Review

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History of medical education in neurosurgical training: moving from illustrations and cadaver dissections to virtual simulation

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Background: The main objective of the study is to trace the history and evolution of neurosurgical education, examining the parallels between pre-Hellenistic, Islamic Golden Age, and modern educational methods. The study explores how the pioneering teaching approaches can inspire continuous improvements in current neurosurgical education. Additionally, the importance of mentorship and clinical clerkships in advancing international neurosurgical education is highlighted.

Methods: This is a historical narrative review study, aiming to trace the evolution of neurosurgical education from antiquity to the present. The literature search was conducted between January 2020 and March 2024 using the databases PubMed, Scopus, JSTOR, and Google Scholar. Search terms included: "history of neurosurgical education," "cadaveric dissection in medical training," "Al-Zahrawi surgery," "anatomy teaching Renaissance," and "VR simulation in neurosurgery." Sources included primary historical texts (e.g., Edwin Smith Papyrus, Sushruta Samhita), secondary academic reviews, classical medical treatises, surgical textbooks, and biographies of key historical figures. Inclusion criteria focused on relevance to neurosurgical teaching, anatomical education, and educational methods, spanning both Western and non-Western civilizations.

Results: As this is a historical narrative review, the results are presented through qualitative data – primarily events, milestones, educational practices, and biographical contributions – rather than statistical or outcome-based data. The historical analysis reveals a continuous link between mentorship, clinical clerkships, and hands-on neuroanatomy training as key factors that have shaped modern neurosurgical education. Notable advancements include Osler's introduction of bedside rounds and clerkships, and Rhoton's modern method of dissection of cadaveric heads for neuroanatomy teaching.

Conclusions: The study concludes that historical insights into neurosurgical education methods provide valuable lessons for future improvements in teaching and mentoring in the field. The legacy of figures such as Sir William Osler and Dr. Albert Rhoton continues to inform and inspire modern neurosurgical education, particularly in clinical and anatomical learning practices.

Keywords: cadaveric dissection, clinical clerkships, historical evolution, medical education advancements, mentorship in medicine, neuroanatomy teaching, neurosurgical education, pre-hellenistic medicine, Sir William Osler, surgical education history

Introduction

The relevant physicians of ancient Mesopotamia, Egypt, India, Greece, and the Roman Empire, as well as the more recent figures who established the foundation of the modern neurosurgery, have been exhaustively documented, listing their unique contributions in the academic and clinical fields[1–3]. Ancient Mesopotamian medical texts, such as those from the library of Ashurbanipal, include early evidence of surgical practices. Egyptian medicine, illustrated in the Edwin Smith Papyrus, describes trauma management and cranial interventions. Indian surgical traditions, notably from the Sushruta Samhita, describe detailed procedures including trepanation and rigorous surgical training frameworks. The method of neurosurgical education has evolved over the years, going from medical illustrations, plastic, silicon, or ceramic sculpturing, to animal vivisections, cadaveric dissection, and surgical practicing, and finally leading to phantom models and 3D simulation with virtual or augmented reality (VR/AR). The several

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educational periods in neurosurgery have been consistently shaped by the evolving roles of the educators, pioneers who broke the skepticism and barriers of their eras and paved the way for neurosurgical progress thanks to their enlightened vision, passion, self-denial approach, and endurance. Still, several analogies can be observed across different neurosurgery educational eras, embodying the ever-recurring cycles of human history. A memorable example is set by the Renaissance's "Epitome," which allowed students to learn from anatomical illustrations as a handbook manual, and its modern counterpart "Handbook of Neurosurgery" by Mark S. Greenberg published in 1990, loyal white-coat companion of neurosurgical residents during rounds and surgical planning. Similarly, in the field of medical artistic illustrations for neurosurgical education, while Leonardo da Vinci was famous in the Renaissance for the anatomical precision and detailed description of his illustrations, many modern artists have signed some of the most beautiful and accurate surgical artistic drawings in the current time. In the current paper, we present an overview of the evolution of neurosurgical education with a focus on the most important educators and pioneers that led the path toward the current surgical and teaching strategies.

HIGHLIGHTS

- **Historical Continuum**: Neurosurgical education evolved from ancient Greek and Alexandrian anatomical explorations to modern-day digital simulations, reflecting a continuous interplay between mentorship, technical innovation, and hands-on practice.
- **Pioneering Figures**: Visionaries like Vesalius, Leonardo da Vinci, Harvey Cushing, and Albert Rhoton revolutionized neuroanatomical understanding through meticulous dissections, groundbreaking illustrations, and open sharing of educational resources.
- **Transformative Training Models**: The transition from traditional apprenticeships ("See One, Do One, Teach One") to structured surgical residency programs laid the groundwork for modern, comprehensive neurosurgical education methods.
- **Rise of Endoscopy**: Early attempts in endonasal surgery paved the way for today's advanced neuroendoscopic procedures, spotlighting the role of evolving technology in expanding neurosurgical capabilities.
- **Emerging Technologies**: Cadaveric dissection remains a cornerstone of neurosurgical training, but virtual reality (VR), augmented reality (AR), and mixed reality (MR) now provide immersive, high-fidelity simulations for both anatomical study and operative skill development.

Materials and methods

This study is a historical narrative review focused on tracing the evolution of neurosurgical education through multiple cultural and temporal lenses. A comprehensive literature search was performed from January 2020 to March 2024. The databases PubMed, Scopus, JSTOR, and Google Scholar were systematically consulted. Specific search terms used included: "history of neurosurgical education," "cadaveric dissection in medical training," "Al-Zahrawi surgery," "anatomy teaching Renaissance," and "VR simulation in neurosurgery." Inclusion criteria comprised primary historical sources (e.g., medical treatises, ancient surgical manuals), peer-reviewed historical reviews, biographies of prominent figures in medical education, and landmark textbooks. Sources representing both Western and non-Western medical traditions were considered essential to ensure comprehensive coverage and reduce cultural bias. No exclusion was made based on geographic origin. The focus was placed on key contributors, methodologies, pedagogical transitions, and technological influences in neurosurgical education across civilizations. The findings were synthesized into chronological and thematic narratives emphasizing the continuity and transformation of teaching strategies. Artificial intelligence was used solely for the purpose of generating an illustrative image within this project/content. It was not employed for writing text, performing analysis, or making any critical decisions. The generated image complies with the principles outlined in the TITAN Guidelines 2025[4], particularly in relation to transparency, accountability, and ethical AI use. Appropriate measures were taken to ensure that the content is neither misleading nor manipulative, in accordance with internal guidelines and applicable regulations.

Results and historical analysis

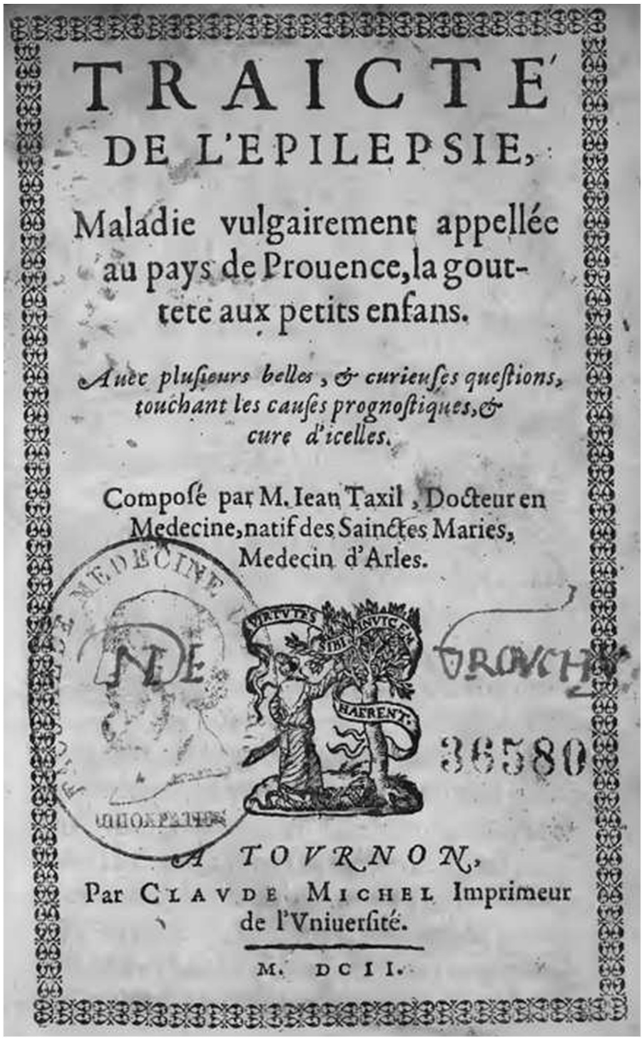
Ancient traces of neurosurgical history

Non-western foundations of neurosurgical education

In ancient Mesopotamia, cuneiform tablets such as those from Ashurbanipal's library reveal descriptions of cranial injuries and early surgical techniques. The Code of Hammurabi even included laws referencing the outcomes of neurosurgical procedures[5]. In ancient Egypt, the Edwin Smith Papyrus – dating to around 1600 B.C. – details case-based observations of skull fractures and traumatic brain injuries, emphasizing physical examination and rational assessment over spiritual explanations[6]. In ancient India, the Sushruta Samhita outlined over 300 surgical procedures, including cranial surgeries, and defined the roles of surgical students, tools, and anatomical understanding[7]. These non-Western traditions established empirical approaches to neurosurgical conditions long before the classical Greek period, underscoring the global roots of surgical education[8].

Pre-hellenistic age

The period from the pre-Socratic scientist–philosophers of 5th century B.C. to Hellenistic Alexandria in 3rd century B.C. was characterized by important achievements in science and medicine. Although the most famous treatise of the Hippocratic corpus is "*On the Sacred Disease,*" describing epilepsy (described later in detail in the XVII century by Jean Taxil – Fig. 1), the Hippocratic doctors could not practice cadaveric dissection mainly for religion issues, as the Greeks had profound respect for the dead body. Several historical references narrate that Aristotle performed many dissections and vivisections only on animals, observing that the brain in all animals was placed in the front portion of the head and was surrounded by two membranes, which he called the meninges. Epicurus, believed that death signified the termination of the individual in body and soul, thus leading to a better acceptance to practice human cadaveric dissection.



TRAICTÉ
DE L'EPILEPSIE,
Maladie vulgairement appellée au pays de Prouence, la gouttete aux petits enfans.
Auec plusieurs belles, & curieuses questions, touchant les causes prognostiques, & cure d'icelles.
Composé par M. Iean Taxil, Docteur en Medecine, natif des Sainctes Maries, Medecin d'Arles.
A TOVRNON,
Par Clavde Michel Imprimeur de l'Vniuersité.
M. DCII.

Figure 1. Authenticated reproduction of the original title page from Book I of "Traicté de l'Epilepsie" (1602), authored by Dr. Jean Taxil. This rare historical text represents one of the earliest comprehensive treatises dedicated entirely to epilepsy. Taxil's work reflects a pivotal shift in early modern medicine by challenging supernatural interpretations of neurological disorders and embracing a more observational, clinical approach grounded in Hippocratic tradition.

From hellenistic to medieval age

Anatomic dissections' dawn dates back several millennia when the incorporation of this practice has greatly contributed to the development of neuroanatomy and neuroscience. After the Hippocratic era, marked by religious convictions inhibiting corpses manipulation, Herophilus set the stage for human cadaveric dissections[9]. In fact, from Socrates onward, the body has been considered "of less concern" than the soul, and the most eminent post-Socratic philosophers shared this conception. Aristotle himself is believed to have performed many dissections and vivisections[10]. Under the liberal political and intellectual climate of Alexandria, Herophilus set the stage for unpaired neuroanatomic discoveries (e.g., the *torcular Herophili*[11]) and is credited to be the father of Neuroanatomy and the first dissector in Western medicine[12]. Notably, after his death, the human cadaveric dissection came temporarily to an end. Herophilus and Erasistratus, as the first dissectors in Western medicine, believed in the importance of anatomic knowledge in medicine. Unlike Aristotle, Herophilus believed that the brain was the seat of the soul, as demonstrated by the depth of his discoveries in the nervous system. As estimated by Celsus and Tertullian, Herophilus and Erasistratus vivisected more than 600 live prisoners in public and private settings to learn the characteristics of the organs. Such incredible events would have been regarded as the most progressive education, attracting students from all over the Mediterranean. The number of anatomic structures, especially in the brain, that Herophilus accurately discovered and named was unprecedented; these anatomic structures were described in his textbook "*On Anatomy*," which was unfortunately lost to posterity. Erasistratus' description of the ventricular system of the brain and other aspects of circulation was not surpassed until William Harvey's work centuries later.

Islamic golden age contributions

During the Islamic Golden Age (8th–13th century), physicians and scholars made groundbreaking advances in surgical education. Al-Zahrawi (Abulcasis), often considered the father of modern surgery, composed the medical encyclopedia *Al-Tasrif*, which included diagrams of surgical instruments and case-based approaches to neurosurgical issues[13,14]. He emphasized hands-on training and surgical ethics, influencing both Islamic and European medical education for centuries. Avicenna (Ibn Sina), through his *Canon of Medicine*, provided a systematic and pedagogical framework for medical education, including neuroanatomy and mental health[15,16]. These contributions preserved, expanded, and integrated knowledge from Greek, Roman, and Indian sources, creating a bridge between ancient and modern neurosurgical education.

The renaissance and modern era

Claudius Galenus, also known as Galen, was both a Greek physician and a philosopher, as he wrote in his treatise titled "*That the Best Physician Is Also a Philosopher*." The legacy of Galen's medical authority lasted well into the Renaissance, and even in some respects in the 19th century. He performed anatomic dissection on living and dead animals, mostly focusing on primates and swine because of their similarities to the human body. Galen is believed to have formulated his major contributions to anatomy, such as his descriptions of the circulatory system, while living in Alexandria, where he stayed until age 28 years (about 157 A.D.). Both Vesalius and Leonardo da Vinci overcame Galenism and drag anatomy toward a new era. Educated as Doctor of Medicine, Vesalius was later appointed as professor of surgery and anatomy. His "*De humani corporis fabrica libri septem*," published in 1543, is an artistic and scientific milestone, containing a comprehensive reexamination of the anatomy as intended by Galen, since Vesalius's dissections allowed him to discover several inaccuracies[17,18]. The "*Fabrica*" was published in the same period of its illustrative version, "*The Epitome*." Vesalius not only encouraged his students to participate in dissections, but he also supervised an "everyday guide" for help his students learning through dissections, the *Epitome*, personally supervising its production and publishing format[19–21].

In brief, not only did Vesalius create two of the most influential anatomic books ever, but he courageously challenged classical anatomical conceptions and was directly involved in dissemination and publication with the aim of mentoring new generations of anatomists. Leonardo's studies marked another step forward. Between 1504 and 1510, Leonardo da Vinci's desire for anatomic realism and experience led him to become "a rapacious consumer of cadavers." Leonardo began to record his experiences, detailing his anatomy. Not only he performed dissection to master anatomical detail for his paintings and sculptures, but his increasing curiosity brought him the will to explore the interior functioning of human body, looking for the relation between anatomy and function[1]. Artist, investigator, anatomist, divulgator, teacher: Leonardo was one of a kind, but its legacy runs beyond also his tremendous harmful of discoveries. The search for detail requires continuous and meticulous anatomical knowledge that must be learnt from reality, dissections, and practices. Leonardo valued vision above all other senses and trusted his formidable intuitions to postulate theories about the nervous system that have been demonstrated as true[22,23].

During the Renaissance, the new impulse to cadaveric studies fostered by Vesalius was remarkably carried on throughout the following centuries by eminent anatomists like Thomas Willis, Paul Broca, Carl Wernicke, and Giovanni Battista Morgagni, among others. In these years, Morgagni introduced autopsy as a mean to deeply understand clinical medicine[12,24], marking a shift in the concept of dissection usefulness, later continued by Harvey Cushing. Thomas Willis in his book, The Anatomy of the brain in 1681, unveiled elemental discoveries through anatomical dissections. Moreover, he had the "vision" to strive to build up a network, since lab work and medical teaching needed support from the community in term of institutional and financial support[25]. Thomas Willis understood that medical research and teaching required proper support, and, accordingly, he was a visionary in arranging institutional, financial, and logistic support for his organized research and teaching efforts from influential members of the Oxford community. Willis' team discovered the complex distribution of the cerebrovascular blood supply, supporting the notion that the brain itself was more important to bodily function and the psyche than was believed at the time. It was in Beam Hall that, according to Charles Sherrington, "Willis put the brain and nervous system on their modern footing." Although these giants of neuroanatomy are perhaps most hailed for their realistic illustrations, which have continued to enthrall us, their greatest contributions have been as teachers breaking through the pedagogic barriers of their days, using information from their own dissections and experiments, augmented by their detailed renderings, to convey the structure of the brain.

The legacy of the main fathers of neurosurgery

Leonardo da Vinci, Vesalius, and Thomas Willis probably represent the main pioneers in discovering and demonstrating brain anatomy. As refined artist-neuroanatomists, they set a brand-new way to approach human body structure, retrieving classical doctrine to make it source of knowledge and inspiration. Clearly, their real contribution was to have revolutionized the field of anatomy studies, comprising personal experimentation, viewing the brain in new ways, breaking free of orthodoxy, interacting with students while teaching, establishing new venues for instruction and exploration, closely working with illustrators to show their discoveries, promoting change, and thus leaving a legacy.

The path toward a blended view of anatomy and function at the dawn of holistic medicine was run by Harvey Cushing (1869–1939): "A physician is obligated to consider more than a diseased organ, more even than the whole man—he must view the man in his world." Following this belief, Cushing started his career as a general surgery fellow to Dr. William Halsted, before turning his interest toward neurological surgery, despite his Chief's skepticisms[1,26]. Encouraged by his true mentor and friend Dr. William Osler, Cushing established his career in the pursuit of excellence, in a continuous effort to learn from the scientists and surgeons of the time, especially during his travels abroad. Cushing himself was a talented artist, aside being a gifted surgeon and writer[27]. Famously, after each surgery, he took time to sketch technical notes about the surgical procedure just finished, accurately recording every detail, errors included. His sketches were considered an appendix to the operative report and a source of learning. Going through Cushing's notes drawings, wings a continuous evolution of his technique and ideas comes clear. Interestingly, he drew sketches in coronal, axial and sagittal planes, suggesting the importance of a tridimensional perspective and, thus, being ahead of time once again. His exceptional professional merits rooted and were nurtured by a mentor whose door was always open, whose example of trust toward pupils will inspire Cushing throughout his entire career. Osler encouraged Cushing to travel abroad to learn and was highly confident in his abilities as surgeon, which was crucial in building his success. Along with his enormous scientific and surgical entail, Cushing should be especially mentioned for his foresight in keep his mind wide open toward collaboration with other professionals (not only surgeons or physiologists, but also artists) and in the restless search for ameliorate his own work every day[28].

The XXI century was lightened up by the talent of Dr. Gazi Yarsagil, who modern neurosurgery owes the development of new instruments and the refinement of the technique. Yasargil represents the still alive testimony of neurosurgical historical progress. As he was used to declare: "*You are not just a brain but each of you is an outstanding structure*," he dedicated his whole body and soul to neurosurgery. His dedication and enormous talent resulted in unlocking surgical procedures never successfully attempted before. Yasargil revolutionized neurosurgery transposing microscopic lab dissections technique into the operating field. Since him, no one would have approached a brain tumor without the use of the microscope, assuring a tremendous improvement of surgical performance and patient life. He wrote books and inspired with his talent neurosurgeons of the coming decades. Briefly, his work is unanimously considered a watershed in the history of the field, welcoming the microscope era, and thus influencing whatever came next[29].

The XXI century has been marked also by Dr. Albert L. Rhoton Jr. (1932–2016), arguably the most famous neuroanatomist of the modern era. When invited by a psychology instructor to observe a brain operation performed on an animal in the laboratory, he was impressed when he witnessed how a tiny lesion improved the animal's behavior. He had literally fallen in love with the power of the brain with his neuroanatomical features and functional behavior so that it remained famous his definition of the brain as "…the crown jewel of creation and evolution." The passion for the brain and the awareness that only a deep and accurate microsurgical anatomy knowledge would provide an adequate competence to deal with the brain pathologies, induced him to dedicate his life in neuroanatomy researching and teaching. He was used to say: "We want perfect anatomical dissections, because we want perfect surgical operations." He was a keen researcher and a passionate educator since his youth. Furthermore, he developed a center for training neurosurgeons in microsurgical techniques, following his desire to build a program that would create roadmaps to make surgery more *"accurate, gentle and safe."* His efforts resulted in the establishment of a laboratory, the known "Rhoton's Lab," which opened in 1975 as a center for international teaching and studying the microsurgical anatomy of the brain. Rhoton contributed significantly to the education of neurosurgeons globally through: (1) dissection courses, (2) publications and lectures, and (3) the education of his 119 international research fellows. One of his goals was to teach and mentor as many neurosurgeons as possible. He was used as well to share his presentations, microsurgical anatomy pictures and text with the fellows and students and he was used to say: *"take all these materials, are yours, but promise me that you will use them to teach many other students from all over the world."* Among his many educational achievements are his numerous publications, including the textbook "RHOTON: Cranial Anatomy and Surgical Approaches" and the Rhoton Collection, along with dissection courses for training neurosurgeons and 3D lecture presentations (Table 3).

The one-shot era in the early twentieth century: *"See One, Do One, Teach One"*

Paralleling medical education, surgical education has also undergone significant changes over the centuries. Up until the 19th century, surgeons learned their craft through "apprenticeship"[1, 4]like the modern-day surgical residency, followed by a "journeys manship," like the modern-day surgical fellowship. The typical surgical apprenticeship in the mid-sixteenth century started at approximately age 12 and lasted 5 to 7 years[4].The young surgeon-to-be learned the craft through direct observation, then imitating the actions of a skilled mentor, both in the operating room and at bedside, providing history to the popular saying: "*See One, Do One, Teach One*." The masters taught with the same principle as the popular saying, they taught what they themselves had "seen" and "done." Without structure for what should be taught, guiding principles for training, or investigative inquiry for new methods or practices, medical education reached an unfortunate standstill by the late 19th century. The beginning of the 20th century marked the first major shift from "apprenticeship" training to surgery residency as we know it today. The surgical training model used to train residents in the United States for the past century is, in part, due to the principles laid forth by Dr. William S. Halsted[30]. This innovative training model was based on the triad of principals of surgical training: (1) the resident must have intense and right opportunities to take care of patients under the supervision of a surgeon teacher; (2) the resident must acquire all scientific basis of surgical disease; (3) the resident must improve skills in patient management and technical surgical details with increasing complexity and acquiring progressive independence. In this regard, Halsted delivered a landmark lecture in 1904 on surgeons' training and he stated that *"We need a system, and we shall surely have it, which will produce not only surgeon but also surgeons of the highest type, men who will stimulate the first youths of our country to study surgery and to devote their energies and their lives to raising the standard of surgical science"*[31]. Surgical knowledge has been disclosed on the wards and in the operating theater, with the contribution of lectures from experienced surgeons, grand rounds, conferences, journal clubs by residents. He established a school of surgery that would eventually disseminate the principles and attributes that he considered appropriate in the surgical world. His major objective was to also train teachers, not only competent surgeons.

Endoscopy era

The very first attempts to perform endonasal procedures date back to the Egyptians, known for removing the brain through the nose during mummifications of corpses. Later, this corridor has been abandoned for centuries, until the 1800s, when Phillip Bozzini invented the "*lichtleiter*" (light conductor)[32,33]. However, the lack of technological instruments capable to provide proper illumination made experience as the first endoscopic transnasal surgery by Hermann Schloffer (1906), almost anecdotic events. In the same years, Victor de L'Espinasse, a urologist, performed the first neuroendoscopic procedures to treat hydrocephalus with the aid of a cystoscope. This experience was then followed by Dr. Walter Dandy, who consistently refined tools and technique[34]. Thanks to his huge contribution to the field, Dandy is unanimously recognized as the father of neuroendoscopy. Extremely demanding toward his colleagues and students, Dandy was a gifted surgeon and Master to his pupils, always able to find time for their educational needs. Accordingly, his obituary read: *"…and when they (his students) got to know him well, they found beneath the hard exterior—(…)—a deep vein of tenderness"*[35].

Endoscopic surgery had a consistent revival in the '60s thanks to Gerard Guiot, who took advantage from the introduction of rod lenses by Hopkins. However, at that time, the microscopy era was about to revolutionize neurosurgery, leaving not much interest in endoscopy. Only in the mid '90s, the development of technical instruments tailored for the endonasal corridor, along with a renewed interest in related anatomic research led to the "rebirth" of endoscopy. The first clinical series by Carrau, Jho, Laws and Cappabianca marked the beginning of the endoscopic skull base surgery era[36–40]. As pertinent literature and academic interest increased, the caseload of the first endoscopic surgeons constituted the basement on which the neurosurgical community looked at this "new" technically demanding and innovative mini-invasive technique. Hands-on courses based on endonasal anatomic dissections were a natural response to the curiosity raised by the spreading of endoscopic endonasal surgery. Indeed, technological innovation in endoscopic equipment has been of paramount importance over time, allowing to visualize human body structures "through the looking glass"[41]. As a result, neuroendoscopy is currently performed mainly for intraventricular, skull base and spinal surgery, and as assisting visualization tool for several cranial surgeries to maximize close-up view also during microscopic procedures (Table 1).

Table 1

Evolution of neurosurgical education methods

Historical period	Predominant educational techniques	Key figures	Geographic region
Ancient (Mesopotamia, Egypt, India)	Clinical observation, empirical texts, early surgical methods	Sushruta, Egyptian healers	Mesopotamia, Egypt, India
Greek & Hellenistic Era	Philosophical inquiry, animal dissection	Aristotle, Herophilus, Erasistratus	Greece, Alexandria
Islamic Golden Age	Illustrated manuals, ethical surgical practice, structured teaching	Al-Zahrawi, Avicenna	Middle East
Renaissance	Human cadaver dissection, anatomical illustration	Vesalius, Leonardo da Vinci	Western Europe
19th–20th Century	Mentorship, cadaver labs, surgical documentation	Osler, Cushing, Rhoton	Europe, United States
21st Century	VR/AR simulation, digital anatomy, global education tools	Yasargil, Rhoton Jr.	Global

Phantom surgery and 3D virtual/augmented/mixed reality simulation.

In the last half of the 20th century, anatomy teaching and practice was strongly influenced by the Flexner Report by the Paris School, that highlighted the importance of scientific method application in teaching medicine[42] (Table 2). The spreading and establishment of classic cadaver model dissection in both American and European surgical training programs brought gradually the need of improvement, namely going next to reality. Neurosurgeons like Gazi Yasargil and Albert Rothon Jr. have dedicated their careers to advancement in cadaveric studies, in terms of improvements in surgical technique and didactic involvement[43]. Yasargil microneurosurgery studies impacted on both cadaveric dissection and surgical practice. The paradigm of this period relied on the need to explore the finest anatomic details in the less invasive way into the lab with the aim to transpose these skills to the patients. Anatomic laboratories became indispensable for surgical training and students and residents were strongly encouraged to explore anatomy themselves at any possible occasion. Detailed illustrations, true artworks, enriched anatomical publications, conceived not just as textbooks but true roadmap to guide and enlighten dissections. Progressively, anatomic dissection moved from being a static practice to becoming an interactive ground, as new models simulating real cerebral vasculature and arachnoid cisterns were developed. At this point, dissections were meant not be just an occasion to learn anatomy but a tangible way to improve continuous surgical training. Infusion pumps and special coloring techniques, along with a wide range of materials aimed at reproducing nervous and vascular structures were implied to create models resembling real anatomy. As a result, cadaver lab allowed the study of anatomy in motion, simulating a surgical approach as in a real-life scenario, including vessel pulsation and eventual bleeding. Trainees could perform vascular dissection and attempt to clip artificially created aneurysms, performing vascular anastomosis, and removing deep-seated skull base tumors[44].

The following step came with the development of virtual reality and its application to education. As resident hours of duty have been reduced, technological progress helped in an easier way to pursue neuroanatomical knowledge. Along with this, the need to reduce hospital costs and hospitalization has forced education in medical schools into a narrower space than before[4,45]. These factors were among conditions that catalyzed a change in this field. E-learning constituted a first step to increase accessibility and personalized content of educational material by electronic means. The potential high interactivity of this means contributed to its success and faster acquisition of knowledge and skills by digital pupils. More than an extensive amount of high-quality learning material, the online source has the capability to create specific learning environments, and it has been proved to ameliorate performance and motivation[4,46]. Tridimensional computerized modeling can generate both virtual and physical anatomical models, with the aid of 3D printers, thus providing interesting insight into the physiology and pathological condition of each patient. In the wake of Aristotle motto: *"We are what we repeatedly do. Excellence, then, is not an act but a habit,"* simulation machines met enthusiastic feedback from surgical communities. The repetition of specific skills is of

Table 2

Tools and technologies in neurosurgical education

Tool/Method	Period introduced	Primary educational purpose
Manuscripts and scrolls	Antiquity	Knowledge transmission through text
Anatomical illustrations	Renaissance	Visual learning and anatomical accuracy
Cadaveric dissection	Hellenistic–Renaissance	Direct anatomical learning
Plastic/silicone anatomical models	20th Century	Hands-on practice without cadavers
Operating microscope	20th Century (Yasargil)	Precision in microsurgery training
VR/AR/MR simulation platforms	21st Century	Immersive, interactive surgical training

Table 3

Major contributors to neurosurgical education

Name	Key contribution	Historical context
Al-Zahrawi	Illustrated surgical instruments, case-based learning	Islamic Golden Age
Andreas Vesalius	Systematic human dissection, De humani corporis fabrica	Renaissance
Leonardo da Vinci	Anatomical precision in illustration and functional insight	Renaissance
William Osler	Introduction of bedside teaching and clinical clerkships	Late 19th century
Harvey Cushing	Operative notes with drawings, modern neurosurgery mentor	Early 20th century
Albert Rhoton Jr.	Microsurgical anatomy lab, global neuroanatomy training	Late 20th–21st century

paramount importance for the acquisition of technical skills. In particular, the most complex tasks could be parted into easier component skills and each part performed several times until mastered and then reproducible in the operating room scenario by the resident[47]. This learning experience can be improved thanks to tactile feedback through haptic interfaces[48,49].

More recently, virtual (VR), augmented (AR), and mixed reality (MR) have provided tremendous progress into tridimensional surgical planning, making the surgeon able to simultaneously process data coming from different imaging modalities. VR is a computer-generated world that can be manipulated using controllers; AR is a real-world-centered environment, where digital objects are displayed and may be overlayed on the real objects; in MR the real world and 3D digital objects are mixed and can be "physically" manipulated using next-generation sensing controls like finger pulse, voice control, etc. At the same time, VR and AR/MR have improved interactive surgical learning and reinforced procedural memory and confidence. Intuitively, since most neurosurgical corridors can be very narrow and characterized by several critical neurovascular structures, a virtual surgical manipulation of anatomic structures can become a crucial instrument of learning for residents and students, testing and increasing their bimanual dexterity[50–54]. Potentially, VR/AR/MR have a wide variety of uses, from diagnostic to intraoperative assistance, to rehabilitation[55–57]. MR has been reported to improve the planning simulation of surgical procedures as well as the evaluation of newly patented devices, allowing them to validate the efficacy of surgical instruments and being able to offer a reliable prediction of its efficacy and safety by merging multimodal testing modalities at the same time[58]. Recently, MR potentiality has been used to enhance the educative and ethical aspects of publishing, by offering to the readers the possibility to read and analyze the whole dataset of images used by a published document[59]. In this way, readers may get access in an immersive environment to the paper, read it in a MR setting, visualize the entire dataset of image of the reported case series, both improving the transparency of publishing since the possibility to display only the best images is excluded, but also offering to the readers the best condition to acquire new information and knowledge from the paper, in a familiar way, simply "touching, seeing through the document" using a new disruptive way of learning. New materials associated with VR/AR may offer an innovative way of training where cadaver-less dissection allows to trainees' experience in undedicated context like home the study of anatomy and surgical techniques[60,61]. The use of digital teaching represents a cost-effective resource, of great value for the spread of knowledge in Lower Middle-Income Countries (LMIC), by breaking down the geographical and economical barriers[61]. The potentiality of this technology in education, remote proctoring and telesurgery are limited. The use of AR and MR to train or support surgeons remotely is just reality and there are several ongoing studies to validate this technology, thus contributing to increase safety and efficacy of treatment in patients affected by the most complex surgical conditions that can be faced with the highest standard of care[62,63]. Moreover, AR/MR technology plays a key role in space medicine, by providing real-time clinical support during deep space missions[64], and this is the next history to come. Technical development complexity constitutes the main challenge to face to allow further evolution and spreading of VR/AR technologies.

This evolution, from early trepanation practices to modern microsurgery and, more recently, immersive VR/AR-based training, is visually summarized in Figure 2.

Discussion

This historical narrative review outlines the deep roots and evolution of neurosurgical education, revealing a rich, multicultural tradition that has shaped modern training systems. From early records of cranial procedures in Mesopotamia and Egypt, to the structured surgical curricula of ancient India, the foundations of neurosurgical learning were laid well before the classical Western tradition[5–7]. These early practices highlight an empirical, rational, and student-focused approach, which remains relevant in modern contexts.

The Islamic Golden Age (8th–13th century) represented a second pivotal phase in surgical pedagogy. Figures such as Al-Zahrawi, with his illustrated *Al-Tasrif*, and Avicenna, through the *Canon of Medicine*, emphasized structured teaching, hands-on training, and ethical responsibility[5–8]. Their work not only preserved Greco-Roman and Indian knowledge but provided methodological advances that strongly influenced European surgical education.

During the Hellenistic and Renaissance eras, the transition from speculative to observational science led to the formalization of human cadaveric dissection, as seen in the revolutionary works of Herophilus, Vesalius, and Leonardo da Vinci[6,7,30–32]. These pioneers reformed anatomical study as both scientific and artistic practice. The "Epitome" and the *Fabrica* introduced reproducible visual learning tools – early precursors of today's manuals and digital atlases[7–9].

The modern foundations of neurosurgical education were established by the likes of Harvey Cushing, Thomas Willis, and Andreas Vesalius. Their meticulous dissections, anatomical illustrations, and personal teaching philosophies laid the groundwork for contemporary hands-on training models[1,6,12–15]. Cushing's practice of documenting operations through drawings, and Rhoton's microsurgical lab dissections, emphasized technical detail, mentorship, and continuous refinement[2,3].

The 20th-century model of "See One, Do One, Teach One," popularized under Halsted's residency structure, embedded apprenticeship within a formalized academic and institutional framework[13,17,18]. This model, while revolutionary in its time, has increasingly been challenged by duty hour restrictions, complexity of procedures, and the demand for reproducibility in training outcomes.

Parallel to this shift, technological innovation has radically transformed surgical learning. The resurgence of endoscopy, first attempted in the early 20th century by pioneers like Dandy and Guiot, evolved into the minimally invasive skull base techniques of Cappabianca, Jho, and Carrau in the 1990s[19–27]. These advancements demanded a new form of education rooted in anatomic precision, endonasal dissections, and targeted instrumentation[28].

In the past two decades, simulation-based education has gained increasing relevance. The integration of phantom models,

Figure 2. Chronological visual synthesis of neurosurgical education. Left: A neolithic human skull showing evidence of intentional trepanation, considered one of the earliest forms of cranial surgery. Center: the pioneer of modern microneurosurgery, working at the surgical microscope – symbolizing the 20th-century revolution in precision and training. Right: A medical trainee using virtual reality (VR) equipment, representing the immersive and interactive direction of 21st-century neurosurgical education. This triptych is an AI-generated artistic reconstruction based on authentic historical and photographic references, created to visually represent key milestones across eras.

haptic systems, and virtual/mixed reality platforms has created immersive, safe environments for procedural rehearsal[35,39–42]. VR/AR/MR allow residents to visualize complex neurovascular anatomy, perform virtual resections, and simulate adverse events – skills that complement but do not replace cadaveric experience[43–45].

Importantly, digital learning tools have democratized neurosurgical education, especially for trainees in LMICs[53]. The potential for telesurgical support, remote proctoring, and even intraoperative guidance through AR/MR is no longer theoretical – it is being actively tested and implemented[54–56].

In conclusion, the history of neurosurgical education is defined by a tension between tradition and innovation. While simulation and digital technology are reshaping how we teach, the core pillars – cadaveric dissection, mentorship, ethical apprenticeship, and global collaboration – remain vital. Recognizing the contributions of diverse historical actors across civilizations, and integrating their values into future training frameworks, is essential to sustain a neurosurgical community that is both excellent and equitable.

Conclusion

This historical review emphasizes how the evolution of neurosurgical education has been driven by mentorship, anatomical exploration, and continuous innovation. From ancient surgical manuscripts to modern simulation labs, the principles of hands-on learning and guided apprenticeship have remained central. By integrating insights from non-Western traditions, the Islamic Golden Age, Renaissance anatomists, and modern neurosurgical pioneers, we gain a holistic understanding of how neurosurgical training has been shaped over millennia. Future directions should prioritize mentorship, global accessibility, and ethical integration of emerging technologies. These historical insights can serve not only as a tribute to the past but also as a framework to refine and expand neurosurgical education worldwide.

Ethical approval

There is no ethical issue in this paper.

Consent

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Author contributions

Conceptualization: F.G., R.M.G., and G.S.; Methodology: F.G. and G.E.U.; Validation: P.P. and G.S.; Formal analysis: I.G.; Resources: G.S. and F.G.; Data curation: I.G. and V.D.; Writing – original draft preparation: F.G. and R.M.G.; Writing – review and editing: P.P., G.S., and G.E.U.; Visualization: F.G., R.M.G., G.S., P.P., and G.E.U.; Supervision: G.F.N.; all authors have read and agreed to the published version of the manuscript.

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