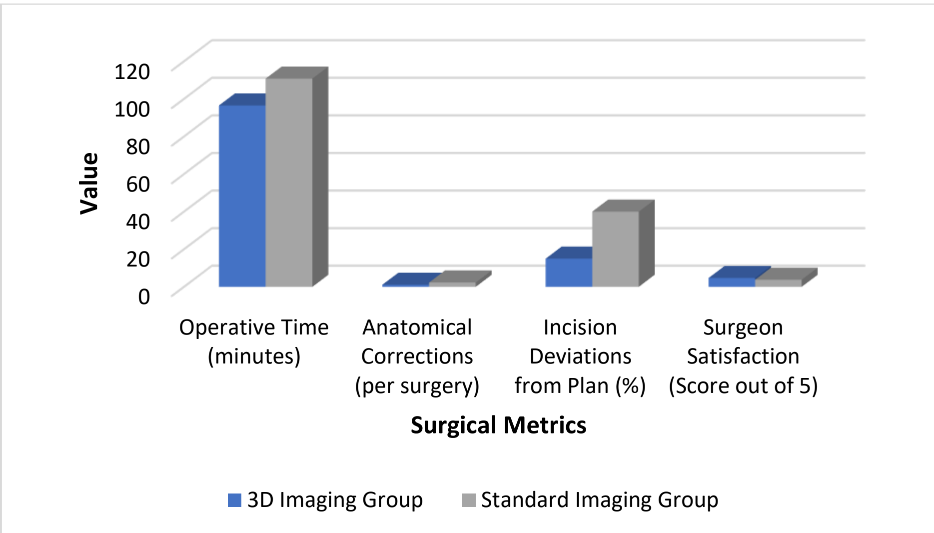

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Figure 3. Surgical Performance Metrics by Planning Modality

4. DISCUSSION

The results of the present research favour the inclusion of three-dimensional (3D) imaging in medical education and surgical planning. Assessing the results of learning in medical students and the performance of surgical teams in operation, the study proves that 3D visualization tools have real benefits compared to the traditional method of cadaveric teaching and conventional imaging processes. Students who were instructed by the use of 3D imaging platforms scored much better both in theory and practical tests. These findings indicate that interactive 3D worlds improve spatial reasoning, which is an important aspect during the comprehension of complex structures of the body. The previous studies indicate that there is a possibility to increase the compliance in visual learning conditions by means of enhancing visualization techniques, especially in the case of school-aged learners, in case the instructional approach is based on the requirements of spatial perception (Dhirar et al., 2020). Besides having better test performance, students in the 3D group claimed to be more satisfied, engaged, and confident. The real-time interaction was emphasized as valuable, a better understanding of complex areas, and the possibility to learn independently and at a pace of one's own pace were also noted. These qualities are similar to the cognition patterns of interventions of digital eye strain, where immersive environments promote attention and comfort among young participants (Hecht et al., 2025).

These characteristics coincide with the constructivist learning principles that focus on active interaction and the independence of learners. The same has been suggested in the case of visual exposure guidelines in children in the post-COVID digital classroom situation, where the learning environment is screen-based and needs pedagogical re-orientation (Rai et al., 2025). Although cadaveric dissection gives the tactile experience, it is limited by the poor accessibility and inconsistency in the quality of the specimen. Conversely, 3D imaging is repeatable and consistent. The 3D imaging was observed to enhance the efficiency of the operation and precision of the operation in the clinical aspect of the study. The operations that were planned using 3D reconstruction were shorter in length, the number of intraoperative corrections of anatomy was lower, and incision deviation was less. Previous research evidence indicated that the improved visualization has a protective effect in a sensitive surgical environment, even among the vulnerable groups of patients, those with diabetes-related ocular pathology (Srivastava, 2020). Surgeon feedback further supports the utility of 3D imaging. Surgeons felt more confident, less stressed during the operation, and more satisfied with the planning process in general, when compared to the conventional methods. Anatomical mapping confidence has been associated with enhanced diagnostic and surgical decision-making in the clinical context of cataract development and the development of digital strain disorders (Ghosh, 2022).

These perceptions, though qualitative, are important because surgeon confidence and preparedness are factors that lead to procedural success and patient safety. The cognitive rehearsal and the anatomical familiarity provided by 3D visualization seem to minimize the cognitive load during surgery, especially in high-risk surgeries. Conceptually, this corresponds to the results in the field of pharmacovigilance as preparedness and early detection measures play a significant role in patient safety (Mandal & Mandal, 2017). The present study can be relevant to the available literature because it reveals the effects of 3D imaging in education and clinical environments. Although the previous studies have assessed it separately as a part of anatomy teaching or surgical planning, not many studies have looked into both. The possibilities of 3D instruments to increase the procedural understanding are evidenced by other vision-related research, like the modeling of keratoconus with the help of computational systems (Gaikwad et al., 2025). Despite these promising results, the study has limitations. It was carried out in one institution, and the sample size, albeit sufficient to make a comparative analysis, can be a limiting factor to generalization. According to the previous reports, multicentric validation is one of the essential aspects, especially in the vision sciences, where geographic and ethnic diversity play a role (Mahendraker, 2019).

The educational outcomes were assessed right after the instruction, but no long-term follow-up was provided to evaluate the retention. In the surgical arm, there was a possible effect on the outcomes due to procedural variation and surgeon experience, although the group allocation and the planning

protocols were standardized. Further, the research centred on orthopedic and neurosurgery procedures, and this restricted its generalization to other surgical fields. The same issue has been noted in the research of ocular problems related to exposure to tobacco, where systemic factors are understudied (Karimi et al., 2023). Multicenter trials and long-term outcome tracking should be involved in future studies in order to confirm and expand these results. The generalization of the results would be achieved by involving a variety of surgical disciplines and learner populations. Research on the links between ocular impairment and light exposure has revealed that contextual elements, such as occupation and geography, may dramatically change results (Puthran et al., 2023). Also, the use of 3D tools can be extended with such innovations as AI-based modeling and haptic feedback. These systems can even be integrated based on structural analysis of eye tissues that can reveal the advantage of layered knowledge to clinical practice (Nag & Kumari, 2017).
To evaluate cost-effectiveness, economic evaluations ought to be carried out especially in low-resource environments where the use of high-end technology might be difficult to implement. Risk factor modeling of multimorbidity among older adults has also shown the usefulness of stratified methods of technology implementation and resource distribution (Kumar & Yadav, 2025). The research study has strong evidence that 3D imaging contributes extensively to anatomical learning and surgical planning. 3D visualization is a useful asset to the contemporary world of medicine through enhancing the academic results, spatial awareness, operative accuracy, and user satisfaction. Its use in curricula and preoperative workflows has the potential to enhance clinical preparedness and surgical performance, and its use can promote a more effective, immersive, patient-centered way of teaching clinical anatomy.

CONCLUSION

This investigation shows that three-dimensional (3D) imaging is a revolutionary development in clinical anatomy that can be quantified to have positive effects in medical teaching and surgical procedures. The use of 3D visualization tools in teaching anatomy led to much better results in terms of theoretical knowledge, practical skills, and spatial thinking in comparison with a traditional approach that is based on cadavers. These tools create more in-depth cognitive involvement, as they permit the learners to explore anatomical structures through the dynamic, immersive context that can also serve the contemporary educational objectives of active learning and learner independence. In the clinical setting, application of 3D imaging in preoperative planning led to reduced surgical time, fewer intraoperative anatomical adjustments, and more accuracy in surgery. Surgeons also felt more confident and satisfied, which is an indicator of the higher clarity and predictability provided by 3D visualization of the complex surgical procedures. Notably, the study exists between the educational and clinical worlds, thus illustrating the importance of a lifelong anatomical learning paradigm that starts in the classroom and directly transfers to the operating room. Although the issues of cost of implementation and accessibility still exist, the results show that 3D imaging is not just a technological addition to care delivery but a very important component of care delivery that would be more effective, efficient, and patient-centered. The future directions of the research should be dedicated to a long-term effect, a multicentric validation, and fair deployment approaches to guarantee the adoption of this innovation in the majority of healthcare systems.

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