The History of Otologic Surgery at Mayo Clinic, 1883 to Present

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For the past 130 years, Mayo Clinic in Rochester, Minnesota, has maintained an active, uninterrupted otologic practice with activities that are well documented and preserved through the Mayo Clinic Historical Archive. This historical narrative focuses on the development of the modern surgical subspecialty of otology from the perspective of a single tertiary academic center and highlights the importance of continuous innovation and reinvention within medicine and surgery. Source material for this report comprised the annual reports to the Mayo Clinic Board of Governors, the *Mayovox* newsletter, the illustration archives of the Mayo Clinic Division of Creative Media, staff biographies, curriculum vitae, memoirs, full-text journal articles, and book publications. The interested reader is encouraged to reference "The History of Otorhinolaryngology at Mayo Clinic,"[1] which provides relevant historical context with separate but complementing material.

THE EARLY YEARS

The earliest beginnings of otology at Mayo Clinic can be traced to Dr William Worrall Mayo, who was born in Eccles, a small town neighboring Manchester, United Kingdom, on May 31, 1819.[2,3] Notably, William Worrall Mayo came from a lineage of great physicians and scientists, including Herbert Mayo (1796-1852), who first accurately described the separate sensory and motor function of the fifth and seventh cranial nerves (Figure 1).[4,5] In 1845, William Worrall Mayo immigrated to the United States and secured a position as an assistant pharmacist in New York but soon migrated westward, where he obtained 2 separate medical degrees at Indiana Medical College and University of Missouri Medical School.[3,6]

During the following 10 years, William Worrall Mayo and his growing family traveled to several cities in Minnesota in search of steady work before finally settling in Rochester to serve as the medical examiner for draftees during the Civil War. Notably, William Worrall Mayo's oldest son, William J. Mayo ("Will") received his medical degree in 1883 from the University of Michigan under Dr George E. Frothingham, professor of ophthalmology and otology.[6,7] His second son, Charles H. Mayo ("Charlie") completed his medical doctorate at Northwestern University in 1888 and shortly after graduation acquired whooping cough requiring 6 months of medical leave. During this time, Charlie spent several formative months in Europe observing otorhinolaryngologic procedures under several eminent surgeons of the time.[7,8]

The timing of the Mayo brothers' education was auspicious because they completed their training only decades after Sir William Wilde of Ireland described the postauricular incision with removal of the mastoid cortex for the treatment of acute suppurative mastoiditis, only years after Herman Schwartz and his assistant Adolf Eysell reviewed the surgical indications and technique of cortical mastoidectomy using mallet and chisel in place of the trephine and trocar, and near the same time that the radical mastoidectomy was described by Küster, Stacke, and Zauful.[9-11] The Mayo brothers' early exposure to ear surgery during this pivotal time in the field of otology provided them with a unique surgical skill set that was immediately put to work after returning to Rochester to join their father's growing practice.

In just the third entry in his extensive 575-article bibliography, William J. Mayo published an account of a 33-year-old man presenting with suppurative otomastoiditis. The patient was initially treated with myringotomy and cortical mastoidectomy using a gimlet and dental drill.[12,13]

> "*Chloroform was administered, the mastoid process freely exposed by incision, and a small quantity of fetid pus found beneath the periosteum. The temporal bone for some distance was rough, and the periosteum dissected up by this pus. With an ordinary gimlet I opened the mastoid process to a depth of 3/4 inch. The relief was immediate and improvement marked. On the fifth day the opening in the [mastoid] process was enlarged with the dental engine, which was done rapidly and perfectly*" (Supplemental Appendix 1, available online at http://www.mayoclinicproceedings.org).

Published in 1886, this was among the earliest accounts documenting use of the electric drill to perform mastoidectomy, occurring only 20 years after its invention and at least 30 years before Julius Lempert was credited with popularizing its use in otologic surgery.[14] In a similar account published 5 years later, in the second entry of a 413-item bibliography, Charles H. Mayo reports caring for a 17-year-old woman with mastoiditis and epidural abscess who was treated via mastoidectomy and abscess drainage.[15]

> "*Complaining of more or less headache, she was again taken with severe pain in the left ear, and during the following night had three spasms, epileptoid in character. The next day the ear again began discharging, and she returned home, where she remained about ten days before coming to the hospital. During this time she suffered from increasing photophobia and intense pain in and behind the left ear, loss of memory, and cold sweats.... The mastoid was opened with a gouge chisel, and pus found in the cells, at a depth of 1/4 inch. With a bone curette a sinus leading into the antrum was enlarged, and also a sinus leading upward to a small space between the dura mater and skull, evacuating in all about 1 gram of pus. The opening was drained and kept open for three weeks, when it was allowed to heal.... All headache was relieved, and the suppuration from the ear ceased in a few days. The photophobia passed away, but was followed the first few days by a partial paralysis of the right external rectus, existing about a week.*" (Supplemental Appendix 2, available online at http://www.mayoclinicproceedings.org)

ERA OF SPECIALIZATION

Early on, Will and Charlie saw the importance of dividing surgical cases between themselves to meet high clinical demands and to cultivate specialized clinical skills. Will was primarily involved in abdominal and gynecologic surgery, and Charlie concentrated on head and neck surgery, neurosurgery, and orthopedic surgery.[6,7] Thus, Charles H. Mayo should be considered the first otologic specialist at Mayo Clinic.

After completion of Saint Marys Hospital in 1889, 21 new staff were hired in response to the exponential growth in annual surgical case volume. Specific to the field of otology were the additions of Gertrude B. Granger (1898-1914), who assisted Charles H. Mayo in the treatment of diseases of the ears, nose, throat, and eyes; Carl Fisher (1909-1917) as the section head of ophthalmology and otology; and Donald Guthrie (1906-1909), an intern and second assistant to Charles H. Mayo.[6,12] With the increasing number of specialty staff, the number of otologic procedures tripled between 1910 and 1916 (Figure 2).[6]

By 1917, the practice had grown large enough to justify apportionment of specialty care to individual divisions. On July 1, 1917, the Section of Otolaryngology and Rhinology was inaugurated and Harold I. Lillie was assigned chief, where he served in this capacity for 34 years (Table).[6,7] Lillie received his graduate medical training under the instruction of Roy Bishop Canfield at the University of Michigan. Notably, Roy Canfield was a house surgeon at the

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Massachusetts Charitable Eye and Ear Infirmary and subsequently assistant surgeon to the Manhattan Eye and Ear Hospital before his appointment as clinical professor at the University of Michigan. Although he published on many subjects, Harold Lillie's primary interest was in the prevention and treatment of otitis media and related complications.

EVOLUTION OF THE SPECIALTY

Before the introduction and widespread availability of antibiotics after World War II, ear, nose, and throat specialists were primarily engaged in the treatment of infectious and inflammatory conditions of the head and neck, including acute tonsillitis, otomastoiditis, and sinusitis. As a result of the significant volume of infectious disease and the acute need for timely intervention, the Section of Otolaryngology and Rhinology largely forfeited treatment of head and neck cancer and functional surgery to other sections. During this era, intracranial complications of otitis media and sinusitis were frequent causes of patient morbidity and mortality. As a result, radical external approaches to the ear and sinuses were commonly performed to exteriorize and control advancing infection (Figures 3 and 4).[16]

The introduction of "chemotherapy" for the medical treatment of infectious disease in the 1930s significantly transformed the work of the otologist.[17] The first report of sulfonamide was made in the Mayo Clinic Department Annual Reports in 1939, penicillin in 1942, and streptomycin in 1945.[16,17] As a result of this development, most cases of acute infection could be effectively managed with medical therapy, and surgery was mainly reserved for recalcitrant acute and chronic infections.[17]

Coinciding with the introduction of effective antibiotic drug therapy were several key technological developments in the field of otology. The first commercial vacuum tube audiometer in the United States was introduced in 1922 by Bell Telephone Labs, called the Western Electric 1A.[7,18] That same year, the illuminated binocular operative microscope was first adapted to otologic surgery by Gunnar Holmgren while pioneering lateral canal fenestration surgery for otosclerosis.[19] The refinement of electric and air-driven drills with cutting and diamond bur assortments occurred between the 1920s and the 1940s.[14,20] Interestingly, despite the distinct advantages offered by the operating microscope in otologic surgery, many US surgeons did not adopt its use for several decades secondary to significant limitations, including narrow field of view, short working distance, poor illumination, large size, and poor maneuverability.[19] For example, Julius Lempert and Maurice Sourdille commonly resorted to binocular 2x to 4x loupe magnification. Similarly, although operating loupes had been widely used since the 1940s at Mayo Clinic, it was not until 1959 that the operating microscope first became a standard part of otologic surgery with the introduction and greater availability of refined operating microscope systems.[19,21] Notably, otologists were

FIGURE 1. Dr Charles H. Mayo with a portrait of Dr Herbert Mayo during his visit to Middlesex Hospital Medical School in June 1925. Reproduced with permission from the W. Bruce Fye Center for the History of Medicine, Mayo Clinic, Rochester, Minnesota.

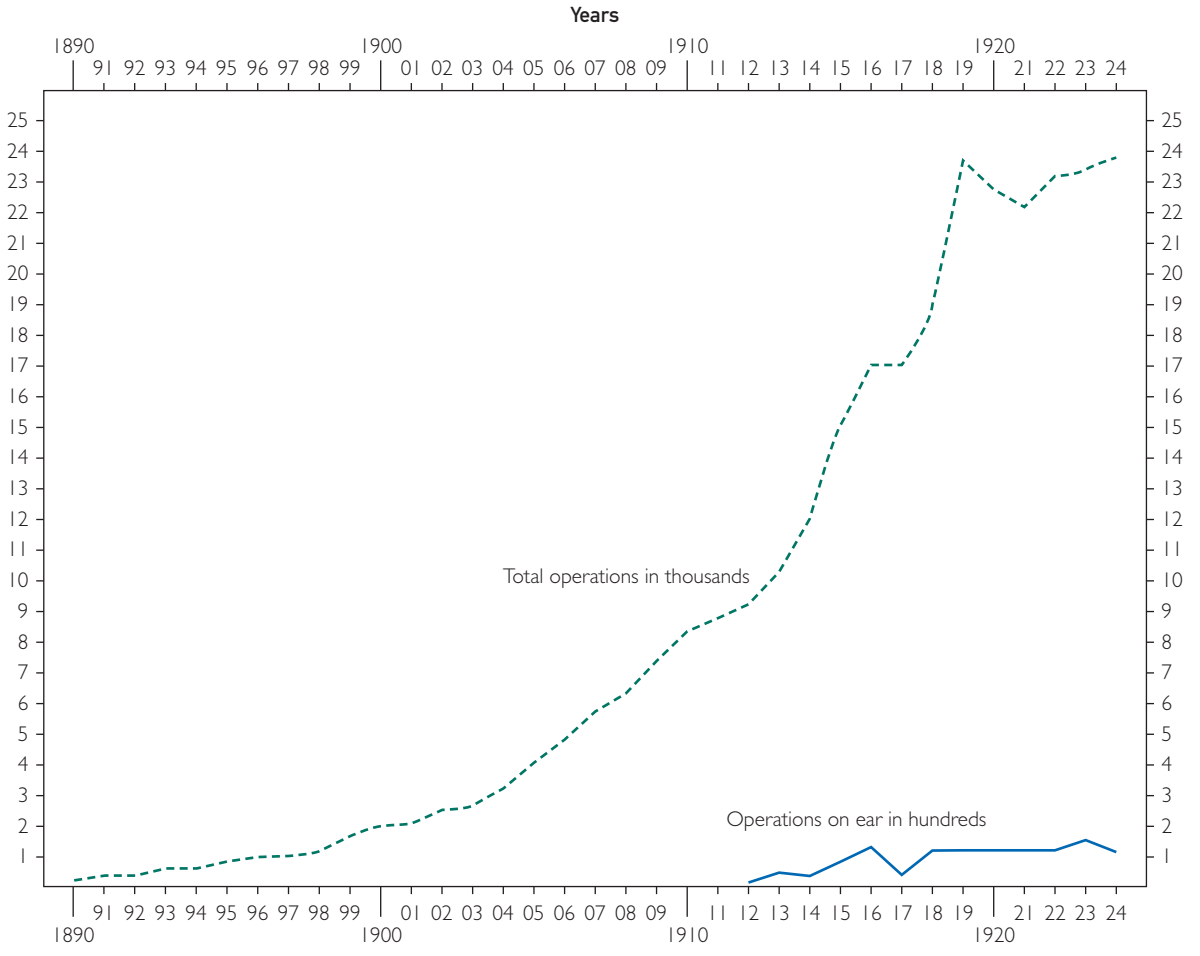

FIGURE 2. Early surgical caseload of operations of the ear compared with the total surgical volume from 1890 to 1924. Reproduced with permission from *Sketch of the History of the Mayo Clinic and the Mayo Foundation.* Philadelphia, PA: WB Saunders; 1926:46, chart 17.

the first surgeons to use the operating microscope, with several other specialties adopting its use shortly thereafter, including ophthalmology, neurosurgery, and oral surgery.[19]

Also during this time, many requisite advances in general anesthesia took place that allowed for increasingly complex surgeries to be performed with greater patient tolerance and safety.[9] Recall that the use of ether, nitrous oxide, and chloroform were originally pioneered in the 1840s. However, it was not until the late 1920s that intravenous anesthetics such as thiopental would be become available, and even later until nonflammable, nontoxic inhalation anesthetics were developed. In the 1929 annual report to the Mayo Clinic Board of Governors, the developments in general anesthesia were noted: "The use of intratracheal anesthesia has supplanted rectal anesthesia and the use of amytal. This is a step forward particularly in the radical paranasal sinus operations. There has been a great improvement in the methods of administration of anesthetics."[16]

OTOSCLEROSIS

The success of antibiotic drug therapy permitted otolaryngologists to shift focus

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TABLE. Otologists of the Department of Otorhinolaryngology, Mayo Clinic, Rochester, Minnesota, 1917 to Present

Emeritus/active (MD)	Years
Harold I. Lillie	1917-1953
Bert E. Hempstead	1921-1950
W. Berkeley Stark	1925-1934
Henry L. Williams	1934-1963
Kinsey M. Simonton	1937-1970
O. Erik Hallberg	1942-1970
Henry A. Brown	1942-1974
D. Thane R. Cody	1963-1987
Jack L. Pulec	1963-1969
George W. Facer	1970-2000
Thomas J. McDonald	1972-2007
Stephen G. Harner	1973-2003
Charles W. Beatty	1982-2018
Colin L.W. Driscoll	1999-Present
Brian A. Neff	2005-Present
Matthew L. Carlson	2012-Present

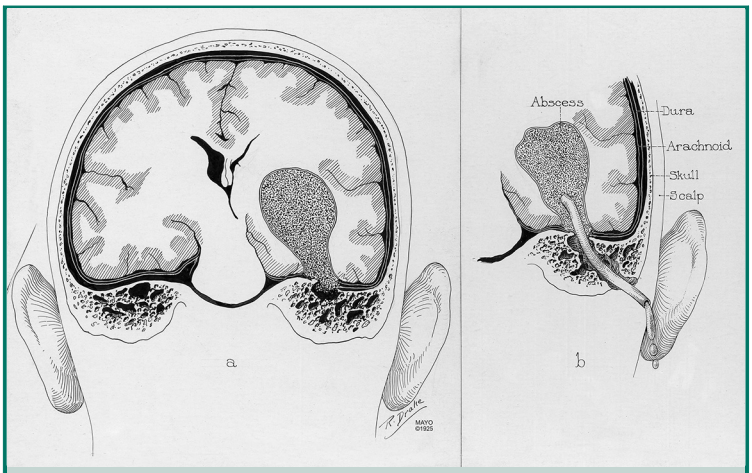

FIGURE 3. Illustration from 1925 demonstrating the technique of transmastoid drainage of an otogenic temporal lobe abscess from acute suppurative otitis media, a relatively common occurrence in the pre-antibiotic era. Reproduced with permission from the W. Bruce Fye Center for the History of Medicine, Mayo Clinic, Rochester, Minnesota.

from prevention and treatment of life-threatening infection to functional surgery. This transition was most appreciable in the early years of modern otology with the management of otosclerosis and Ménière disease (Figure 5). Following the seminal work of Adam Politzer and Joseph Toynbee describing the condition and underlying pathophysiology of otosclerosis, several innovative surgeons began performing procedures of the stapes footplate with the intent of hearing restoration—Johannes Kessel in Gras with stapes mobilization in 1878, and Blake and Jack with stapedectomy in 1892 and 1893, respectively.[22,23] However, at the turn of the century, several eminent leaders in the field of otology, including Politzer, Bacon, Siebenmann, and Denker, denounced stapes footplate surgery given the attendant risks of sensorineural hearing loss and meningitis. In 1924, Harold I. Lillie remarked, "It is quite evident that the treatment of the stapes fixation type deaf person is futile. There are certain exceptions to this, but they are few." Three years later, while accounting for the declining annual patient clinical volume, Lillie surmised that "another factor which may have influenced the registration in this service is that in answering inquires from patients who are troubled with deafness, we have not urged them to come for treatment…. Little or nothing can be done to benefit them and naturally they are disappointed for having spent their time and money; they are liable to be dissatisfied."[16]

In place of stapes footplate surgery, pioneering ear surgeons, including George Jenkins in the United Kingdom, Gunnar Holmgren in Sweden, Maurice Sourdille in France, and Julius Lempert in New York, established and refined the technique of lateral semicircular canal fenestration for the treatment of otosclerosis.[22,23] In 1943, Dr Henry L. Williams attended a 5-week temporal bone course with Julius Lempert to acquire skill in single-stage lateral canal fenestration surgery and address this significant clinical need in Rochester.[17] Because of the implications of inner ear infection, it was not until the following year that Williams began performing this procedure. In 1944 he performed 10 cases with good outcomes, and in 1945 it was said that "as a result of an article appearing in the Readers Digest last February, hundreds of patients presented themselves for operations [at Mayo Clinic];

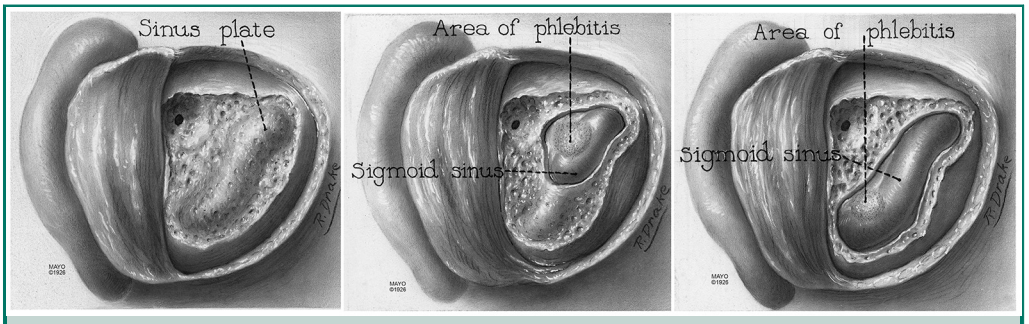

FIGURE 4. Illustrations from 1926 depicting a case of thrombophlebitis of the left sigmoid sinus. Reproduced with permission from the W. Bruce Fye Center for the History of Medicine, Mayo Clinic, Rochester, Minnesota.

patients with deaf mute children to persons eighty odd years old."[17] In 1946, Drs Kinsey M. Simonton, O. Erik Hallberg, and John C. Lillie also visited Lempert in New York for instruction on lateral canal fenestration. Figure 6 outlines the dramatic upsurge in the number of labyrinthine fenestration operations that were performed by the section between 1945 and 1948 to address the significant backlog of patients with untreated otosclerosis.

The first stapes mobilization performed at Mayo Clinic was in 1955, 2 years after Samuel Rosen had revisited the stapes mobilization procedure of Kessel.[17,22] After this, the first vein plug "stapedoplasty" (stapedectomy) was performed in 1959, 3 years after Dr John J. Shea Jr first performed this

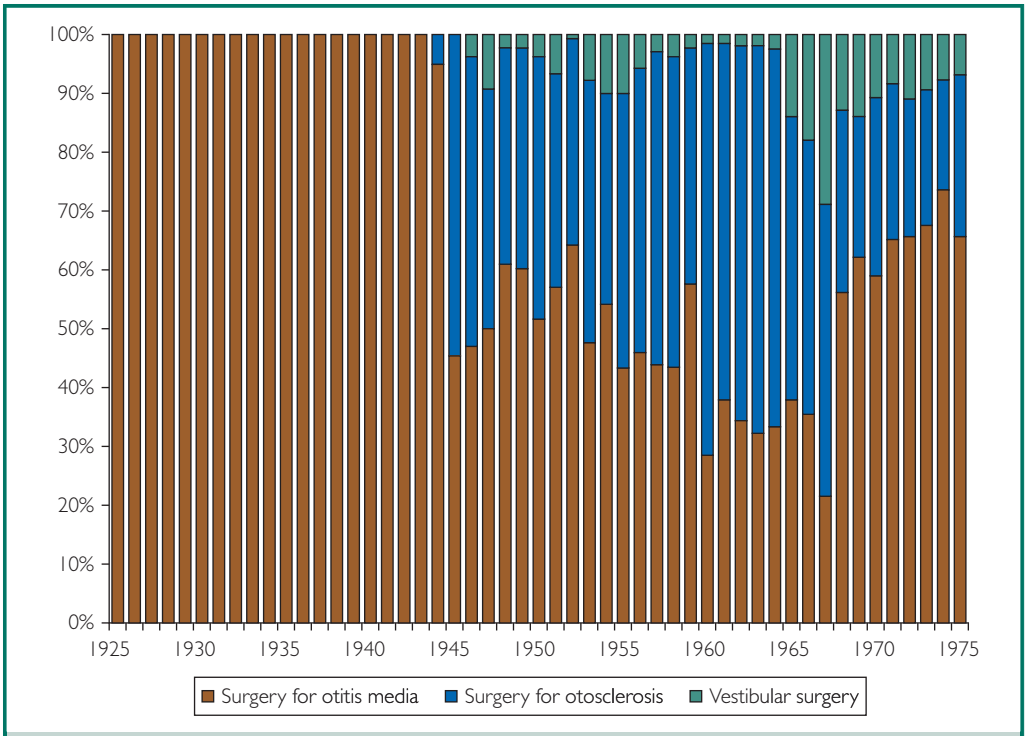

FIGURE 5. Change in otologic surgical case distribution at Mayo Clinic in Rochester, Minnesota, between 1925 and 1975.

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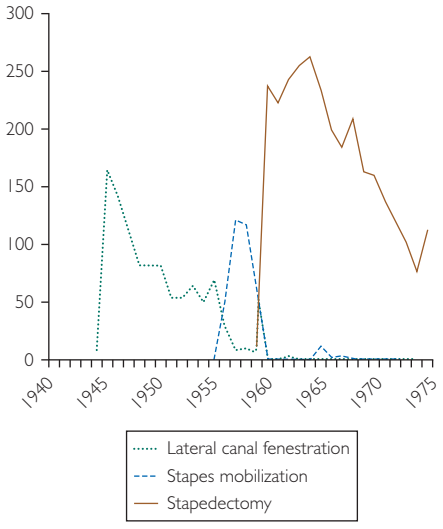

FIGURE 6. Change in otosclerosis surgical case distribution at Mayo Clinic in Rochester, Minnesota, between 1940 and 1975.

procedure on a 54-year-old housewife on May 1, 1956.[17,23] Although the techniques of stapedectomy varied significantly across the country, initially a tantalum wire (0.005 in, 36 gauge) attached to a vein graft plug taken from the dorsal hand was preferred by otologists at Mayo Clinic.[24] After several years, the technique was altered to incorporate a connective tissue plug attached to a stainless steel wire designed by Schuknecht. Only in cases of obliterative disease was a Shea Teflon piston or the stainless steel piston designed by McGee used. The success of this surgery brought great demand, with an average of 220 primary stapedectomy surgeries performed each year at Mayo Clinic for the following decade.[17] As seen elsewhere, over time there was a gradual decline in the number of stapedectomy procedures performed as the backlog of patients with advanced disease dwindled, and possibly from widespread measles vaccination.[23] In 1965, 234 stapedectomies were performed, and this decreased to 112 in 1975 and to 61 in 1985.[25,26]

MÉNIÈRE DISEASE

Near the same time that lateral canal fenestration was introduced, surgery for Ménière disease received increasing attention. If a patient failed dietary salt modifications as outlined by Furstenberg, Lashmet, and Lathrop or desensitization to histamine as recommended by Shelden and Horton, surgical intervention was considered.[27-29] Before this, retrosigmoid craniotomy with vestibular nerve section, popularized by Walter Dandy, was one of the only surgical means for treating medically refractory vertigo.[30] Secondary to the higher risk of surgery and inconsistent results, otologic surgeons, including Cawthorne, Portmann, Wright, and Day, sought alternative measures for surgical treatment.[31-33] First described in 1943 by Day, the first 11 labyrinthotomy operations were performed at Mayo Clinic in 1946, followed by 25 the following year.[33] The Day operation was described as a simple yet technical procedure performed through a mastoid exposure with lateral canal labyrinthotomy and application of weak diathermy current to the membranous labyrinth.[17] This procedure was described as highly effective and low risk, with the potential to preserve residual hearing. Over time, the transmastoid labyrinthectomy, first described by Cawthorne in 1943, was used with greater frequency.[32]

Although endolymphatic sac surgery for the treatment of Ménière disease was first described by Georges Portmann in 1926, it was several decades before it became more widely adopted by centers in the United States.[34] The first endolymphatic sac surgery was performed in 1965 at Mayo Clinic, with 32 cases the first year and an average of 18 cases per year during the following 5 years.[17] At this same time, Dr Thane Cody of Mayo Clinic described a novel surgical treatment for Ménière disease.[7,17] Dr Izhak Fick, from South Africa, had visited Rochester in 1967 to attend the first international symposium on Ménière disease.[35] It was at this conference that Fick described his pick sacculotomy procedure for Ménière disease, and it was from this collaboration that Cody developed the tack procedure. This operation involved implanting a tack prosthesis into the vestibule that would decompress the saccule during hydropic episodes.[36] In this

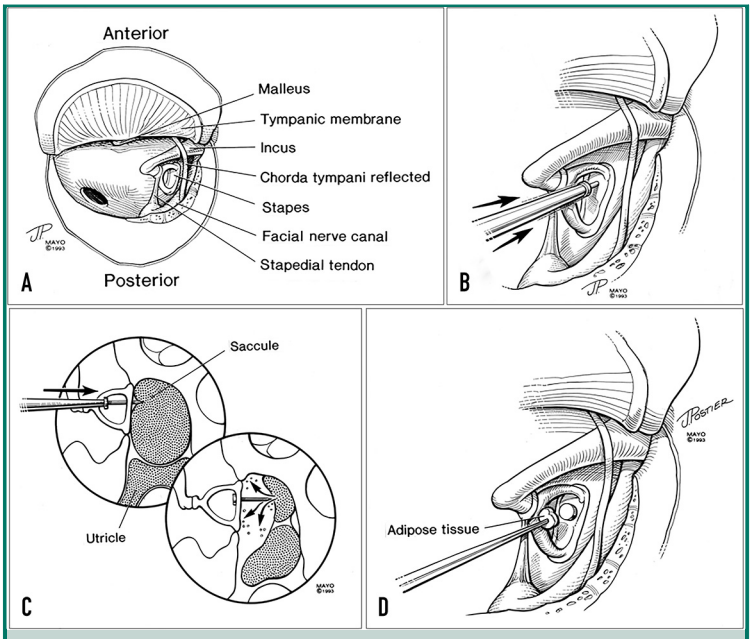

FIGURE 7. The Cody tack procedure (automatic repetitive sacculotomy) for surgical treatment of Ménière disease. A and B, Placement of a tack prosthesis through the anterior footplate. C, With endolymphatic hydrops, the dilated saccule will contact the sharp tack and decompress the membranous labyrinth. D, After tack placement, a small fat graft is placed to reduce the risk of perilymphatic fistula. From *Mayo Clin Proc.*[37] Reproduced with permission from the W. Bruce Fye Center for the History of Medicine, Mayo Clinic, Rochester, Minnesota.

surgery, a 1.0- to 1.9-mm stainless steel tack was introduced via a transcanal stapedectomy approach using a magnetic probe through the anteroinferior aspect of the footplate (Figure 7).[38] In reviewing the first 290 cases, Cody reported that vertigo was satisfactorily controlled in 79% of patients and hearing was improved or maintained in greater than 60%.[39] Given its success, the Cody tack procedure was the most common surgical procedure performed for Ménière disease at Mayo Clinic until a change in prosthesis manufacturers in the 1980s led to its disappearance. Between 1965 and 1985, 664 tack procedures were performed in total.[25,26]

A final notable contribution to the treatment of Ménière disease was the early observation that certain aminoglycosides carried ototoxic effects. As noted in the 1945 Annual Report of the Section: "Dr. H.A. Brown has encountered a side effect in the general use of streptomycin in that it affects unfavorably the ear endorgan. No suitable explanation is available yet."[17] Subsequently, in 1964 it was documented that "Dr. Vrabec's project done under Dr. Cody's direction produced a very valuable piece of original research dealing with the concentration of antibiotics in the perilymphatic fluids of the labyrinth. The results indicate the reason for Streptomycin toxicity to the labyrinth."[17] These early findings laid the groundwork for the gentamicin injection used today. That same year, Simonton and Cody[40] published their results of corticosteroid therapy for the treatment of sensorineural hearing loss.[17]

CHRONIC EAR DISEASE

In the pre-antibiotic era, the priority of otologic surgery was control of infection, and aural surgeons largely disregarded the thought of middle ear and tympanic membrane reconstruction for hearing improvement, particularly in patients with recurrent acute or chronic infection.[41] Furthermore, during this era, technologies were primitive, audiological testing was onerous and inaccurate, and the diseased ear was frequently left wasted by severe acute and chronic otitis media.

Between 1930 and 1970, surgery for acute and chronic ear disease evolved dramatically. Before the 1940s, radical mastoidectomy was used nearly exclusively at Mayo Clinic given its ability to reliably eradicate disease and create a "dry and safe ear." Because of the poor hearing outcome associated with radical mastoidectomy, several groups in the early 1900s began to explore more conservative mastoid approaches, leaving an intact and undisturbed tympanic membrane and ossicular chain when feasible. Although several descriptions were published, the classic modified radical mastoidectomy described by Bondy in 1910 is the only lasting relic from these early years.[10] At the time of description, however, conservative mastoid surgery was out of favor, and it was not until the late 1930s that Mayo Clinic and other centers in the United States considered the Bondy

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mastoidectomy a viable alternative to radical mastoidectomy in select patients.[41] Also during this time there was a change in the operative incisions used. Before 1940, surgery for chronic ear disease at Mayo Clinic was performed through a standard postauricular incision. However, when endaural surgery was popularized for lateral canal fenestration by Lempert, endaural approaches for chronic ear disease were used with greater frequency because it was believed that the incision inherently made the middle ear more accessible.[41,42] The postauricular incision was still widely used for extensive cholesteatoma, otogenic complications such as lateral sinus thrombosis, labyrinthectomy, and other operations in which the middle ear was not accessed.

The 1950s and 1960s marked a second significant turning point in the surgical treatment of chronic ear disease as outlined in O. Erik Hallberg's 1958 publication "Operations on the Middle Ear and Mastoid: Changing Aspects of Treatment in Chronic Active Disease."[41] Reflected in the case numbers, obliterated cavity and intact canal wall surgeries were gaining favor given patient preferences for avoiding an open cavity and demand for better hearing outcomes.[41] During this decade, 740 classic modified radical and radical mastoidectomies were performed at Mayo Clinic — with nearly an even distribution between the two.[21] By 1955, several of the surgeons were experimenting with intact bridge mastoidectomy in select patients, a forerunner to the refined intact canal tympanomastoidectomy popularized by House and Sheehy in the 1960s. By the 1960s, intact canal wall was used with greater frequency at Mayo Clinic. A 1977 publication by Cody and Taylor reported that from 1963 to 1969, 40% of mastoid operations were open cavity, 19% were obliterated cavity, and 41% were intact canal wall operations.[43]

As Thane Cody outlined in a 1969 publication in *Mayo Clinic Proceedings*, during this year there were 3 primary discoveries that drove the success of myringoplasty and tympanoplasty: (1) Wullstein's description of denuding the remnant tympanic membrane and placement of a postauricular skin graft on the lateral surface in 1950; (2) Austin and Shea's report of freshening the edges of the perforation and placing a vein graft medial to the remnant drum, supported by absorbable gelatin sponge, in 1961; and (3) Storrs' description of temporalis fascia use for tympanic membrane reconstruction that same year, which proved more durable than the former 2 techniques.[37]

Regarding restoration of the middle ear sound-conducting mechanism, a variety of methods using autograft and homograft incus interposition and synthetic substrates were devised.[21,37,44,45] A favored method of the surgeons at Mayo Clinic in the 1960s was the use of a double loop wire prosthesis, where various defects, such as a long process of incus to head of stapes or head of malleus to head of stapes, could be reconstructed (Figure 8). In patients with an absent malleus and incus with an intact stapes suprastructure, a myringostapediopexy was commonly used with satisfactory results.[37] In subsequent years, the incus interposition and use of cartilage was used with increasing frequency given lower rates of extrusion. Over time, improvements in titanium alloys and growing concerns over viral and prion disease transmission with allographic material led to a transition to manufactured middle ear prostheses.[46] Despite significant

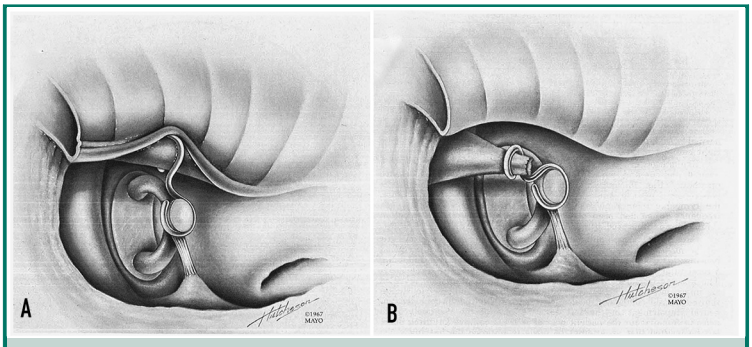

FIGURE 8. Transcanal views of the right middle ear. A, The long and lenticular processes of incus are absent. A double loop wire prosthesis has been used to unite the handle of malleus and the head of the stapes. B, The lenticular process of incus is missing. A double loop wire prosthesis has been used to unite the long process of incus and the head of the stapes. From *Mayo Clin Proc.*[37] Reproduced with permission from the W. Bruce Fye Center for the History of Medicine, Mayo Clinic, Rochester, Minnesota.

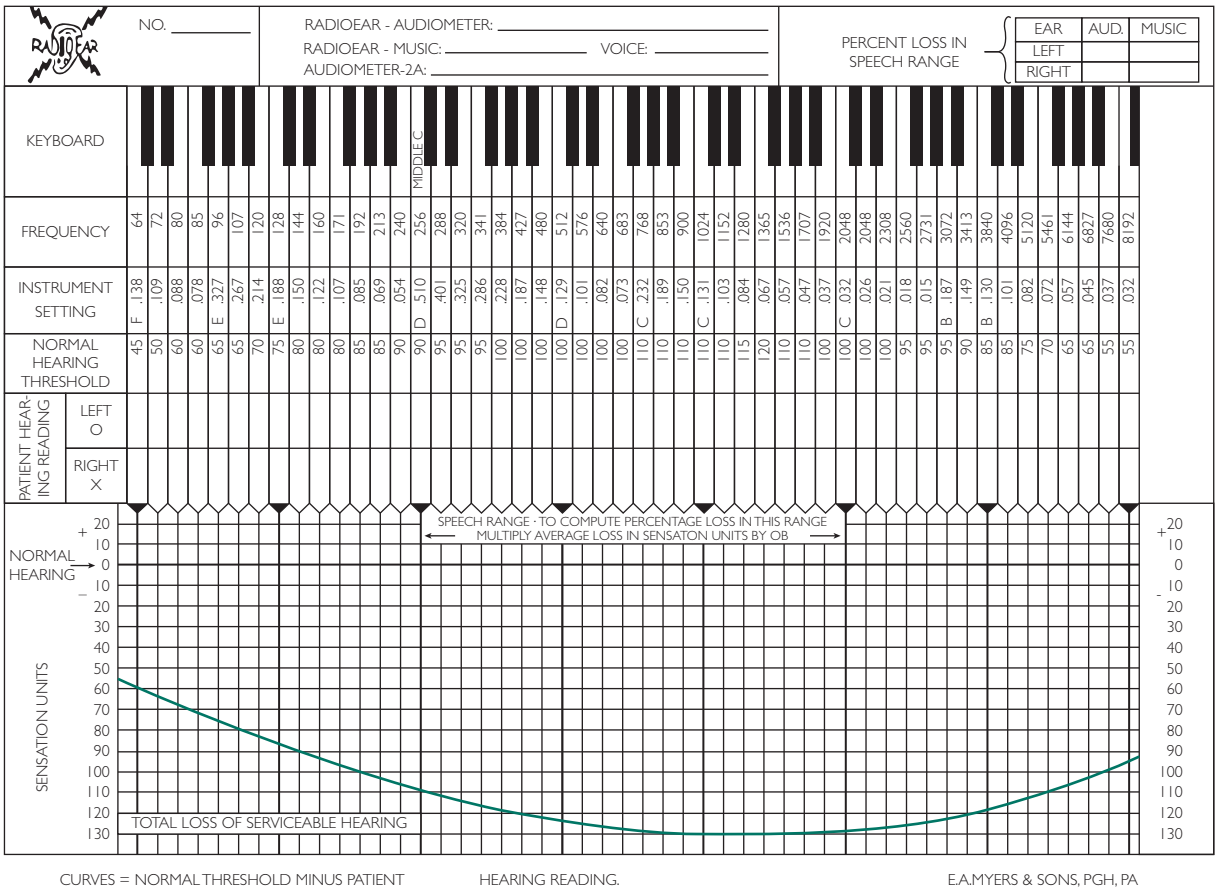

FIGURE 9. Audiogram worksheet intended for use with the Radioear dual audiometer type DO-25. The Radioear dual audiometer type DO-25 was supplied to Mayo Clinic in 1930 and was capable of reproducing the tones and half-tones of the piano. In addition to these tonal frequencies, the audiometer integrated a phonograph for measuring the level at which music was heard and a microphone for testing speech recognition.[7,48] Reproduced with permission from the W. Bruce Fye Center for the History of Medicine, Mayo Clinic, Rochester, Minnesota.

strides in prosthesis development, consistent satisfactory air-bone gap improvement remains an elusive goal in otologic surgery even today, particularly with total ossicular chain reconstruction.

AUDIOLOGY

Although Harold Lillie had experimented with objective measures to quantify hearing levels as early as 1924, hearing acuity was still commonly assessed using imprecise methods such as the whispered voice, watch tick, and tuning fork examination into the early 1940s.[17,47] For example, 6 tuning forks were commonly used for gross audiometric testing at octave intervals between 128 and 4096 Hz. Air and bone conduction thresholds were estimated using the Schwabach test, where the difference between the patient's and the examiner's thresholds were measured in seconds, and the Rinne test, where the difference in patient thresholds for air conduction and bone conduction were examined via tuning fork.[18] A cumbersome Radioear dual audiometer (E. A. Myers & Sons) was acquired by Mayo Clinic in 1930 but was rarely used for clinical purposes because of the impractical design (Figure 9).[7,48] At this same time, the duty of vestibular testing was transferred to the resident physicians. Bithermal caloric testing was performed using water irrigation at 95°F

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and 101°F for 60 seconds, and the period of nystagmus was timed.[7] After a period of rest, rotational testing was performed in the horizontal and vertical planes. After the patient was turned 10 revolutions, the resulting nystagmus was once again timed.

Beginning in the 1940s, the need for improved audiovestibular diagnostic testing became increasingly apparent as the demand for otosclerosis and vestibular surgery rose steeply.[17] Initially a graduate nurse, Margaret Thomas, began serving as an audiometrist, devoting 2 to 3 hours daily.[7,17] During this time, a General Electric 6-A audiometer and, subsequently, 2 Maico audiometers were acquired for clinical audiometric testing.[7,48] Despite significant controversy in the otology field about the requirement for a noise-insulated room for testing, Mayo Clinic chose to move forward with construction of a custom-built dedicated soundproof booth in 1947.[17] The benefits of dedicated testing facilities were soon realized, and 7 additional prefabricated sound suites were installed in 1966.[17] At a time when the field of audiology was still very young, Williams presented to the Board of Governors a plan to establish an "audiometric and hearing advice unit" in 1948. Ultimately, after considerable deliberation, LeRoy D. Hedgecock, PhD, was hired as the first dedicated consulting audiologist at Mayo Clinic in 1949.[7,48] Hedgecock served as the head of the Department of Audiology through 1971, and during this time he trained a complement of proficient audiologists and audiometric technicians.[48] Before joining Mayo Clinic, Hedgecock worked as a speech pathologist at Indiana University and the University of Minnesota from 1944 to 1949. As a result of his previous experiences, Hedgecock introduced speech pathology to the Clinic practice in 1949 and specialized in this field until Josephine Simonson, MA, Fredric L. Darley, PhD, and Arnold E. Aronson, PhD, were appointed speech-language pathologists in the Department of Neurology approximately 6 years later.[7] After 1950, differential ice water calorics were used, and an observer would record the presence, direction, and intensity of induced nystagmus.[7] Electronystagmography was first used in 1964, when Dr Jack Pulec converted a Swedish electrocardiogram machine to detect corneal retinal potentials based on Nils Henriksson's thesis on electrical analysis of eye movements in nystagmus in 1956.[35] An apparatus was devised through the department of engineering for administering alternate binaural bithermal calorics, a technique first reported by Fitzgerald and Hallpike in 1942.[49]

Also during this time, between 1964 and 1966, were the notable contributions of Thane Cody to the development of auditory evoked myogenic and cortical potentials, precursors to modern-day auditory brainstem response and vestibular evoked myogenic potential testing.[50-52] In 1965, Cody and Bickford found that the intensity of pure tones when the scalp vertex response disappeared offered an objective and accurate method of assessing auditory levels in awake patients or when in a moderate to deep sleep.[53,54] Cody called this test *cortical audiometry*.[55] These studies were performed approximately 5 years before Jewett and Williston were credited with describing the human auditory brainstem response signature in 1971 and decades before vestibular evoked myogenic potentials were first used clinically.[18,52]

Together with Terry Griffing, MS, a clinical audiologist who joined the audiology staff on June 1, 1959, Hedgecock developed and validated a screening test for the Minnesota Preschool Survey of Vision and Hearing, the Verbal Auditory Screening for preschool Children (VASC), which gained widespread adoption.[17,56] The early success of the audiology program led to formal establishment of the Section of Audiology in the Department of Otolaryngology in 1972.[17] By this time, the newly formed division was already performing 13,000 audiograms and 1800 electronystagmography tests annually. In 2001 the Section of Audiology was formally renamed the Division of Audiology.[48]

NEUROTOLOGY

Although otology remains the focus of this report, the history of otologic surgery at Mayo Clinic would not be complete

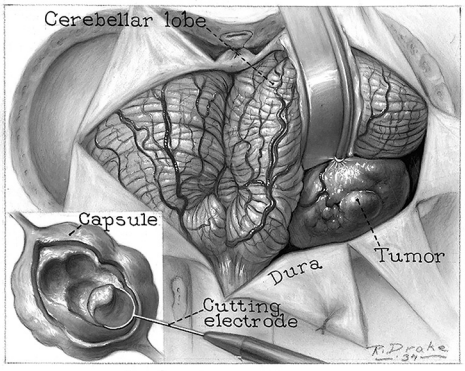

FIGURE 10. Illustration from 1934 depicting wide suboccipital craniectomy for resection of a left-sided vestibular schwannoma using the technique of piecemeal intratumoral debulking followed by capsule dissection. Reproduced with permission from the W. Bruce Fye Center for the History of Medicine, Mayo Clinic, Rochester, Minnesota.

without reference to the co-development of neurotology and modern lateral skull base surgery. The Mayo Clinic Department of Neurosurgery is one of the oldest and largest neurosurgical programs in the country.[57] Before the 1960s, vestibular schwannoma surgery remained largely within the purview of the Department of Neurosurgery, performed exclusively through a suboccipital approach (Figure 10).[58] Dr Jack Pulec was the first fellowship-trained neurotologist to join Mayo Clinic. Before joining the staff in 1964, Pulec completed fellowship training at the Otologic Medical Group in Los Angeles during the time when Drs William House and William Hitselberger were refining the subtemporal middle fossa and translabyrinthine approaches for vestibular schwannoma resection with the aid of the electric drill and operative microscope (Figure 11).[59-61] After his fellowship, Pulec was eager to establish a similar collaboration between the neurotologist and the neurosurgeon, believing that patients would benefit from the combined expertise of these complementing specialties.[35] During the 5 years that Jack Pulec was on staff he collaborated with several key members of the neurosurgical department, including Dr Albert Rhoton Jr. Through this collaboration, several seminal papers on microanatomy of the facial nerve and posterior fossa microsurgery were completed.[62,63] Jack Pulec had a very strong interest in facial nerve tumors and compiled the largest series of the time.[64,65] He also first described the combined mastoid–middle cranial fossa approach for removal of facial nerve schwannomas.[64]

This strong partnership between neurotology and neurosurgery toward treatment of skull base disease, in particular vestibular schwannoma, has strengthened over the years through collaborations with several key neurosurgical colleagues, including Dr Albert Rhoton Jr, Edward R. Laws Jr, Michael J. Ebersold, and, currently, Drs Michael J. Link and Jamie J. Van Gompel. Mayo Clinic was the third center in the United States to install a Leksell Gamma Knife unit for radiosurgery in 1990, and it currently remains one of the few centers to equally employ radiosurgery, microsurgery, and conservative observation for the approximately 150 new vestibular schwannoma consultations performed each year. Most recently, in February 2018 the Department of Otorhinolaryngology received approval from the Accreditation Council for Graduate Medical Education for a fellowship program in neurotology and lateral skull base surgery.

COCHLEAR IMPLANTATION

Although there have been a variety of notable accomplishments in the field of otology in the past century, in recent years the specialty has been primarily defined by innovations in the surgical treatment of sensorineural hearing loss. Before the invention of cochlear implants, patients with advanced bilateral deafness from congenital, sudden, or progressive sensorineural deficits were left with no hope of aural rehabilitation. Cochlear implantation marks one of the greatest modern technological innovations not only within the specialty but also in all of medicine, as deafness remains the only sense that can be dependably restored.

The modern period of otologic surgery at Mayo Clinic was inaugurated by the first

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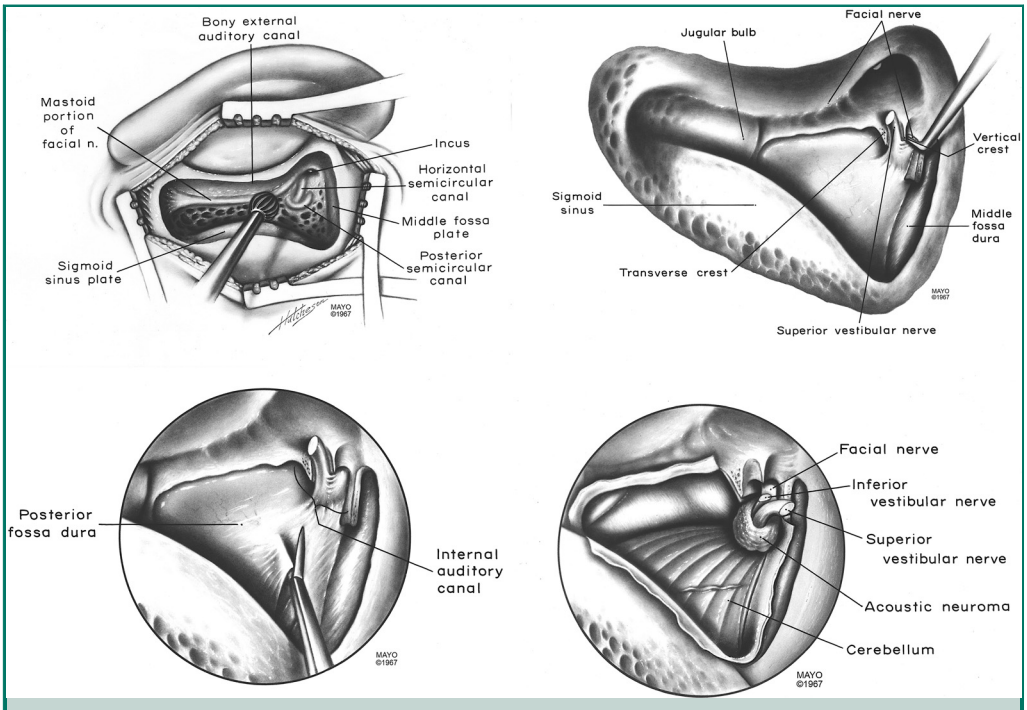

FIGURE 11. Illustrations from 1967 depicting the translabyrinthine approach for resection of a left-sided vestibular schwannoma. Reproduced with permission from the W. Bruce Fye Center for the History of Medicine, Mayo Clinic, Rochester, Minnesota.

cochlear implant surgery performed at Rochester Methodist Hospital on December 17, 1982, by Dr George Facer.[48] Most of the early cochlear implant surgeries used a single electrode placed at or just through the round window membrane. During these first years, the number of cochlear implant surgeries performed was sparse because patient benefit was largely restricted to enhanced lip reading, voice modulation, and recognition of limited environmental sounds, while open set speech recognition was uncommon.

On November 26, 1984, the first single-channel cochlear implant system was approved by the Food and Drug Administration for adults with bilateral profound postlingual deafness. Subsequently, in October 1985 the first multichannel cochlear implant was approved in the United States. Single-channel designs were soon replaced by multichannel cochlear implants after witnessing the benefits of improved spectral perception and open set speech recognition. Over time, candidacy criteria have expanded and now include children and adults with greater degrees of residual hearing.[66]

More recently, cochlear implantation has demonstrated benefit even in subgroups of patients with retrocochlear pattern hearing loss, a condition that has traditionally been considered a contraindication to implantation. Mayo Clinic continues to be a leading center for cochlear implant research in neurofibromatosis type 2 and auditory neuropathy.[67-69] In the most recent years, the use of cochlear implantation for the treatment of single-sided deafness and intractable tinnitus has become a major focus of attention.[70] Since the first cochlear implant surgery was performed at Mayo Clinic in 1982, cochlear implantation has remained a major focus of the department. The 1000th cochlear implant was performed on August 30, 2013, and each year more than 150 patients undergo implantation.

CONCLUSION

This historical account serves to commemorate a formative period in the history

of otologic surgery at Mayo Clinic and to remember the contributions of our predecessors. This narrative also illustrates the importance of continuous innovation and discovery to ensure the growth and advancement of our specialty. From the treatment of life-threatening complications of acute suppurative otitis media in the pre-antibiotic era to the management of profound sensorineural hearing loss in more recent years, the history of otology has been marked by innovation, driven by a force of dedicated physician-scientists.

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SUPPLEMENTAL ONLINE MATERIAL

Supplemental material can be found online at http://www.mayoclinicproceedings.org. Supplemental material attached to journal articles has not been edited, and the authors take responsibility for the accuracy of all data.

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