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REVIEW

The history of Rhoton's Lab

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Abstract The work performed in Dr. Rhoton's Lab, represented by over 500 publications on microneurosurgical anatomy, greatly contributed to improving the level of neurosurgical treatment throughout the world. The authors reviewed the development and activities of the Lab over 40 years. Dr. Albert L. Rhoton Jr., the founder of, and leader in, this field, displayed great creativity and ingenuity during his life. He devoted himself to perfecting his study methodology, employing high-definition photos and slides to enhance the quality of his published papers. He dedicated his life to the education of neurosurgeons. His "lab team," which included microneuroanatomy research fellows, medical illustrators, lab directors, and secretaries, worked together under his leadership to develop the methods and techniques of anatomical study to complete over 160 microneurosurgical anatomy projects. The medical illustrators adapted computer technologies and integrated art and science in the field of microneurosurgical anatomy. Dr. Rhoton's fellows established methods of injecting colors and pursued a series of projects to innovate surgical approaches and instruments over a 40-year period. They also continued to help Dr. Rhoton to conduct international educational activities after returning to their home countries. Rhoton's Lab became a world-renowned anatomical lab as well as a microsurgical training center and generated the knowledge necessary to perform accurate, gentle, and safe surgery for the sake of patients.

Keywords Rhoton's Lab · Rhoton · Microsurgical anatomy · Historical review

Abbreviations

CN	cranial nerve
ICA	internal carotid artery
MVD	microvascular decompression
UF	University of Florida
3D	3-dimensional

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Introduction

Dr. Albert L. Rhoton contributed greatly to laying the foundations of modern neurosurgery [18, 107]. His work is a treasure not only for neurosurgeons all over the world but also for all patients suffering from neurosurgical diseases. Dr. Rhoton founded the Theodore Gildred Microneurosurgical Laboratory, known as "Rhoton's Lab," in 1975 at the University of Florida (UF). In 1998, when the entire department moved to the newly opened McKnight Brain Institute, the Lab was re-named as the George Schrader Colter Microneurosurgical Anatomy Lab. Rhoton's Lab produced approximately 500 articles, 2 supplements for NEUROSURGERY, and the textbook "RHOTON: Cranial

Anatomy and Surgical Approaches." Now, the Rhoton Collection, a compilation of anatomy presentations by Dr. Rhoton and his co-workers, is being built on the website of the AANS [97, 101]. The large volume of work accomplished by the Lab was a result of Dr. Rhoton's strong leadership, brilliant ideas, and strenuous effort. He often ascribed much of the success to the dedicated work of the 119 research fellows, 4 medical illustrators, laboratory directors, and administrative staff.

Carolina Martins in writing of the activities of the George Schrader Colter Microneurosurgical Anatomy Lab after 1998 also related the Lab's success to Dr. Rhoton's overall philosophy [48]. In this article, the authors, one of whom was among the earliest fellows at the Lab (T.M. (1980–1982, 1992)) and worked continuously with Dr. Rhoton for over 35 years, present an historical review of the 40-year progress of the Lab's activities. Special attention is paid to the period from the early stages up to the 1990s when Dr. Rhoton and his fellows overcame many difficulties to establish a methodology for studying the microsurgical anatomy of the brain at the Theodore Gildred Microneurosurgical Laboratory. We will also explain how the foreign fellows taught each other and shared their knowledge of what they had studied at the Lab. Dr. Rhoton always hoped that the fellows would see it as their mission to disseminate this knowledge in their home countries when they returned.

Dr. Albert L. Rhoton Jr.: founder and leader

Dr. Rhoton started his professional career as a staff neurosurgeon at Mayo Clinic in 1966. This was around the time that microsurgery, after the introduction of the operative microscope, started to develop. He became convinced of the great necessity to extend the knowledge of microneurosurgery and microneurosurgical anatomy in order to improve care for his patients. He was eager to establish ways of using a more precise understanding of surgical anatomy to access dangerous lesions of the brain. When he started to study the cranial nerves (CNs), such as CNs V and VII, through the operative microscope at Mayo Clinic in the 1960s, he had rarely seen CN VII preserved during the surgical removal of an acoustic neurinoma [8, 13, 23, 78, 89, 93]. The results of his study were reported in a paper entitled "Nervus Intermedius" in 1968 [89]. This was the dawn of microsurgical anatomy as a new field of research [61].

In 1972, Dr. Rhoton became the Chief of the Division of Neurosurgery in the Department of Surgery at the UF. He had a desire to build a program to create roadmaps that made surgery more accurate, gentler, and safer for patients. He made a great effort to build a laboratory. In 1975, through the generosity of grateful patients, private donors, and the University of Florida Foundation resources, a great amount of fund was gathered and the Lab was opened for the study of the microsurgical anatomy of the brain and for teaching microsurgery. From 1975 to 2016, over 100 US and international young neurosurgeon research fellows studied with Dr. Rhoton in the Lab. It was his hope and desire that each domestic and international fellow would return to his or her home to spread the knowledge they learned.

He was a hard-working, diligent, and patient person. With the heavy demands of a clinical practice, administrative duties as department chair, and a vigorous lecture/travel schedule, it was often necessary that he work with his fellows on the weekends. In the days before internet-based communication, he would telephone his neurosurgical office every morning when traveling in order to give instructions to his fellows and medical illustrators. To improve the quality of the figures in his papers, he gave his fellows careful instructions on how to make difficult dissections and take good photographs of specimens, in order to make what seemed impossible possible. He always made every effort to ensure that the quality of the papers was as good as possible. He was a tenacious perfectionist [14, 48]. He was also a skilled author and fast worker. He always had 2 to 4 fellows working in the Lab and he submitted at least 2 or 3 original articles every year either to Journal of Neurosurgery or Neurosurgery. Even after he turned 80, he continued to publish original articles [9].

Beside studying anatomy, he developed several new surgical instruments, known as Rhoton Microsurgical Dissectors [17, 80, 81, 84, 85, 90–92]. Dr. Rhoton was eager to teach as many neurosurgeons as he could. He was a great researcher, teacher, and neurosurgeon.

Rhoton's microneuroanatomy research fellows

As there were many candidates from all over the world every year, seeking to gain a better understanding of microneurosurgical anatomy to benefit their patients, obtaining a position as a Rhoton's research fellow was a highly competitive endeavor. A total of 119 research fellows (residents of UF and neurosurgeons from 15 different countries outside the USA) studied at the Lab during those 40 years [4, 9]. About 100 of them were from outside the USA, mostly from Japan (41), Latin American countries (24: 15 from Brazil, 7 from Argentina, and 1 each from Chile and Mexico), and Turkey (11) [4, 104, 110]. For recruitment of international fellows, Dr. Rhoton took advice from three former fellows who worked together in the early 1980s in the Lab and continued to collaborate with him thereafter (Fig. 1a–c). They are Toshio Matsushima (Japan), Evandro de Oliveira (Brazil), and Erdener Timurkaynak (Turkey), and subsequently became responsible for recommending future research fellows from their respective countries to Dr. Rhoton. As for the

Fig. 1 Dr. Rhoton and his research fellows. **a** Three fellows in the old Lab (1981). They collaborated with Dr. Rhoton after returning to their own countries. Evandro de Oliveira (Brazil; front row), Erdener Timurkaynak (Turkey; back row, left), and Toshio Matsushima (Japan; back row, right). **b** Research fellow's assist in the dissection course (1992). **c** Research fellow's study scene at the old Lab (1981). Evandro de Oliveira (Brazil; right) and Toshio Matsushima (Japan; left). (provided courtesy of the UF Health Science Center Archives [7]) **d** Dr. Rhoton and his former fellows celebrating Dr. Rhoton's 40 years at the UF in 2012. (from an article written by Fernandez-Miranda JC [14] with permission)

Japanese fellows, there were always one or two working in the Lab during those 40 years [9, 58, 61].

Most of the research fellows from foreign countries were not good at communicating in English. Dr. Rhoton patiently listened to the poor English spoken by the foreign fellows. He spoke slowly and softly to be easily understood by them and this was greatly appreciated. Each fellow was engaged in dissecting the head specimens and took photographs. Dr. Rhoton requested them to take photos that were distinct and perfectly fit for purpose. He regularly held anatomical dissection courses where his fellows were asked to assist in the teaching (Fig. 1b). Since the fellows, especially those from foreign countries, studied at the Lab for a limited period (usually 1 or 2 years) without a salary, they were highly motivated to achieve their goals. They worked hard until late in the evening and/or during weekends. They could write English manuscripts neither well nor fast, but obtained perfect data with which to complete Dr. Rhoton's projects. Most of them continued their research after they returned to their home countries. When a celebration for Dr. Rhoton's 40 years at the UF was held in 2012, he was pleased to learn that about 40 of the 100 former foreign fellows had become professors (Fig. 1d).

Research methods

In the early years, research at the Lab was conducted in the following way. First, the research fellows and laboratory technicians prepared the formalin-fixed cadaveric head by injecting the coloring matter into the intracranial vessels through the vessels in the neck (Fig. 2a, b). The arterial injection of red-colored acrylic or latex was started around 1977 for the projects dealing with arteries and their perforators [76], and the venous injection of blue-colored matter around 1980 for the projects on ventricles [65, 113] (Fig. 2c, d). Injection through the neck vessels was not successful in all specimens, as the quality of the specimens varied. Successful injection depended on the pressure of the manual infusion as well as on the presence of blood clots remaining in vessels after formalin fixation. Post mortem clots hindered the filling of distal vessels with latex. As the injection methods improved, the Lab began to receive occasional visits from researchers and technicians from other laboratories interested in learning about the methods. Well-injected specimens were used to produce figures for publication and the other specimens were used for measurement and observation. In research projects concentrating on arteries, the measurements of their sizes and elucidation of anatomical variations were important, so usually, the measurement of 50 sides among 25 specimens was required for a complete study. As most of the major measurement was done and surgical approaches drew more attention, especially after the development of the skull base surgery, Dr. Rhoton stopped requiring them. Various surgical approaches were demonstrated by employing photos of step-by step dissection. The glossy prints of the photographs were retouched by medical illustrators to bring out important anatomical features (Fig. 3). Until the early 1980s, only black-and-white films were used because color slides were very expensive.

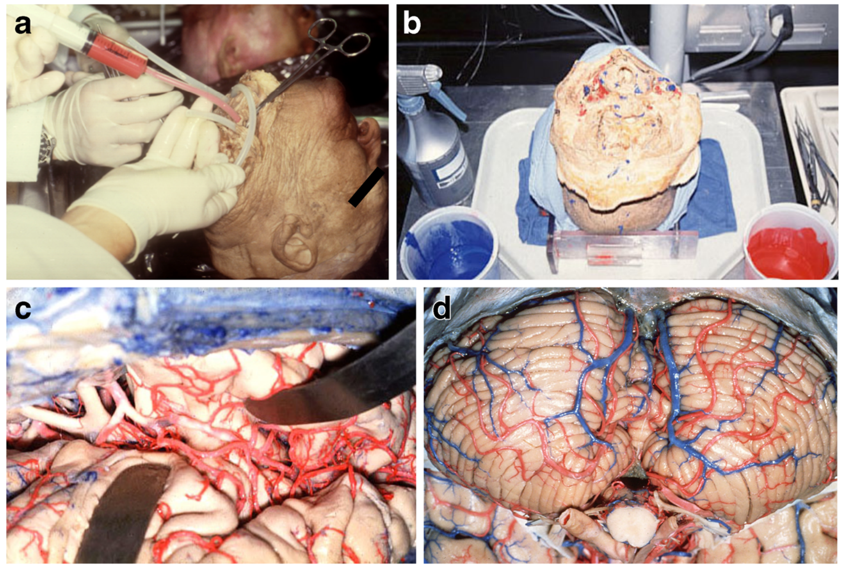

Fig. 2 The arterial and venous injection method and injected specimens. (**b** and **c** from an article written by Matsushima T et al. [61] with permission) **a** Injection method through the vessels of the cut surface of the neck. **b** The red and blue coloring materials for injection and the colored vessels on the cut surface of the neck of an injected specimen. **c** Specimen with arterial injection. Dissection of the right trans-Sylvian approach. **d** Specimen with arterial and venous injection. Posterior views of the cerebellum with colored arteries and veins

The procedure of removing the arachnoid membrane from the vessels and brain tissues so that the intracranial structures would appear more clearly was introduced by one of the fellows (T.M.) in 1980. In the following year, another fellow (E. de O.) began to insist on taking color slides of the specimens, and other fellows followed suit, even though the cost remained a problem. These changes allowed the Lab to produce more beautiful and sharply defined slides. In the early 1990s, monochrome photographs were wholly replaced by color photographs [3]. After the development of computer

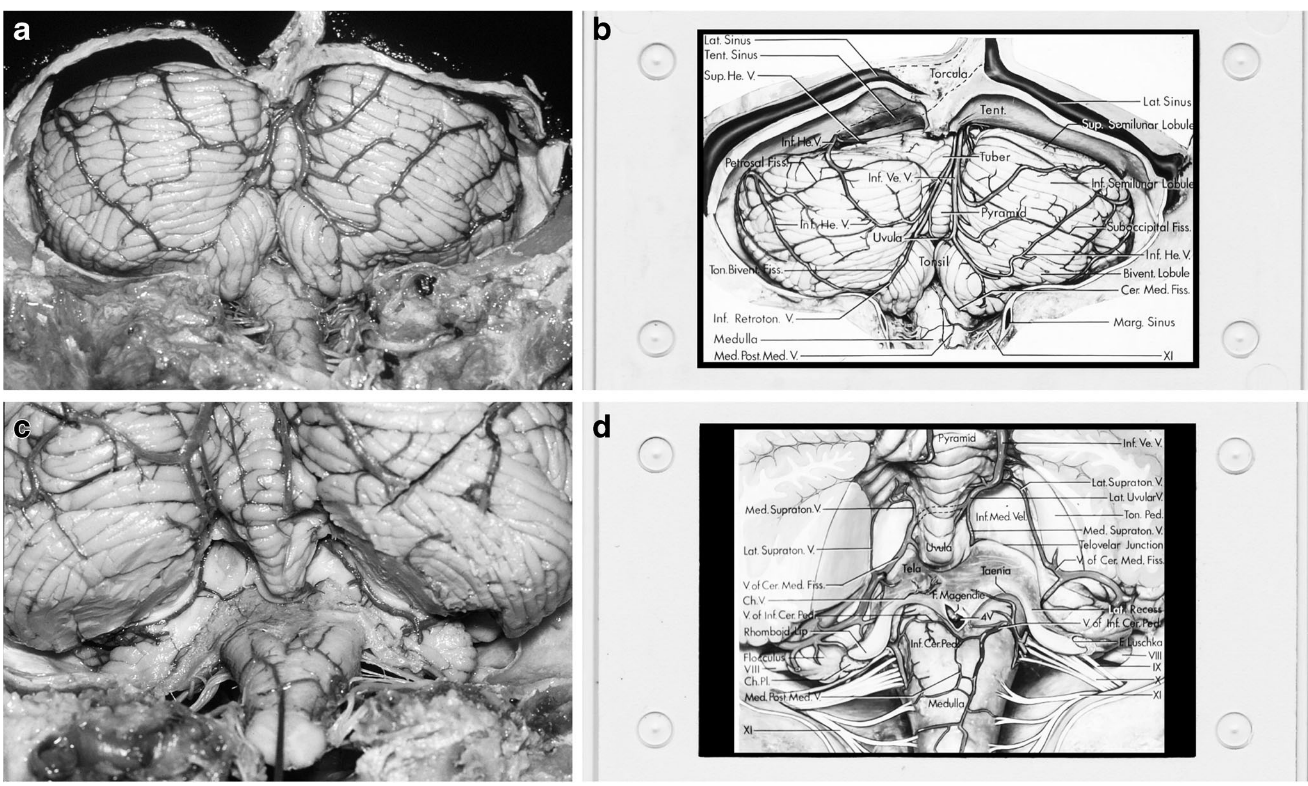

Fig. 3 Dissected specimens and slides with retouched black and white illustrations. Posterior views of the cerebellum showing the step-by-step dissection of the cerebellomedullary fissure and the veins in each step. **a** A dissected specimen for the project of the veins of the posterior fossa. The suboccipital cerebellar surface with the veins after removal of the arachnoid membrane and the arteries. **b** A slide with a retouched black and white illustration of the "a" photogram. The posterior view of the suboccipital surface with the veins. **c** A dissected specimen. The exposed cerebellomedullary fissure with the veins after removal of the tonsils and parts of the biventral lobules on both sides. **d** A slide with a retouched black and white illustration. High magnification of the cerebellomedullary fissure with the veins

systems and digital cameras, research fellows were able to take as many photographs as they liked for later selection.

In the 1990s, Dr. Rhoton became keenly interested in 3-dimensional (3D) imaging, which would aid in more accurate understanding of depth during surgical procedures. Dr. Toshiro Katsuta (1993–1995) started to take stereo photos of dissected specimens and first presented the 3D projection figures in his article of the jugular foramen in 1998 [35]. In the early stage, 3D projection could be obtained by using a double set of slides, projected through two slide projectors. With advancement of the digital image equipment, 3D projection rapidly advanced at the Rhoton lab and became an important tool for teaching the complex anatomy of surgical fields in the 2000s [49, 100].

With new developments in neurosurgical endoscopic surgery, the number of surgical cases using this technology increased rapidly from the late 2000s. In the Lab, endoscopes began to be utilized for taking research photos. Following the increase in brainstem surgery and the development of fiber-tractography, the fiber dissection of brain specimens was also adopted as a new research focus [55, 112].

Medical illustration work: art and science

One of the most important elements in the Rhoton's Lab papers was the illustrations. Dr. Rhoton had worked with several medical illustrators including the famous Frank Netter at Mayo Clinic [74]. The illustrations had to be not only clear and accurate but also beautiful in order to maintain the high quality of the papers. Dr. Rhoton's perfectionism in his approach to the production of the illustrations led some people to see the Lab's work as combining "art and science" [14]. In fact, over the years, 11 color illustrations were selected for the cover of the "Journal of Neurosurgery" [4, 51, 61, 62]. The number of illustrations in the papers gradually increased, and by the 1980s, a typical paper from the Lab consisted of 60 to 70 black and white images and several color illustrations [74]. Four medical illustrators, Robert Beach (1975–1978), Carla Lenkey (1978–1982), David Peace (1979–2014), Margaret E. "Robin" Barry (1982–2017), worked for Dr. Rhoton over the 41 years of his tenure at UF [4, 74]. These medical illustrators played an integral part in what Dr. Rhoton accomplished.

In the 1970s and 1980s, there were two major jobs for the medical illustrators: one was to retouch black and white photograms, and the other was to draw color illustrations. Initially, the research fellows took black and white photos using 35-mm film. This was more than 40 years ago and their dissections, even with microsurgical techniques, were not meticulous by current standards. First, the best photos were selected and printed as 11″ × 14″ matte prints and mounted with wax onto 15″ × 18″ boards. Then, the medical illustrators would retouch by hand and label the enlarged black and white prints, which would then be re-photographed and printed as 5″ × 7″ glossy prints for journal submission [4]. The retouched prints were very beautiful and brought out all the important details lacking in the original photographic image (Fig. 4). Usually, three or four color illustrations were included to depict the highlights of the paper.

A big breakthrough for the medical illustrators occurred with the introduction of computers and illustration software around 1995 (Fig. 5). The use of computers, in conjunction with Adobe Photoshop, Adobe Illustrator, and other desktop publishing software, brought a welcome change to the way medical illustrators produced illustrations [4, 74]. Color reproduction in the journals became less expensive and digital color images soon replaced the black and white prints in nearly all of Dr. Rhoton's papers [3]. The full-color illustrations that had previously been created using acrylic paint and water color were now done using the computer [4, 74]. A typical color illustration began with a detailed pencil drawing which was scanned and saved as a TIFF file and then rendered and labeled in multiple layers using Photoshop. The use of the computer made changes and revisions to the illustrations relatively simple and effortless. The entire project with all its figures could easily be put together and the labels and leader lines added. Projects that formerly took a year or more to complete could now be completed in half that time.

Research themes: transitions over 40 years

Dr. Rhoton and his fellows undertook various projects, rebuilding them along with the development of new surgical treatment modalities, approaches, and instruments. From a chronological perspective, over 160 original papers can be divided into the following five stages: First stage: dawn of microneurosurgical anatomy, second stage: study of basic microneurosurgical anatomy for general neurosurgery, third stage: studies for skull base surgery, fourth stage: study of the internal structure of the brain using the fiber dissection technique, and fifth stage: surgical anatomy combined with new advanced technology [62]. During these long research projects, from the educational point of view, Dr. Rhoton proposed new methods of classification such as the three-part segmentation of the intradural internal carotid artery (ICA) [21], anatomical rules such as the "rule of 3" in the posterior fossa [46, 53, 55–57, 64, 65], and changes in nomenclature to create terms more appropriate to neurosurgeons, such as, for example, in the case of the veins of the posterior fossa [64].

In the first stage, Dr. Rhoton studied the microsurgical anatomy for his major surgeries. After studying the CNs VII and VIII and internal acoustic meatus, he reported that the CN VII was stretched mostly around the anterior half of the acoustic tumor capsule [47, 79, 89]. Regarding the sellar region and the cavernous sinus, he re-organized the anatomical knowledge

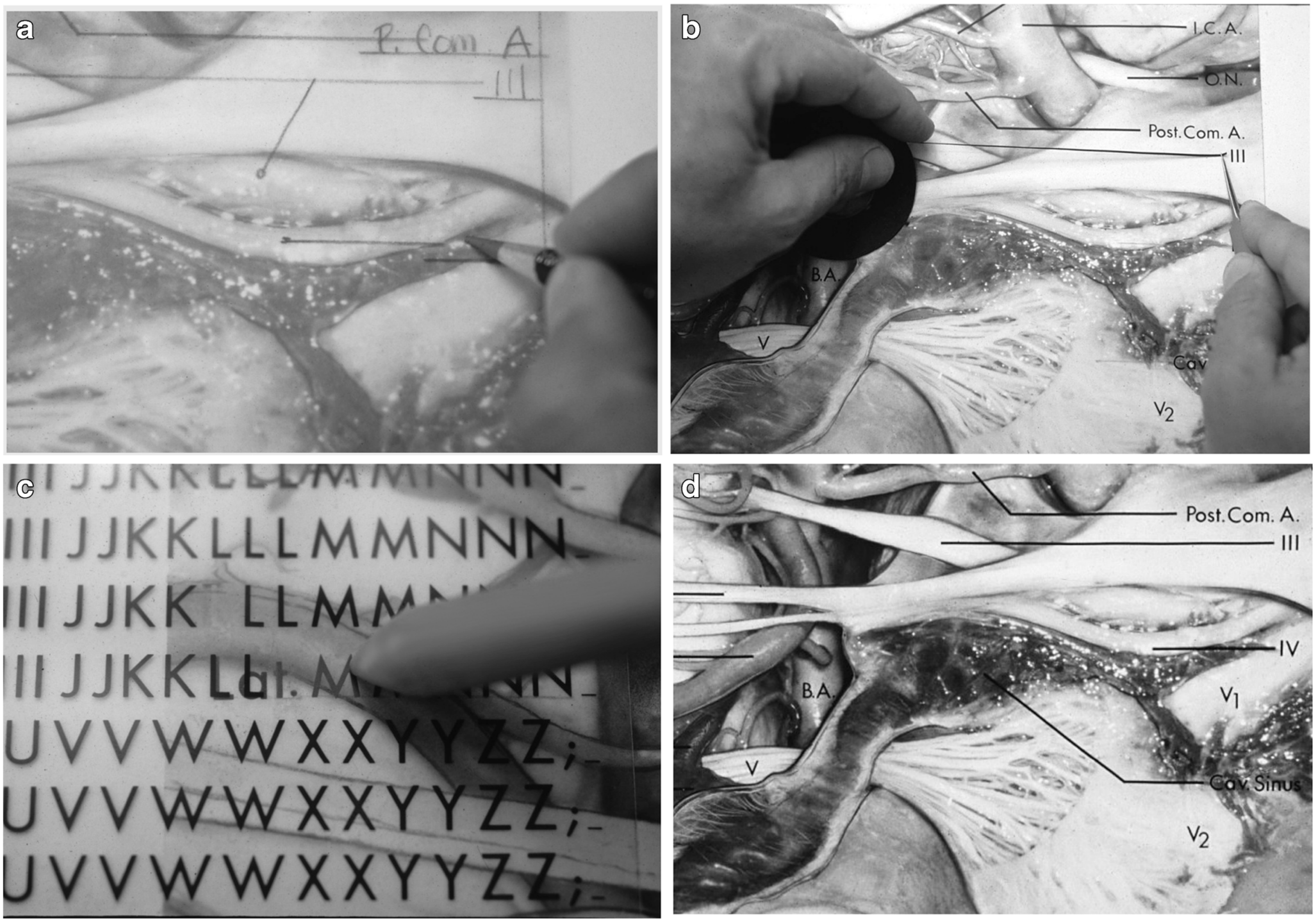

Fig. 4 Manufacturing process of a black-and-white figure. (**a**, **b**, and **c** from an article written by Margaret E. "Robin" Barry [4] with permission) **a** A print mounted on illustration board. **b** Retouching on the print and application of leader lines with Chartpak Tape. **c** Press type used for labels added to print. **d** A final black and white figure retouched and labeled

necessary for transsphenoidal surgery and reported this with the figures consisting of color illustrations and retouched black and white photos [19, 77]. The retouching was one of his ingenious ideas [4, 74]. With the development of intracranial aneurysm surgery, he started a series of projects on intracranial arteries, especially their branches and perforators [21, 75, 87, 95, 98].

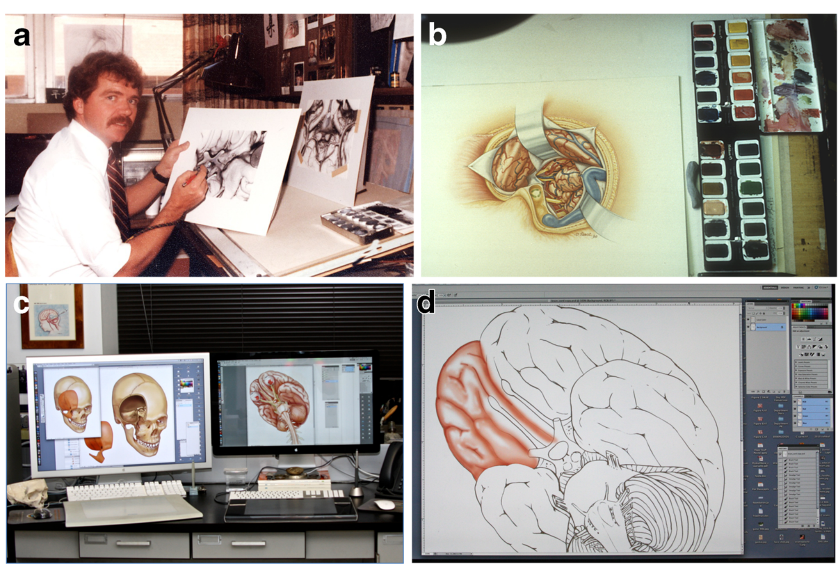

Fig. 5 Medical illustration before (**a** and **b**) and after (**c** and **d**) the introduction of computer systems. **a** Illustrator (David A. Peace) retouching enlarged black and white matte photographs at his old work station. **b** A full-color illustration drawn in water color. **c** The new computer work station with Photoshop. **d** A computer graphic illustration: Scanning of a pencil sketch and color rendering with airbrush tool in layers

For microvascular decompression (MVD) procedure, he studied the relationships between the CNs and the arteries in the cerebellopontine angle [22, 27, 28, 46, 47, 82]. During this stage, a few projects were conducted to prepare dissection manuals and a 5-day microvascular and dissection course was held every month [9, 73, 83, 88].

In the second stage, in 1980s, Dr. Rhoton extended his study to the ventricles, venous systems, foramen magnum, tentorial incisura, and cisterns in order to make a road map for neurosurgery [10, 31, 50, 64, 65, 67, 70–72, 105, 113]. With regard to the ventricles, he collected all the anatomical information, including the neural structure described by anatomists and the related vessels described by radiologists, and composed from them a single structure for the benefit of surgeons. He also studied surgical approaches, seeking to make them safer [67, 94, 113]. In the fourth ventricle project, the step-by-step dissection of the cerebellomedullary fissure later led to a new and innovative approach, widely adopted as the trans-cerebellomedullary fissure approach or the telovelar approach [32, 56, 57, 59, 60, 66, 102].

In the third stage, mainly in 1990s, Dr. Rhoton again studied the cavernous sinus, orbit, temporal bone, jugular foramen, and foramen magnum because of new developments in skull base surgery. He examined the various approaches to skull base and presented a step-by-step dissection of specimens for these procedures [33, 39, 40, 63, 103, 111]. They included a combined epi- and subdural direct approach to carotid-ophthalmic aneurysm, so-called Dolenc's approach [11, 12], the anterior and posterior trans-petrosal approaches [2, 25, 26, 37, 38], the lateral foramen magnum approaches including the far lateral and transcondylar approaches [6, 29, 99], the carotid cave aneurysms of the ICA [41], and the unilateral subtotal maxillectomy approach [30]. The jugular foramen is one of the most difficult regions not only on account of the challenge it presents to surgeons seeking different approaches but also because its intra- and extra-cranial location makes anatomical study problematic. Therefore, it became the subject of three major studies [8, 36, 43]. Regarding the orbit, the transcranial approach, lateral approach, and superior orbital fissure were studied separately [3, 68, 69].

In the fourth stage, starting with the 3D study of the optic radiation in the early 2000s, Dr. Rhoton began to study the internal structures of the brain using fiber dissection techniques [96, 108, 109]. Several studies were reported using a combination of fiber dissection and diffusion tensor images [15, 16, 24]. With the development of brainstem surgery, he extended his studies to the anatomy of the brainstem, focusing especially on the safe entry zone to this vital region [45, 55, 112]. Along with the diversification of neurosurgery, the fiber dissection technique has been applied to various fields such as auditory brainstem implantation and deep-brain stimulation [5, 44].

The fifth stage overlapped with the fourth stage in the early 2000s. Treatment methods in neurosurgery had become increasingly diverse, and several of the Lab's projects were concerned with new methods, such as less or minimally invasive surgery, including endoscopic surgery [20, 54], or incorporated new technology such as neuronavigation systems [42], endovascular surgery [52], auditory brainstem implantation [1, 44], and deep-brain stimulation [5]. 3D interactive models of the skull base and CNs were also made for educational purposes from the anatomical studies conducted in the Lab [34].

Dr. Rhoton's hopes and his research fellows' achievements

Dr. Rhoton embarked on his research in order to "better care for his patients" and often talked about "competence and compassion [86]." One of his goals was to teach and mentor as many neurosurgeons as possible. In the late 1970s, he began a monthly 5-day microvascular and dissection course in the old Lab. Over the years, more than 1000 neurosurgeons attended these courses [4, 9]. Later in his career, he also held many dissection courses in AANS and CNS meetings and in the new Lab at UF [48]. He gave countless educational lectures as an invited guest to meetings and seminars all over the world. It was also his hope that his foreign research fellows would return to their departments in their own countries and over their own lifetimes teach others and share the knowledge that they had gained at the Lab. In fact, after returning to their countries, some of them opened microneurosurgical laboratories, naming them after Dr. Rhoton, while some translated the English textbook "RHOTON: Cranial Anatomy and Surgical Approaches" into Spanish, Chinese, or Portuguese [61, 104, 106, 110]. The Japanese version is due to be published later this year. Written in the fellows' native languages, these manuals have become indispensable for neurosurgeons in the countries concerned.

In 1986, the Japanese fellows established an annual meeting for microsurgical anatomy, the first annual microsurgical anatomy seminar in the world. This meeting, organized by the Japanese Society for Microsurgical Anatomy, was held for the 31st time this year [58, 61]. The proceedings of the seminar in Japanese are widely read. The first International Symposium on Microsurgical Anatomy (ISMA) (co-presidents: Matsushima T and Dr. AL Rhoton Jr.) was held in 2002 in Matsumoto, Japan, and Dr. Erdener Timurkaynak from Ankara, Turkey, Dr. Evandro de Oliveira from Sao Paulo, Brazil, and Turker Kiliq from Istanbul, Turkey, have held subsequent international meetings, four times in Turkey and once in Brazil, each time inviting Dr. Rhoton as their co-president [58, 61] (Fig. 6). The international symposium has contributed to improving the professional abilities of neurosurgeons through the study of microsurgical anatomy both in the host countries and in the countries of all those attending the meetings.

Fig. 6 International Symposia on Microsurgical Anatomy. (**a** and **b** from an article written by Matsushima T [58] with permission) **a** The front cover of the proceeding of the first international symposium on microsurgical anatomy, held in October 2002 in Matsumoto, Japan. **b** Lecturers in the first international symposium: Dr. Rhoton, his former fellows, and Dr. Slobodan Marinkovic (front row, extreme right). **c** The front covers of the proceedings of the second through sixth international symposia

Conclusion

For over 40 years, Dr. Rhoton and his "lab teams" developed unique research methods, masterful illustration techniques, conducted important research projects, and produced numerous publications which helped advance and improve the care of patients with neurosurgical disorders. The Lab also served as a microsurgical training center for neurosurgeons from all over the world. As a tribute to the life, legacy, and spirit of Dr. Rhoton, similar laboratories have been established all over the world for training and the study of microneurosurgical anatomy. The Rhoton's fellows will continue to teach other neurosurgeons using the knowledge and experience obtained in the Lab at the UF. Dr. Rhoton declared that "There is no finishing line," and the study of microneurosurgical anatomy will continue hand-in-hand with the development of neurosurgery and new technology.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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