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The microneurosurgical anatomy legacy of Albert L. Rhoton Jr., MD: an analysis of transition and evolution over 50 years

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Dr. Albert L. Rhoton Jr. was a pioneer of the study of microneurosurgical anatomy. Championing this field over the past half century, he produced more than 500 publications. In this paper, the authors review his body of work, focusing on approximately 160 original articles authored by Rhoton and his microneuroanatomy fellows. The articles are categorized chronologically into 5 stages: 1) dawn of microneurosurgical anatomy, 2) study of basic anatomy for general neurosurgery, 3) study for skull base surgery, 4) study of the internal structures of the brain by fiber dissection, and 5) surgical anatomy dealing with new advanced surgical approaches. Rhoton introduced many new research ideas and surgical techniques and approaches, along with better microsurgery instruments, through studying and teaching microsurgical anatomy, especially during the first stage. The characteristic features of each stage are explained and the transition phases of his projects are reviewed.

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KEY WORDS Rhoton; microsurgical anatomy; historical review; history

As a pioneer of the study of microneurosurgical anatomy, Albert L. Rhoton Jr. brought excitement and understanding to this expanding field. The impact of his work has been heralded as one of the cornerstones in the history of neurosurgery that led to safer and gentler surgical treatment by neurosurgeons all over the world. A large number of excellent works published by Dr. Rhoton, his 119 fellows, and 4 medical illustrators (Bob Beach, Carla Lenkey, David Peace, and Margaret E. "Robin" Barry) were compiled into the textbook *Cranial Anatomy and Surgical Approaches* and "The Rhoton Collection" (Fig. 1, Tables 1 and 2).[99,111,116] However, the process by which his research ideas evolved over the years is not well known. In this article, we review his numerous works from a historical perspective, on behalf of all his former research fellows, and discuss future prospects for microneurosurgical anatomical research.

We reviewed approximately 500 publications written during the last 50 years, including over 160 major original articles, and then divided them chronologically into 5 stages. Each stage is explained individually, and the epoch-making studies of the first stage are discussed in some detail. The front covers of the *Journal of Neurosurgery* issues with the figures from the manuscripts written by Dr. Rhoton and his fellows[17,19,21,53,68,82,95,108,120,121] and some figures representing the features of the historically important projects are shown for visual reference (Figs. 2 and 3).

Dawn of Microneurosurgical Anatomy

As is the case with many pioneers, Dr. Rhoton had to work in an environment that was far from optimal when he performed his initial research. While a member of the staff at the Mayo Clinic in Rochester in the latter half of the 1960s, he began his anatomical study of the cranial nerves (CNs) for clinical purposes using monkeys.[12] Then, using autopsy brains and temporal bones, he focused his reporting on the detailed anatomy of the cranial nerves

ABBREVIATIONS AANS = American Association of Neurological Surgeons; CN = cranial nerve; ICA = internal carotid artery; MVD = microvascular decompression.
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FIG. 1. Rhoton's microneuroanatomy research fellows. **A:** Photograph from the 1st International Symposium on Microsurgical Anatomy, October 2002, Matsumoto, Japan. Republished with permission of Elsevier, from Rhoton and his influence on Japanese neurosurgery, by T. Matsushima, *World Neurosurg 92:*608–613, 2016; permission conveyed through Copyright Clearance Center, Inc. **B:** Photograph from A Celebration of the Art and Science of Teaching Neurosurgery recognizing Dr. Albert Rhoton's 40 years at the University of Florida, January 2012, Gainesville, Florida. Republished with permission of Elsevier, from Prof. Albert L. Rhoton, Jr.: His life and legacy, by J. C. Fernandez-Miranda, *World Neurosurg 92:*590–596, 2016; permission conveyed through Copyright Clearance Center, Inc. **C:** Photograph from Dr. Albert Rhoton Memorial at the 27th Annual Meeting of the North American Skull Base Society, March 2017, New Orleans, Louisiana. Published with permission from Jacques Morcos.

with variations (Fig. 3A).[24,96,102,104,105] One of the reasons for his choice was that the cranial nerves coursed on the surface of the brainstem and skull base.

In 1972, he moved to Gainesville, Florida, and was appointed Chief of the Division of Neurosurgery in the Department of Surgery at the University of Florida. In 1975, thanks to several philanthropic contributions, he was able to establish the Theodore Gildred Microneurosurgical Laboratory, a facility for both research and education. By developing and refining a system of colored-latex injection of arteries and veins in human cadaveric specimens coupled with artists' renderings and retouched photos, he set a new standard for visualizing and understanding microsurgical anatomy with his publications. The well-equipped laboratory also allowed him to focus in greater detail on his surgical areas of interest, such as the safer treatment of patients with tumors of the pituitary gland and acoustic neuromas. He was a keen student of the operative techniques of other contemporary neurosurgeons from around the world. He was particularly impressed by the operative and published reports of Dr. M. Gazi Yaşargil. Utilizing his injected cadaveric specimens, Dr. Rhoton examined the contents of those reports in great detail from the anatomical point of view.

One of his great works in the earliest stage was his study of CN VII for acoustic neuroma surgery. In those days, most of these tumors were not found until they were very large, and CN VII was often damaged during surgery. He found anatomically at surgery that CN VII was often stretched over the anterior half of the tumor capsule; its anterior shifting had previously been pointed out by pathologists.[63,100,110] He stated that the anterior shift of CN VII was because it mostly coursed in the anterosuperior part of the internal auditory canal, while the tumor usually originated from the vestibular nerves coursing in the posterior part of the canal (Fig. 3B).[100] He also suggested

TABLE 1. Rhoton's 119 microneuroanatomy research fellows by country of origin

Country of Origin	No. of Fellows
Japan	41
US	24
Brazil	15
Turkey	11
China	7
Argentina	7
Korea	5
Spain	2
Australia	1
Chile	1
Egypt	1
England	1
France	1
Iceland	1
Mexico	1

TABLE 2. Rhoton's 4 medical illustrators

Name	Years in Rhoton's Lab
Bob Beach	1975–1978
Carla Lenkey	1979–1982
David Peace	1979–2014
Margaret E. "Robin" Barry	1982–present

2 regions for finding CN VII intraoperatively, namely, in the lateral end of the internal auditory canal and the nerve's brainstem exit zone. In these 2 regions, CN VII was not displaced markedly by the tumor, and the original anatomical interrelation of neural components was likely to be maintained. This study benefited the efforts to preserve CN VII during acoustic tumor surgery and attracted the attention of other neurosurgeons. Dr. Rhoton also studied the trigeminal nerve for the purpose of percutaneous stereotactic radiofrequency lesioning,[11,24,30,105] the optic nerve for optic nerve decompression,[26,27] and the jugular foramen and the lower cranial nerves for the treatment of glossopharyngeal neuralgia and jugular foramen tumors.[102] At that time, because making color slides was costly, only black-and-white photographs were taken during the research. Dr. Rhoton asked his medical illustrators to retouch black-and-white photographs to clarify critical structures to help the reader. The retouched prints clearly showed all the important details that the original glossy prints would have failed to display.

Transsphenoidal surgery for pituitary tumors progressed rapidly starting in the late 1960s.[33,34] Dr. Rhoton studied the anatomy of the sellar region and cavernous sinus. He clarified variations of the septal insertion on the anterior floor of the sella turcica and those of the intercavernous venous connections.[35,95] He furthermore studied the lateral surface of the sphenoid sinus and pointed to the carotid prominence (bulging of the internal carotid artery [ICA]), and reported on its thickness and the frequency of its defects.[18] In these reports he accumulated and reorganized the anatomical knowledge necessary for transsphenoidal surgery, providing color illustrations and retouched black-and-white photographs (Fig. 3C). The anatomical knowledge thus obtained has contributed greatly to recent advances in various transnasal approaches, as techniques evolved in recent years from microscopic to endoscopic.

In accordance with the development of direct clipping for intracranial aneurysms,[117,131] Dr. Rhoton also started a series of projects on arteries and their perforators in the late 1970s. He first studied the anterior cerebral–anterior communicating–recurrent artery complex, and in his lectures he often asked which portion the recurrent artery of Heubner originated from (Fig. 3D).[92] The project on the upper basilar artery and its perforators was of great help for clipping difficult basilar aneurysms.[112] Rhoton extended this series to the anterior choroidal artery, perforators from the M_1 segment, and the intracranial ICA and its perforators.[22,103,108] Regarding the supraclinoid portion of the ICA, he suggested a new segmentation: ophthalmic, communicating, and choroidal segments based on the site of origin of the ophthalmic, posterior communicating, and anterior choroidal arteries, respectively.[22] He did not hesitate to reclassify or coin new names if he thought it necessary for readers to have more clarity. In this series, he finally presented 3 facets of the anatomy of saccular aneurysms.[97,106] The results of these studies on surgical anatomy enormously benefited neurosurgeons who had previously been able to study the anatomy of the arteries and their branches only through papers and textbooks written by neuroradiologists and based on angiographic findings. For this series, Rhoton and his group began using the injection of red-colored acrylic or latex into arteries to facilitate dissection of branches.[93]

In the 1970s the operative microscope began to be used for the treatment of trigeminal neuralgia via microvascular decompression (MVD).[47] As Dr. Rhoton began to focus on the operative procedure, he instituted an in-depth series of studies in the microsurgical laboratory of the anatomical relationships between cranial nerves and arteries in the posterior fossa, especially in the cerebellopontine angle.[23,31,32,62,63,101] These studies have aided neurosurgeons throughout the world to more safely perform surgery in the posterior fossa. The first study focused on the relationships of the superior cerebellar artery to CN V and its potential causal relationship with trigeminal neuralgia.[32] Much attention was paid to the study of the anterior inferior cerebellar artery–CN VII-VIII complex[23] in the next project, since the importance of arterial decompression at the exit zone of CN VII was not well known at that time. To clarify the anatomy of hemifacial spasm, the relationships between the exit zone of CN VII and the related arteries were later examined.[77]

To facilitate learning and retention of anatomical relationships, Dr. Rhoton was well known for making "rules" of anatomy. Through these studies, he started to advocate the "rule of 3" as an aid to understanding the basic anatomy of the posterior fossa, including the cerebellar surfaces, brainstem, cerebellar peduncles, cerebellar-brainstem

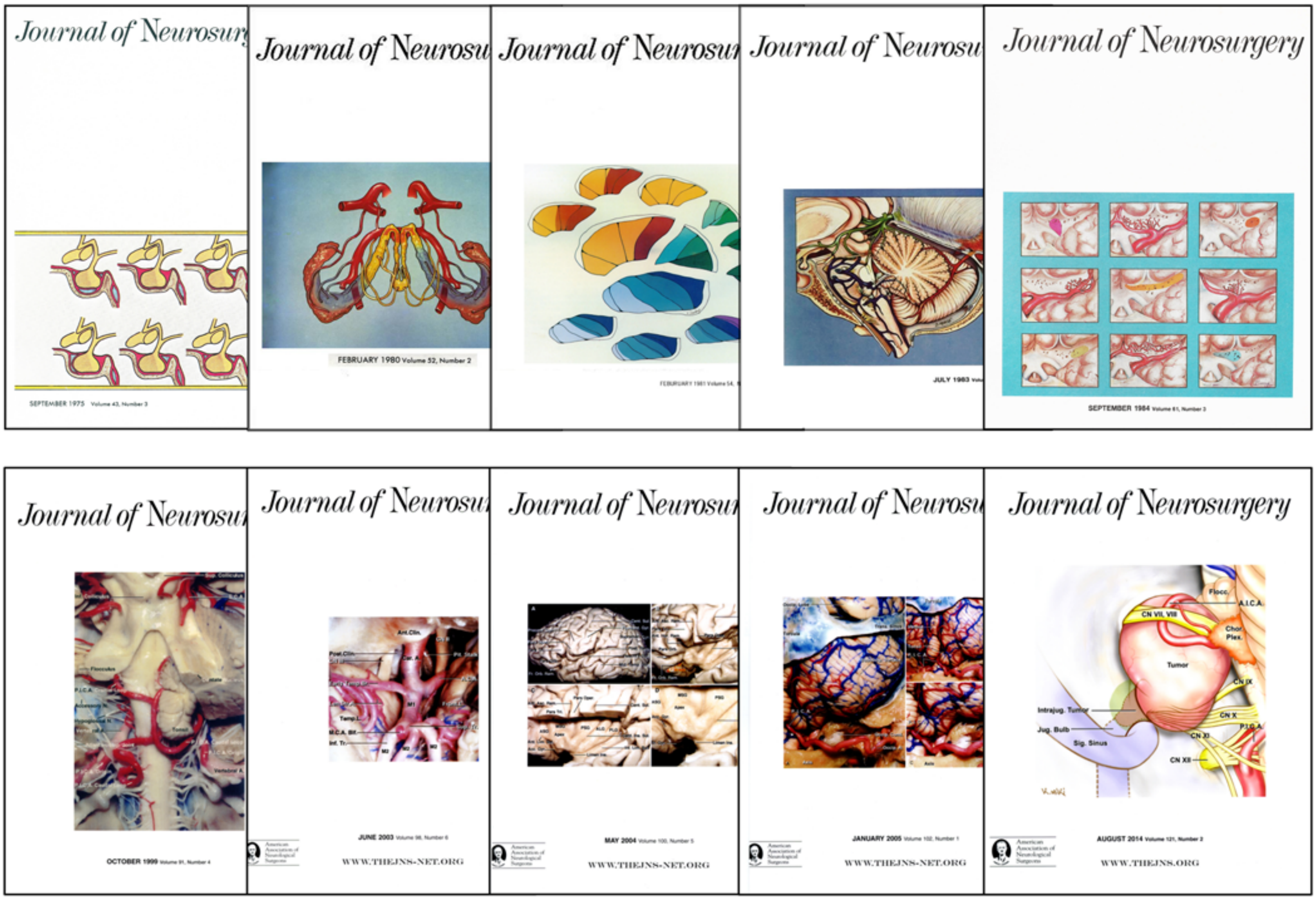

FIG. 2. Ten front covers of *Journal of Neurosurgery* issues featuring illustrations from articles by Dr. Rhoton and his fellows. **Upper** (*left* to *right*): Vol. 43, No. 3, 1975 (from Renn WH, Rhoton AL Jr: *J Neurosurg 43:*288–298, 1975); Vol. 52, No. 2, 1980 (from Fujii K et al: *J Neurosurg 52:*165–188, 1980); Vol. 54, No. 2, 1981 (from Gibo H et al: *J Neurosurg 54:*151–169, 1981); Vol. 59, No. 1, 1983 (from Matsushima T et al: *J Neurosurg 59:*63–105, 1983); and Vol. 61, No.. 3, 1984 (from Rosner SS et al: *J Neurosurg 61:*468–485, 1984). **Lower** (*left* to *right*): Vol. 91, No. 4, 1999 (from Fine AD et al: *J Neurosurg 91:*645–652, 1999); Vol. 98, No. 6, 2003 (from Tanriover N et al: *J Neurosurg 98:*1277–1290, 2003); Vol. 100, No. 5, 2004 (from Tanriover N et al: *J Neurosurg 100:*891–922, 2004); Vol. 102, No. 1, 2005 (from Kawashima M et al: *J Neurosurg 102:*132–147, 2005); and Vol. 121, No. 2, 2014 (from Matsushima K et al: *J Neurosurg 121:*397–407, 2014). Published with permission.

fissures, cerebellar arteries, and veins.[62,70,71,82,83] This rule includes 3 neurovascular complex groups in the cerebellopontine angle: CNs IV and V and the superior cerebellar artery in the upper portion, CNs VII and VIII and the anterior inferior cerebellar artery in the middle portion, and the lower cranial nerves and the posterior inferior cerebellar artery in the lower portion.[62,71,101] These 3 groups are involved in the vascular compression syndromes trigeminal neuralgia, hemifacial spasm, and glossopharyngeal neuralgia. One of the authors (T.M.) applied the "rule of 3 in the cerebellopontine angle" in his MVD surgeries and divided the lateral suboccipital approach into 3 approaches: the infratentorial lateral supracerebellar approach to the trigeminal nerve, the infrafloccular approach to the exit zone of the facial nerve, and the transcondylar fossa approach to the glossopharyngeal nerve.[37,71,74–76,79]

Four of Dr. Rhoton's 5 most-cited papers were written during the first stage (Table 3).[35,92,95,136] The contents of those papers were very new then and considered very important by many neurosurgeons.

Study of Basic Microneurosurgical Anatomy for General Neurosurgery

In the 1980s, Dr. Rhoton extended his studies to other anatomical regions and structures, including the ventricles, the veins, the foramen magnum, the tentorial incisura, and the cisterns.[8,44,65,82,83,85,88–90,124,130] This was a "map-making" process as he initially envisioned it. Prior to Dr. Rhoton's studies, the relationships of important neural structures to the ventricles had been primarily described in textbooks written by anatomists. There had been hardly any descriptions of blood vessels related to the ventricles. He collected information on the ventricles and the neural structures described by anatomists and the vascular structures described by radiologists and reorganized them more along the lines of neurosurgical importance and perspective. In these ventricular projects, he focused not only on the microsurgical anatomy but also on surgical approaches. He first studied the third ventricle, reporting his results in 2 papers: part 1 focusing on microsurgical

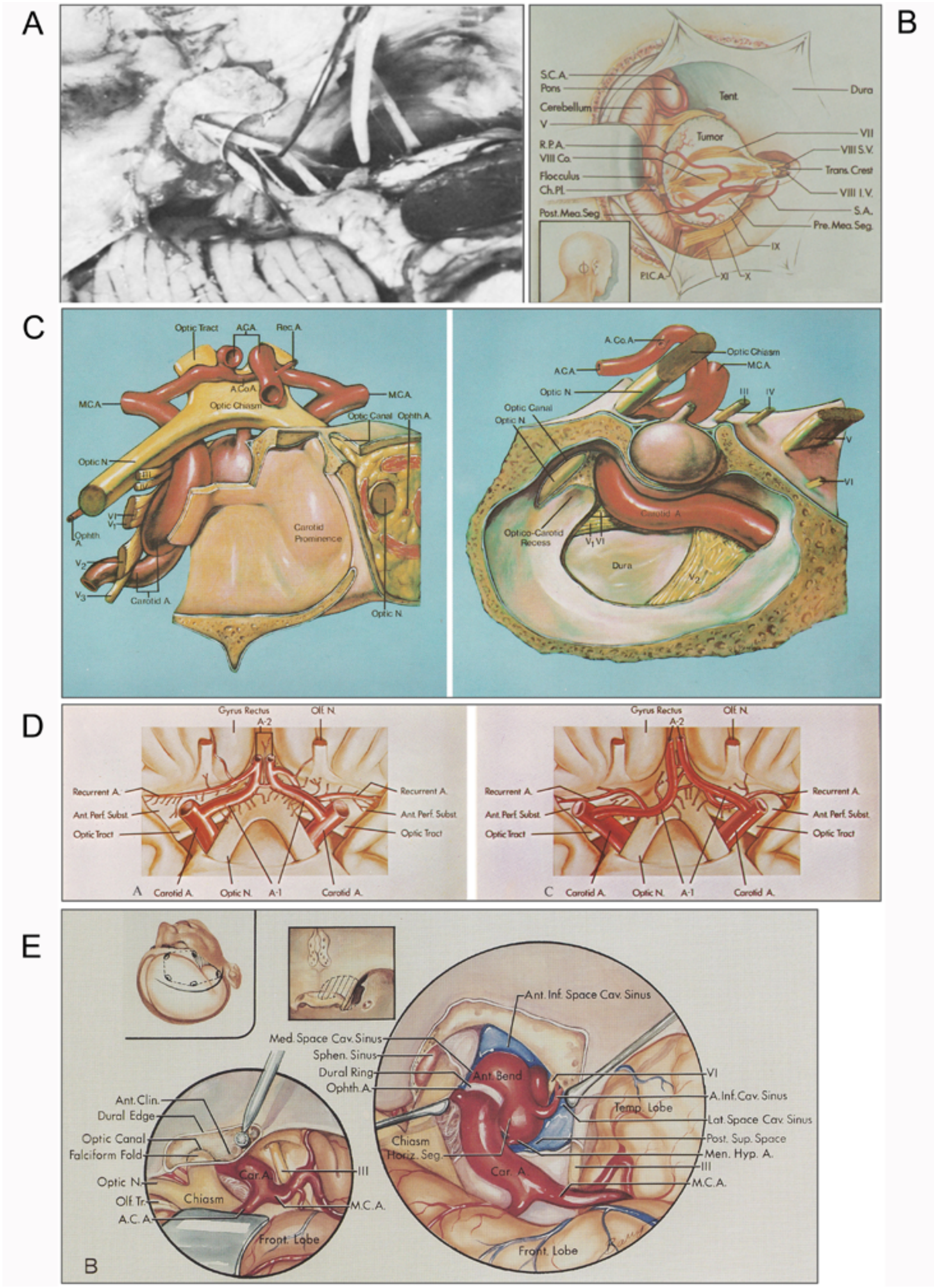

FIG. 3. Figures representing the features of the main projects. **A:** Black-and-white photograph of the left internal auditory canal from Dr. Rhoton's first article on microsurgical anatomy. Reprinted from Rhoton AL Jr. et al: *J Neurosurg 29:*609–618, 1968. Published with permission. **B:** Illustration showing the relationships between the acoustic neurinoma and the seventh and eighth cranial nerves. The facial nerve courses anterior to the tumor. Republished with permission of Oxford University Press, from Microsurgical relationships of the anterior inferior cerebellar artery and the facial-vestibulocochlear nerve complex, by R. G. Martin, J. L. Grant, D. Peace, C. Theiss, and A. L. Rhoton, Jr., *Neurosurgery 6:*483–507, 1980; permission conveyed through Copyright Clearance Center, Inc. **C:** Illustrations showing the neurovascular relationships of the sphenoid sinus. The project was done for pituitary tumor surgery. Reprinted from Fujii K et al: *J Neurosurg 50*:31–39, 1979. Published with permission. **D:** Illustrations showing the microsurgical anatomy of the anterior cerebral artery–anterior communicating artery–recurrent artery complex. The project was done for aneurysm surgery. Reprinted from Perlmutter D, Rhoton AL Jr: *J Neurosurg 45:*259–272, 1976. Published with permission. **FIG. 3.** (*continued*)→

FIG. 3. E: Illustrations showing the surgical approach to the cavernous sinus. The project was done for skull base surgery. Republished with permission of Oxford University Press, from Surgical approaches to the cavernous sinus: a microsurgical study, by T. Inoue, A. L. Rhoton, Jr., D. Theele, and M. E. Barry: *Neurosurgery 26:*903–932, 1990; permission conveyed through Copyright Clearance Center, Inc. A. = artery; A-1 = A_1 segment of the ACA; A-2 = A_2 segment of the ACA; A.C.A. = anterior cerebral artery; A.Co.A. = anterior communicating artery; A.Inf. = anterior inferior; Ant. = anterior; Car. = carotid; Cav. = cavernous; Ch. Pl. = choroid plexus; Clin. = clinoid; Front. = frontal; Horiz. = horizontal; III = CN III; Inf. = inferior; IV = CN IV; IX = CN IX; Lat. = lateral; M.C.A. = middle cerebral artery; Med. = medial; Men. Hyp. A. = meningohypophyseal artery; N. = nerve; Olf. = olfactory; Ophth. = ophthalmic; Perf. = perforated; P.I.C.A. = posterior inferior cerebellar artery; Post. = posterior; Post. Mea. Seg. = postmeatal segment; Pre. Mea. Seg. = premeatal segment; Rec. A. = recurrent artery; R.P.A. = recurrent perforating artery; S.A. = subarcuate artery; S.C.A. = superior cerebellar artery; Seg. = segment; Sphen. = sphenoid; Subst. = substance; Sup. = superior; Temp. = temporal; Tent. = tentorium; Tr. = tract; Trans. = transverse; V = CN V; VI = CN VI; VII = CN VII; VIII Co. = cochlear nerve; VIII I.V. = inferior vestibular nerve; VIII S.V. = superior vestibular nerve; X = CN X; XI = CN XI.

anatomy[130] and part 2 on operative approaches.[107] In the next project, which focused on the fourth ventricle, he and one of the authors (T.M.) also attempted to publish a paper on the operative approaches following an initial paper on microsurgical anatomy, but no approaches other than the midline transvermian approach were described at that time. The step-by-step dissection of the specimen to demonstrate the fourth ventricle from the posterior side, which also revealed the anatomy of the cerebellomedullary fissure, later brought the proposal of a new innovative approach.[73] This new approach is now widely used and well known as the trans–cerebellomedullary fissure approach or the telovelar approach. Both names were derived from this anatomical project and through our discussions in and outside the lab.[45,71,73,78,83,84,122] In the lateral ventricle project, much attention was paid to the choroidal fissure, and a safe approach through that fissure was described;[124] a further study on the surgical approach through the choroidal fissure was reported independently.[85]

Technical difficulties due to fragility of the thin venous wall were encountered in the early stages of the venous studies. Eventually succeeding in establishing proper venous injection techniques while completing projects on the ventricles, Dr. Rhoton chose the veins of the posterior fossa to be studied first.[82] Huang and colleagues[40–43] had reported excellent visualization of the veins during angiography studies and they had already named each vein. Based on their remarkable radiological studies, the naming of the veins of the posterior fossa was reorganized in a way to be more suitable for neurosurgical understanding.[82] The new naming was related to Dr. Rhoton's rule of 3. For example, the vein referred to as "the precentral cerebellar vein" by Huang and colleagues[42,43] was changed to "the vein of the cerebellomesencephalic fissure," the vein named "the superior petrosal vein" by Huang et al.[43] to "the vein of the cerebellopontine fissure," and the vein called "the vein of the lateral recess" by Huang and Wolf[40] to "the vein of the cerebellomedullary fissure." The study on the veins of the posterior fossa was later followed by the projects on the superior petrosal venous complex.[69,119] With regard to supratentorial veins, Dr. Rhoton grouped them into veins of the deep system and veins of the superficial system.[88,90]

Study for Skull Base Surgery

As skull base surgery evolved from the mid-1980s to the early 1990s, Dr. Rhoton again studied the cavernous sinus, orbit, temporal bone, jugular foramen, and foramen magnum for the newly developed skull base approaches. During this period he began to use color photographs and illustrations to present step-by-step cadaveric dissections of the various procedures. In response to the proposal in the 1980s of a combined epi- and subdural direct approach to carotid-ophthalmic aneurysms, the so-called Dolenc approach,[9,10] Dr. Rhoton studied the various surgical approaches to the cavernous sinus and adjacent regions (Fig. 3E).[46] Also responding to the report of carotid cave aneurysms by Kobayashi et al.,[56] he picked up "the dural collars and rings around the clinoidal segment of the ICA" for the study.[114] With the development of the anterior and posterior transpetrosal approaches, the temporal bone was again studied.[2,28,29,51,52,123] Not only were the surgical approaches demonstrated, but also the superior petrosal venous complex was studied as a related project.[119] With the development of the lateral foramen magnum approaches, such as the far-lateral, extreme-lateral, transcondylar, and transcondylar fossa approaches, the posterolateral portion of the foramen magnum was again studied,[5,36,54,55,80,81,113,127] and several modifications of the posterolateral approach thus far proposed were reorganized as the transcondylar, supracondylar, and paracondylar approaches.[127] The jugular foramen is one of the most difficult regions for surgical access and many approaches to this region were reported by both otolaryngologists and neurosurgeons, which caused some confusion and problems. During the course of the development of the approaches to the jugular foramen, efforts were made to clarify them by anatomically studying them 3 times in the Rhoton lab: first, in 1975, mainly on the intracranial side;[102] second, in 1997, on the foraminal portion inside the temporal bone;[50] and third, in 2016, reviewing all the proposed surgical approaches.[59] Regarding the orbit, the transcranial approach, the lateral approach, and the superior orbital fissure approach were studied separately.[3,86,87] The midface and the midline skull base, the unilateral subtotal maxillectomy approach, and the vascular anatomy of the pericranial flap were also examined.[38,39,135]

In the late 1990s, Dr. Rhoton became keenly interested in 3D imaging, which he believed would aid in more accurate understanding of depth during skull base procedures. During the fellowship of Dr. Toshiro Katsuta from 1993 to 1995, Dr. Rhoton began to experiment with stereophotography of microneurosurgical dissection. Katsuta et al.[49] first presented the 3D projection figures in their article on the jugular foramen in 1998. In the early stage, 3D projection could be obtained by using a double set of slides, projected through 2 slide projectors. In the 2000s, 3D projection rapidly advanced at the Rhoton lab with the as-

TABLE 3. Rhoton's 5 most-cited articles

Article	No. of Citations
Renn WH, Rhoton AL Jr: Microsurgical anatomy of the sellar region. *J Neurosurg 43:*288–298, 1975	547
Harris FS, Rhoton AL: Anatomy of the cavernous sinus. A microsurgical study. *J Neurosurg 45:*169–180, 1976	456
Perlmutter D, Rhoton AL Jr: Microsurgical anatomy of the anterior cerebral-anterior communicating-recurrent artery complex. *J Neurosurg 45:*259–272, 1976	436
Zeal AA, Rhoton AL Jr: Microsurgical anatomy of the posterior cerebral artery. *J Neurosurg 48:*534–559, 1978	406
Inoue T, Rhoton AL Jr, Theele D, Barry ME: Surgical approaches to the cavernous sinus: a microsurgical study. *Neurosurgery 26:*903–932, 1990	393

Data from Google Scholar, March 3, 2017.

sistance of international fellows. It became an important tool for teaching the complex anatomy of surgical fields in skull base surgery and for understanding intracerebral fiber topography. In 2006, Shimizu et al.[115] reported a detailed classic 3D documentation. Two slide projectors with polarizing lens filters of horizontal type for each stereoscopic pair projection and a silver screen were used, and the audience members wore 3D glasses. Dr. Rhoton asked his fellows to dissect the temporal bone again for a 3D presentation, and it was published as "Anatomy and Surgical Approaches of the Temporal Bone and Adjacent Areas" with all figures in 3D, occupying an entire supplemental issue of *Neurosurgery*, in 2007.[98] In 2015, Martins et al.[64] summarized the progress of 3D documentation describing 3D digital projection in neurosurgical education.

After his retirement from the chairmanship of the Department of Neurosurgery at the University of Florida in 1999, the topics of his research projects became less focused on his own surgeries and were taken from broader fields of neurosurgery. Eventually he left the selection of research topics to each fellow.

Study of the Internal Structure of the Brain by Fiber Dissection Technique

Dr. Rhoton began to study the internal structures of the brain using a fiber dissection technique in response to Ture and colleagues' revitalization of Klingler's old method of fiber dissection.[125,126] Starting with a 3D study of the optic radiation by fiber dissection,[109] several studies were undertaken with or without accompanying diffusion tensor imaging.[7,15,16,25,129] With the development of brainstem surgery, his studies extended to the anatomy of the brainstem fibers, especially with respect to the safe entry zone.[61,70,128] In accordance with the diversification of neurosurgery, the fiber dissection technique has been applied to the study of various fields, including auditory brainstem implantation[60] and deep brain stimulation.[4]

Surgical Anatomy Combined With New Advanced Technologies

By the end of the 20th century, microneurosurgery had matured, and in the early 21st century neurosurgical treatment became further diversified. Accordingly, in the Rhoton lab several projects were created to meet the demands of new surgical modalities, such as less or minimally invasive surgery including endoscopic surgery,[20,68] collaboration with various technologies including the neuronavigation system,[58] endovascular surgery,[67] auditory brainstem implantation,[1,60] and deep brain stimulation.[4] Some projects were designed to avoid surgical complications during certain surgical procedures.[69,94] In the case of endoscopic surgery, anatomical studies were made in detail not only for endonasal endoscopic surgery but also for endoscope-assisted surgery for aneurysms and cerebellopontine angle lesions.[91,118]

Dr. Rhoton accepted research fellows from many different countries and disciplines, including a plastic surgeons and otolaryngologists, who brought different cultures and new ideas from their fields to the lab.[57,134] He made tremendous efforts in the education of neurosurgeons all over the world, giving countless lectures and holding many hands-on courses in various countries. The 3D interactive model of the skull base and cranial nerves for educational purposes was also made from the anatomical studies in the lab.[48] The Rhoton Collection is being continuously updated on the American Association of Neurological Surgeons (AANS) website.[111,116]

Future Prospects

Many people may have thought that microneurosurgical anatomical study was nearly complete when Dr. Rhoton's textbook, *Cranial Anatomy and Surgical Approaches*, was published. The authors believe, however, that there are still many more projects to work on. The contents of the textbook are the results of research performed over a period of approximately 36 years—up to 2002. During the following 14 years, over 80 original anatomical papers were published from the lab. The topics we described above in the fourth and fifth stages have not covered them completely.

Dr. Rhoton started his studies from the surface of the brain and cranial base, focusing on such structures as cranial nerves, vessels, and cisterns, and continued to study the relationships between the skull and brain for skull base surgery. Toward the end of his life, he started to study the anatomy within the brain, but he was unable to complete it because of some technical difficulties in research methods. He strongly hoped to study the intracerebral distribution of perforating arteries, such as those of the anterior choroidal artery and M_1 segment. For example, in the case of the anterior choroidal artery, it was already known that the artery had several branches supplying the optic nerve, amygdala, uncus, and cerebral peduncle. However, it was and still is unclear which branches of the artery supply which areas of the brain. In the near future, more detailed anatomical study on intracerebral tissues and vessels should be completed after solving problems with current research methods or finding new methods.

As the progress of Dr. Rhoton's work over the past 50 years shows, he kept rebuilding his research projects along with the development of new surgical treatment modalities and instruments. In the case of the cavernous sinus, for instance, he studied its anatomy more than 7 times.[6,14,35,46,66,132,133] As he said, "In the future, there will be new, better, and safer procedures that will continue to evolve out of the continued study of microneurosurgical anatomy" and "New therapeutic possibilities … must be evaluated and directed according to an enhanced understanding of the anatomy." The important role of microsurgical anatomical research is to solve some questions or prove new ideas that are posed clinically or in surgery. Robotically assisted microsurgery has started to develop and will open new frontiers of more delicate and accurate surgery. More adequate and detailed studies of the microsurgical anatomy are and will be required as robotic surgery develops.

Dr. Rhoton began his work on microneurosurgical anatomy to improve the care of his patients. He told us repeatedly "more accurate, gentle, and safe" in the final message of his presentations. Thanks to the great effort by the American Association of Neurological Surgeons (AANS), he leaves a great legacy, "The Rhoton Collection," so neurosurgeons may easily access and learn from all of his microneurosurgical anatomical studies. He believed that we should build up 3D photography of the anatomy to aid in the accurate understanding of depth during surgical procedures. He hoped that microneurosurgical anatomy would become familiar to many neurosurgeons, and he dreamed that in the near future all neurosurgeons would be able to access the subject easily through their desk computers for study and for review of specific areas of interest the night before surgery. To create such an effectual learning environment, there is still more work to be done.

Conclusions

With his lifelong commitment to safer and more accurate surgery, Dr. Rhoton's contributions to the understanding of microneurosurgical anatomy are unparalleled. Following in his footsteps, study should be continued so that new therapeutic possibilities can be evaluated and directed according to an enhanced understanding of the anatomy. The authors would like to emphasize that microneurosurgical anatomy is still the roadmap for neurosurgeons, even though CT scans and MRI studies including 3D reconstruction images may show detailed radiological anatomy. Anatomical knowledge through dissection of cadaveric specimens will always be needed for young neurosurgeons to obtain vital knowledge that is essential for their practice.

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Disclosures

Dr. Morcos reports an ownership interest in Kogent.

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Conception and design: T Matsushima, K Matsushima. Acquisition of data: T Matsushima, K Matsushima. Analysis and interpretation of data: T Matsushima, K Matsushima. Drafting the article: T Matsushima, K Matsushima, Kobayashi. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: T Matsushima.

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