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Transformations and Innovations in Neurosurgical Education: A Global Review and Prospects for a Promising Future

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Abstract

Scientific Needs: Neurosurgery demands exceptional precision and expertise due to the complexity of treating brain, spinal cord, and peripheral nerve disorders. The high stakes of surgical errors underscore the need for advanced, risk-free training modalities to ensure technical proficiency and patient safety, particularly as procedural complexity and technological advancements accelerate.

Introduction: As one of medicine's most intricate specialties, neurosurgery requires innovative educational strategies to prepare surgeons for its challenges. Laboratory-based training has emerged as a critical tool, enabling skill development in a controlled environment. This review addresses the urgent need to evaluate and enhance training modalities to meet the evolving demands of neurosurgical practice.

Methods: We conducted a comprehensive literature review of neurosurgical training, focusing on simulation-based techniques, cadaveric dissection, and advanced imaging integration. Peer- reviewed studies were analyzed to assess the efficacy, benefits, and limitations of each method. Manuscripts published on the last 24 years were evaluated, Current trends and technological innovations were explored to identify their impact on surgical proficiency and patient outcomes.

Discussion: Simulation and cadaveric training offer distinct advantages: simulations provide safe, repeatable practice, while cadaveric dissection ensures anatomical fidelity. Advanced imaging and virtual reality enhance both, yet challenges such as cost, accessibility, and haptic realism persist. These modalities collectively improve technical skills, but their global adoption varies, highlighting disparities in training infrastructure. Emerging technologies promise to bridge these gaps, though evidence of competency transfer to the operating theater remains limited.

Conclusion: Laboratory-based training is indispensable for equipping neurosurgeons with the skills required for modern practice. Integrating traditional and innovative methods addresses current educational needs, but future efforts must prioritize cost-effective solutions and validated assessments to ensure widespread impact. This evolution in training will enhance surgical expertise, ultimately advancing patient safety and care quality worldwide. While new technologies offer valuable adjuncts, the ideal educational approach lies in balancing and integrating both traditional and modern techniques through cooperative models of instruction.

Keywords: Neurosurgical training, simulation, cadaveric dissection, virtual reality, augmented reality, laboratory education

Introduction

Neurosurgery stands as one of the most intricate and demanding medical disciplines, requiring extensive technical and theoretical training to address pathologies of the central and peripheral nervous systems. Laboratories have long served as vital platforms for neurosurgical education, offering a structured setting for skill development and refinement [1]. Recent technological advancements—such as virtual reality (VR), augmented reality (AR), and three-dimensional (3D) modeling—have revolutionized training paradigms, enhancing traditional methods like cadaveric dissection [2]. This article investigates the pivotal role of laboratory-based and hands-on training in shaping competent neurosurgeons, emphasizing simulation, cadaveric practice, and technological integration. The purpose of this article is to analyze the historical and contemporary transformations in neurosurgical education, emphasizing the integration of traditional cadaver-based and microsurgical dissection laboratories with new technological approaches such as simulation and virtual platforms. We highlight their contributions to skill acquisition, patient safety, and the adaptation of training to global needs.

Materials and Methods

The search was performed across four major scientific directories: PubMed, Scopus and Web of Science. A structured literature review was conducted to explore the evolution of neurosurgical education methods and strategies across the past decades.

Inclusion criteria

- Were published between 2000 and 2024.
- Addressed topics related to educational reform, teacher training, curriculum development, institutional transformation, or medical evolution in training.
- Were peer-reviewed and available in full-text format.

Exclusion criteria

- Articles unrelated to medical or neurosurgery ediucation or not explicitly addressing educational transformation.
- Opinion pieces, editorials, or articles lacking empirical data or analysis.

The keywords used included: neurosurgical training, microsurgical laboratory, education transformation, new technologies for medical education, and evolution in medical education.

Historical Context and Evolution

Since the third century BC, cadaveric dissection has been a foundational tool in medical education, particularly for teaching anatomy, and remains a preferred method despite the rise of digital platforms [3]. Traditionally, neurosurgical training adhered to the "see one, do one, teach one" apprenticeship model, where residents progressed from observation to supervised practice and mentorship. However, the increasing complexity of neurosurgical procedures and the high stakes of errors—potentially catastrophic for patients—have exposed the limitations of this approach [4-6]. Cadaveric dissection continues to be indispensable, enabling trainees to master neuroanatomy and refine technical skills, such as precise instrument handling and manipulation of delicate structures [7]. Fava et al. (2023) underscore the value of microsurgical dissection laboratories, noting their irreplaceable role in advanced training [5].

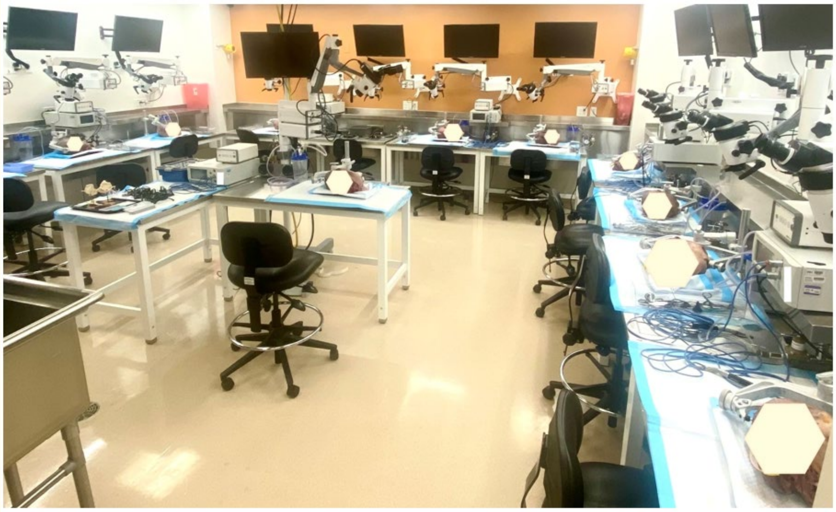

Figure 1: Fully prepared anatomical lab facilities for dissection and surgical training (photo from authors' personal inventory with permission).

Figure 2: Multi tech disponibilite is essential for anatomical studies and surgical training (photo from the authors' personal inventory with permission).

Figure 3: Multi tech disponibilite is essential for anatomical studies and surgical training (photo from the authors' personal inventory with permission).

In resource-limited settings, particularly in developing countries, access to such training has been constrained, a challenge exacerbated by the COVID-19 pandemic [4]. Kato et al. (2020) identified infrastructure deficits as a significant barrier to neurosurgical education in low- and middle-income countries, prompting global initiatives to democratize training through webinars, online platforms, and hands-on courses [4, 8]. Organizations like the World Federation of Neurosurgical Societies (WFNS) and the Latin American Federation of Neurosurgical Societies (FLANC) have spearheaded these efforts, fostering a culture of remote learning and practical workshops.

Technological milestones, including VR and AR simulators, have further transformed training by offering risk-free environments for practicing complex procedures [9, 10]. Stengel et al. (2022) report widespread acceptance of these tools among European trainees, reflecting their efficacy in skill enhancement [9]. Additionally, 3D printed models have shown promise. These models can accurately replicate human anatomy and specific neurosurgical structures, allowing for more immersive and realistic practice for residents [2, 11, 12]. González-López et al. (2024) highlight that the integration of VR technologies with 3D printing is becoming an innovative approach to surgical planning, allowing the prior practice of complex procedures before performing them on real patients. As well as the use of prepared placenta and 3D printing models for microsurgical and microvascular training has shown to be a possible option for a neurosurgical learning lab [13].

Impact of simulation on neurosurgical training laboratories

Surgical simulation is one of the main innovations in surgical training. Over the years, simulation methods have evolved, ranging from simple models to immersive VR and AR environments, capable of reproducing surgical conditions with great precision for training [14]. According to Kelly et al. (2021), the application of simulation modules, both in residency programs and in continuous training, has demonstrated a significant impact on the education of neurosurgeons. These modules provide a safe and controlled platform for technical skill development, offering residents the opportunity to make mistakes and learn from them without compromising patient safety [15].

Given recent technological advancements, specimen dissection can be captured with 3D acquisition techniques for educational purposes. we believe that VR represents a valuable adjunct to traditional cadaveric-based learning methods [16]. Neurosurgical simulation also makes it easier to learn complex techniques such as microsurgical dissection and manipulation of delicate structures such as blood vessels and nerves [17]. Petrone et al. (2022) highlight the usefulness of augmented reality-based neurosurgical simulators for practicing essential skills, such as microsurgery techniques and neuroendoscopy, with real-time feedback, which improves residents' learning curve [10]. This approach is particularly useful in developing countries, where resources for surgical training may be limited and access to cadavers for dissection is scarce [4].

While simulations based on AR, VR and 3D models have proven effective, there are challenges to overcome. One of the main obstacles is the cost of these technologies, which can be prohibitive for many training centers, especially in countries with fewer resources. As discussed by Takoutsing et al. (2023), in regions of Africa, simulation models without the use of cadavers have been successfully implemented, but the lack of funding and infrastructure still prevents their widespread adoption [11]. Another challenge is ensuring that the simulation provides a sufficiently realistic hands-on experience. Although AR and VR technologies are highly advanced, they cannot completely replicate the tactile sensation and physical responses encountered during real surgery [5, 18].

Laboratories that combine cadaveric dissection with AR and VR simulations have shown great effectiveness in neurosurgical training. These hybrid learning environments allow residents to combine theoretical knowledge with hands-on practice, offering a more comprehensive learning experience [19]. The development of new models that, in association with virtual and augmented reality, have been fundamental in expanding access to neurosurgical training, especially in times of pandemic with the restrictions that occurred, when physical access to laboratories was restricted [20].

In developing countries, neurosurgical training faces unique challenges, such as a lack of infrastructure and resources. However, global efforts to improve neurosurgery education have promoted the creation of training laboratories in various regions of the world. According to Kato et al. (2020), neurosurgery in developing countries has benefited significantly from the introduction of laboratories and simulations that replicate real surgical environments, allowing neurosurgeons to practice without the need for expensive equipment or human anatomical specimens [4]. (Fig4, Fig5) In rural and developing regions, simulation-based laboratories have reduced reliance on urban centers, empowering local practitioners [4, 21].

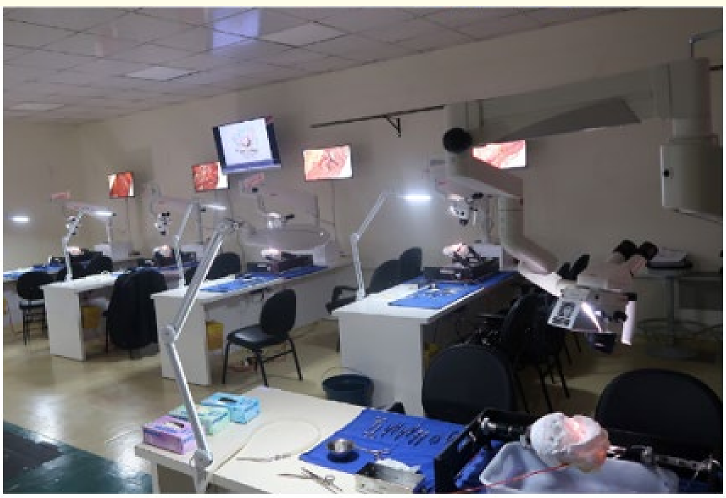

Figure 4: Neurosurgery lab prepared for a microanastomosis training (photo from the author's personal inventory with permission).

Figure 5: 3D printed skull model with craniotomy and placentas for microsurgical training (photo from author's personal inventory with permission).

Future Challenges and Directions of neurosurgical training

As technologies continue to evolve, the future of training neurosurgery seems promising. The integration of mixed reality, 3D models and immersive simulations promises to provide increasingly realistic and effective learning experiences for residents [22]. Furthermore, global collaboration and the creation of virtual teaching platforms, as discussed by Singh et al. (2021), have the potential to transform neurosurgical education, making it more accessible and inclusive, regardless of geographic location [8].

AR and VR-based simulation, combined with the use of 3D anatomical models and cadaver practice, will continue to play a central role in the training of highly qualified neurosurgeons [23]. Cadaveric simulation is a popular training tool among neurosurgical trainees and has been shown to have a positive effect on their training [24].

Despite the clear benefits, there are challenges to the widespread implementation of laboratory and hands-on training in neurosurgery. Resource limitations, such as the availability of cadaveric specimens, high costs of simulation technologies, and limited access to advanced training facilities, can hinder the integration of these methods into residency programs, particularly in low-resource settings [25]. Investment in cost-effective tools—such as AI-driven adaptive simulations and affordable 3D printing—could address these gaps, offering personalized training with real-time feedback [26]. Such innovations promise to refine technical and decision-making skills, aligning education with the demands of modern neurosurgery.

Conclusion

The role of laboratories in neurosurgical training is unquestionable. From traditional cadaveric dissection to advanced AR and VR simulations, these environments provide neurosurgeons in training with the tools necessary to develop critical skills and complex techniques. While there are challenges, especially related to cost and accessibility, the future of neurosurgical training will be shaped by the continued integration of these innovative technologies, enabling more neurosurgeons to gain the experience and confidence needed to address real-world clinical challenges.

As evidenced by the studies reviewed, the use of laboratories and simulations in neurosurgery teaching is a fundamental practice to ensure patient safety and the success of surgical procedures. The importance of training with cadavers remains one of the gold standard pillars for neurosurgery education. Despite technological advances the neurosurgeon needs to spend time at the microsurgical lab during the educational period to train and improve hand hability.

The modern neurosurgeon requires a comprehensive education that integrates both theoretical knowledge and practical skills. Laboratory-based training, including cadaveric dissection and simulation, provides the foundation for mastering neuroanatomy and microsurgical techniques. There is no more time to train on real patient's head, the hands-on experience mimickin the real operating theater is essential for developing the decision-making and technical skills required for successful surgical outcomes. The integration of artificial intelligence (AI) into neurosurgical education has introduced unprecedented opportunities for personalized, scalable, and performance-based learning. AI-driven platforms offer real-time feedback, procedural simulation, and adaptive curricula, enhancing technical precision and cognitive retention. However, exclusive reliance on virtual modalities may lead to significant educational deficiencies, particularly in cultivating the visuo-spatial reasoning and three-dimensional anatomical understanding that are indispensable to neurosurgical competence. Just cadaveric dissection laboratories can provide irreplaceable tactile and spatial experiences, fostering the neuroanatomical intuition that underpins safe and effective surgical practice.

Current evidence, though compelling, often lacks robust, objective validation of training efficacy due to inconsistent use of standardized assessment tools. While new technologies offer valuable adjuncts, the ideal educational approach seems to lie in balancing and integrating both traditional and modern techniques through cooperative models of instruction. Future research must prioritize validated metrics to link laboratory training with operative competency, solidifying its role in shaping the next generation of neurosurgeons.

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Volume 8 Issue 5 May 2025