The history of neuroradiology begins almost simultaneously with Röntgen’s first description of the magic rays, but the discipline of neuroradiology developed over the span of many years. Most early practitioners did not devote their efforts solely to radiology or even to diseases of the nervous system; not until well into the twentieth century were there more than anecdotal reports of the use of X rays in the diagnosis of diseases of the central nervous system.

As a separate discipline within the field of radiology, the history of neuroradiology has been amply documented in several well-written treatises. Most recently Juan Taveras adroitly divided the chronology of the development of neuroradiology into four eras: (1) the early period ran from the discovery of X rays by Röntgen in 1895 to 1918, the landmark development in the latter year being the introduction of air ventriculography; (2) the next era extended from 1919 to 1939, during which technical advances, and particularly the development of contrast materials and techniques for their use, enabled physicians to obtain an indirect view of the nervous system by opacifying the spaces and vessels that surround it; (3) from 1940 to the early 1970s, neuroradiology established its identity as a separate discipline in terms of practice, research, and education. It was also a time of major advances in the description of neuroradiologic anatomy, radiologic-pathologic correlation, and improvement in safety of procedures—one might say it was the beginning of neuroradiology by neuroradiologists; and (4) the year 1972 marked the beginning of the fourth and present era, that of noninvasive sectional imaging. During this era technical advances achieved by the marriage of computers and imaging techniques provided the first direct images of neural tissue and nurtured the development of interventional neuroradiology.

We will follow Taveras’s lead and consider neuroradiologic achievements and achievements within each era. Although North American achievements in neuroradiology loom largest, it would be difficult to gloss over worldwide contributions with conceptual impunity. Especially in the early eras of neuroradiology, our aim is to supply sufficient narrative of international activity to give the present a more realistic historic habitation and name—a just courtesy to those upon whose shoulders we stand.
THE EARLY PERIOD, 1895–1918

As in most other specialized areas of medicine, the systematic radiologic study of the central nervous system began in Europe, and numerous early scientific observations are attributed to surgeons, general physicians, and physicists. Many were pessimistic about how effective a tool the X ray would prove to be in looking at the nervous system. W. W. Keen of Philadelphia remarked in 1896 on the failure to obtain a satisfactory radiograph of the skull using a one-hour exposure. He said, "In tumors of the brain, the bones of the head (especially as the rays would have to penetrate two thicknesses of bone) will absolutely preclude any use of this method in diagnosis." Scattered reports of radiographs of gunshot wounds of the head and neck appeared between 1896 and 1900.

A report of a brain tumor localized clinically by the roentgen rays appeared in 1902. This was the work of Charles K. Mills, a neurologist, and George E. Pfahler, a radiologist (contemporaries called him an "X-ray man"), both of the Philadelphia General Hospital. Their radiograph demonstrated a large density lying between the coronal suture and posterior meningeal artery and corresponding to the area from which the tumor was removed. To verify these findings, Dr. Pfahler also examined a healthy subject to be certain that no similar density was present. Looking at the films today, one suspects that Pfahler was describing either a hair braid or perhaps some sclerotic change in the parietal bone.

In 1902 Béclère, a Frenchman, used radiography to demonstrate acromegaly in a twenty-four-year-old woman. He described hyperostosis frontalis interna, enlargement of the frontal and maxillary sinuses, and increase in the dimensions of the pituitary fossa, diagnostic signs that are still taught to radiologists today.

Most would agree that the first person to systematically study radiography of the skull was Arthur Schüller of Vienna, who published a textbook (Roentgen Diagnosis of Disease of the Head) on the principles of skull radiography in 1905; it was translated into English in 1918. He demonstrated calcification in the pineal gland and offered an early description of Paget's disease of bone. In his book, Schüller stated that early radiologists:

...sought to distinguish, directly on the roentgen picture...soft...tissue changes such as hemorrhages and accumulations of pus in the brain and meninges. It was quickly apparent that those authors who had been able to obtain such pictures had been deceived by phantoms, so that their observations have delayed rather than hastened the progress of knowledge in this sphere.

Perhaps Schüller was referring to the tumor seen on X ray by Mills and Pfahler in 1902.

Schüller included very few radiographs in his textbook; the bulk of the material is a series of line drawings of

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**Table 12.1**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1896</td>
<td>Harvey Cushing uses X rays to evaluate a patient with a gunshot wound to the neck.</td>
</tr>
<tr>
<td>1902</td>
<td>In Paris, Béclère shows skull radiographs of a healthy woman and images of a twenty-four-year-old with acromegaly.</td>
</tr>
<tr>
<td>1904</td>
<td>Pfahler presents a paper on &quot;Cerebral Skiagraphy&quot; at ARRS's annual meeting in St. Louis.</td>
</tr>
<tr>
<td>1905</td>
<td>Schüller of Vienna publishes his first book on skull radiography. Some investigators (Bull and Fischgold, 1967) consider him to be a neuroradiologic pioneer of stature.</td>
</tr>
<tr>
<td>1906</td>
<td>Schüller demonstrates a calcification in the pineal body.</td>
</tr>
<tr>
<td>1913</td>
<td>Stewart describes and portrays air in the ventricles of a patient who sustained a skull fracture.</td>
</tr>
<tr>
<td>1914</td>
<td>Waters's view of the paranasal sinuses.</td>
</tr>
<tr>
<td>1918</td>
<td>Development of air ventriculography (attributed to Dandy).</td>
</tr>
<tr>
<td>1919</td>
<td>Development of pneumoencephalography (attributed to Dandy).</td>
</tr>
</tbody>
</table>
the sella turcica in sagittal projection showing the various changes that occur as the result of intracranial masses and diseases involving the calvarium. One chapter discusses the influence of birth, occupation, position, and race upon the shape of the head. There was a common belief at the time (1905) that large brains "characteristic of greater intelligence seem to occasion the large skulls of those belonging to higher calling."14

In summarizing Schüller's accomplishments Lindgren stated that rather than the "father of neuroradiology," Schüller should be considered as "one of its forerunners," because he expressed no interest in contrast media studies characteristic of true neuroradiology. Lindgren felt that Schüller's work and the work of those who preceded him basically qualified as roentgenology of the skull rather than the brain.15

In 1912, foreshadowing the seminal role that Swedes would play in the development of neuroradiology, Folke Henschel, a neuropathologist, reported a case of acoustic neurinoma in which X rays of both temporal bones, taken by colleague Gosta Fossell, revealed an enlarged internal auditory canal. The diagnosis was suspected because of the earlier pathologic studies by Dr. Henschel (showing enlargement of the porus acusticus in neurinomas) and was subsequently confirmed at autopsy.16

Although its significance could not be imagined at the time, a paper by J. Radon (a brilliant Austrian mathematician) appeared in 1917.17 The work of Radon was cited by Gordon and others as having proved that a two-dimensional or three-dimensional object could be reconstructed from the sum of its projections.18 Years later this concept was to become the basis on which the first computed tomography (CT) scanner was developed.

A chance occurrence which, in retrospect, was of great importance was a 1913 case report by W.H. Luckett that detailed the story of a man who suffered a fracture of the posterior wall of the frontal sinuses. Just prior to repeat X-ray examination (by W.H. Stewart) the patient sneezed and had a "pain in my head and then a flow of a large amount of clear fluid came from my nose." The radiograph obtained at that time showed gas or air in a dilated ventricular system. The patient died three days later, and autopsy confirmed a depressed fracture of the posterior wall of the frontal sinus extending through the orbital plate.19

**INTRODUCTION OF CONTRAST MATERIALS AND PRECISION RADIOGRAPHIC EQUIPMENT, 1919–1939**

Early investigators were quick to note that certain substances, due to differences in the way they absorb X rays, could enhance radiographic demonstration of spaces, potential spaces, and organs in the body. As in all radiologic specialties, development of innovative techniques in neuroradiology was facilitated by individuals who sought to overcome current limitations in quest of better, brighter, more detailed diagnostic images.

**Walter Dandy**

Foremost among these was Walter Dandy, a neurosurgeon at the Johns Hopkins Hospital. As he wrote in an initial article describing the use of air ventriculography in twelve children:

For some time I have considered the possibility of filling the cerebral ventricles with a medium that will produce a shadow in the radiogram. If this could be done, an accurate outline of the cerebral ventricles could be photographed with X rays, and since most neoplasms directly or indirectly modify the size or shape of the ventricle, we should then possess an early and accurate aid to the localization of affections. In addition to its radiographic properties, any substance injected into the ventricles must satisfy two very rigid exactions: (1) It must be non-irritating and non-toxic; (2) It must be readily absorbed and excreted.

He went on to say that it was because of frequent observations by others:

...on the remarkable power of intestinal gases 'to perforate bone' that my attention was drawn to its practical possibilities in the brain...paranasal sinuses and mastoid air cells show up in the thick skull by virtue of the air.
The pathological conditions of the sinuses are evident because inflammatory or tumor tissue replaces the air. From these and many other normal and pathological clinical demonstrations of the radiographic properties of air, it is but a step to the injection of gas into the cerebral ventricles—pneumoventriculography.20

Dandy described a method of injecting the ventricles either through an open fontanelle or through a small craniotomy and the use of gravity to control the location of the fluid.

One year later Dandy noted that air which had been injected into the lateral ventricle appeared over the surface of the brain in subsequent films.21 He surmised that for the air in the ventricle to reach the sulci, it “must have followed the normal pathways by which cerebrospinal fluid circulates.” Since he realized that many brain lesions affect part of the subarachnoid space and that meningeal inflammation could obliterate the cisterns, he believed that other conditions might be demonstrable by the absence or presence of air over the cerebral hemisphere. Dandy described the technique of pneumoencephalography via direct injection of air into the spinal canal; he also discussed the progressive disappearance of the air, pointed out the anatomy of the cisterns, and predicted “that we shall be able to localize spinal cord tumors by means of intraspinal injections of air.” Dandy also described the use of pneumoencephalography for the diagnosis of atrophy and of communicating and noncommunicating hydrocephalus, as well as the location of cerebral and cerebellar masses. His technique, with some modification, was to remain in vogue for more than fifty years.

Myelography

Radiographic demonstration of the spinal subarachnoid space using contrast media or air to enhance anatomic detail began in 1921, when Jacobaeus, a professor of medicine in Stockholm, used the technique in three patients. In one of the patients “the air column stopped somewhat below the lower limit of the tumor.” The article contained no images because “the X-ray pictures obtained by this method of examination are however so difficult to read and so diffuse that no successful reproduction can be considered possible.”22

In 1922 Sicard and Forester of France carried out myelographic procedures using an iodized oil (Lipiodol) as the contrast medium.23 Sicard had developed a reputation for the treatment of pain, particularly sciatica.24 He often used Lipiodol for this treatment and incidentally noticed that it was an excellent X-ray contrast substance. One day a pupil of Sicard’s injected Lipiodol into a patient’s lumbar muscles and withdrew cerebrospinal fluid into the syringe. They immediately placed the patient in an upright position, examined him using fluoroscopy, and noticed that the Lipiodol dropped to the bottom of the subarachnoid space.25 Although many contrast materials subsequently have been developed, including nonionic, water-soluble varieties, neuroradiologists still take advantage of this difference in specific gravity between contrast material and spinal fluid to position contrast material precisely in the area of interest.

American investigators also expanded the use of myelography. Mixter and Barr pointed out the role of intervertebral disk rupture in producing back pain and sciatica. They reported the surgical repair of herniated disks and used Lipiodol myelography to assist in the diagnosis.26 In 1936 Hampton and Robinson reported the roentgen demonstration of rupture of the intervertebral disk into the spinal canal using Lipiodol.27 Iodized oil continued to be the standard contrast material for myelography for the next ten years.

Egas Moniz

Egas Moniz must certainly be the most interesting and charismatic person in the history of neuroradiology; his inventive range crosses many narrative boundaries. Tondreau’s monograph on him is subtitled “Father of Cerebral Angiography, Father of Psychosurgery, Neurologist and Psychiatrist, Politician and Diplomat, Nobel Laureate.”28 Antonio Caetano de Abreu Freire was born in Avanca, Portugal, in 1874 and later
adopted the pen name of Egas Moniz, a gallant Portuguese nobleman of the twelfth century. He received a bachelor of medicine degree from the University of Coimbra in 1899 and took further training in neurology and psychiatry in France under Pierre Marie, Dejerine, and Babinski. In 1911 he was appointed director of neurology at the University of Lisbon. An interest in politics which began in his student days led to his election to the Chamber of Deputies, and ultimately to his becoming foreign minister of Portugal and leader of the Portuguese delegation to the Versailles Peace Conference at the end of World War I.

There was little enthusiasm among neurological scientists for ventriculography in this period. Moniz felt that if the blood vessels of the brain could be visualized by radiographic means, a more precise localization of tumors could be achieved. He postulated that the vascular pattern seen in neoplasms would be different from normal; that vascular tumors would cast a dense shadow. Moniz attempted to outline the brain radiographically with some positive contrast material. He intended to either opacify the brain itself by intravenous or parenteral administration of an opaque substance or by the intra-arterial injection of an opaque substance. According to Bull, "he failed in the first, but succeeded in the second." Moniz performed in vivo studies in dogs and rabbits to determine the characteristics of sodium bromide and sodium iodide. Strontium bromide was thought to be less toxic and was therefore the first to be injected into patients. He had toyed with the idea of using Lipiodol, but feared that it might cause emboli. After a patient died following the injection of strontium bromide, he settled on a 25 percent solution of sodium iodide.

Several attempts at arteriography in humans failed because the patients experienced pain, possibly from extravascular injections. Other studies were degraded by patient motion, but in the ninth case, a young man of twenty with a pituitary tumor; a successful radiograph was produced. In 1927 Moniz presented his work to the Neurological Society of Paris. Before the presentation, in a conversation with Babinski and Sicard, Sicard asked Moniz whether he was bringing something new to the meeting to help localize brain tumors. Moniz showed Sicard the angiograms. After Moniz's presentation Babinski said that if the technique proved safe neurologists would be grateful for the discovery that "would enable us to localize intracranial tumors, the site of which is often difficult to determine."

Moniz's colleague Jose Pereira Caldas devised a radial carousel—a manually operated turntable permitting the exposure of six films in rapid sequence to allow visualization of the arterial, capillary, and venous phases—an important effort because the contrast medium moved quickly through the vessels and valuable information needed to be captured in each phase. Moniz employed sodium iodide for his first three hundred cases, but because of a number of complications, particularly hemiplegia, he ultimately switched to Thorotrast (thorium dioxide).

Over the next several years Moniz and colleagues made significant physiological observations. They realized that the capillary barriers of the internal and external carotid arteries were different; flow through the brain was rapid, while the capillaries of the soft tissues of the head and neck offered great resistance.

Not only did Moniz provide the stimulus for the development of angiography of other areas of the body, but with his neurosurgical colleague, Lima, he devised an instrument for performing frontal leukotomy in patients with aggressive and assaultive behavior without impairing their cognitive functions. Moniz was renowned as a compassionate physician and teacher. He began his research late in life and honors were slow in coming, but in 1949 he was awarded the Nobel Prize in medicine.

Early Boston Neuroradiologists

Whereas Walter Dandy was primarily interested in neurosurgical problems, Harvey Cushing, the noted neurosurgeon at the Peter Bent Brigham Hospital, worked closely with radiologists and produced a large number of publications.
Foremost among these collaborators was Merrill Sosman, who joined the staff at the Brigham in 1922; this began a ten-year collaboration between Sosman and Cushing until the latter's retirement in 1932.

Sosman was a pleasant, dependable, and entertaining colleague "full of humor and hidden warmth." He was "never intimidated by the dominant personality of Cushing who was twenty-one years his senior."[1] Neuroradiology made up only a small part of Dr. Sosman's work load. He was chairman of the radiology department at Brigham and usually had two or three residents in training. He had no other associates and personally did or supervised all of the diagnostic and therapeutic radiology in the department.[2] During Sosman's collaboration with Cushing, thirty-one neuroradiological papers were published from the Brigham. The cooperation between neurosurgeons and neuroradiologists was exemplary, and the young physicians who trained in the two departments during those years left lasting impressions on neuroscience in this country.[3] Cornelius Dyke, a devoted pupil of Sosman, became the first full time neuroradiologist at the New York Neurological Institute in 1939.[4]

Another person with an interest in neuroradiology at this time was John Camp of the Mayo Clinic.[5] Camp received his training in radiology at the Massachusetts General Hospital in the early 1920s.

**Angiographic Pioneers**

In 1936 Loman and Myerson, working at the Division of Psychiatric Research of the Boston State Hospital in Mattapan, Massachusetts, reported the first direct percutaneous puncture of the carotid artery for performing arteriography. In their report they referred to the technique as cerebral encephalography, and observed that earlier studies were generally done by "exposing the common or internal artery, ligating the vessel, and rapidly injecting the Thorotrast." They described "a relatively simple technique to overcome the surgical aspects" of the procedure. Using an 18-gauge needle connected to a three-way stopcock, they punctured the artery directly.[6]

Loman and Myerson recommended compression of the ipsilateral carotid artery to prevent rapid wash-out of the contrast material. They also recommended the technique of bilateral jugular vein compression to slow down the flow. Three films were obtained within nine seconds after the beginning of the injection, and usually they were able to demonstrate arterial and venous phases. Six of the eight patients illustrated in the initial paper suffered from dementia praecox; one patient was scoliosis, and another had arteriosclerosis. Human investigation committees were obviously not a source of concern to investigators in the 1930s.

Although Loman and Myerson admitted that there were already frequent reports of serious side effects from the use of Thorotrast, they reported "no immediate reaction or late untoward effects of the injection."[7] The concept of "outcome research" also was not entertained at that time.

Norman McOmish Dott, an English neurosurgeon with a Rockefeller traveling fellowship, became a junior associate in neurological surgery to Harvey Cushing in 1923 and 1924. "Using sodium iodide, he was the first person in the United Kingdom to demonstrate an arterovenous malformation of the brain by angiography.[8] A year later, using Thorotrast, he performed the first angiographic study in the United Kingdom to show a saccular intracranial aneurysm.[9]

Jessen and de Finc Licht introduced what they called arterial encephalography into Denmark in 1934; in Sweden the noted neurosurgeon Herbert Ollecrona studied vascular abnormalities by angiography.[10] Sjoqvist published a study of vertebral artery angiography in 1937, and Hemmingson published a paper in 1939 on "the arteriographic diagnosis of malignant gliomas."[11] It was obvious that the stage was set for the rapid development of angiographic techniques and diagnosis which was to mark the next two decades in Scandinavia.

**B.G. Ziedses des Plantes**

Although his contributions to the field of neuroradiology span several
ners, the original work of B. G. Ziedes des Plantes in the fields of tomography and radiologic subtraction was carried out during the 1930s. In 1931 he published an article on a special method of making radiographs of the skull and vertebral column. He mentioned that the driving stimulus of his investigations was the difficulty in making exposures when various parts were projected over each other, a problem that was especially apparent in the examination of the skull and vertebral column. He wrote:

It was felt necessary to apply a method which I had thought of earlier, and which would enable us to depict a cross-section of the object on the film. The X-ray tube and film can be moved in such a way throughout exposure that the projections of all points in the desired plane always fall in the same place on the film, while those of all points outside that plane continually change places. Consequently, a sharp image is obtained of all parts situated in that plane, while everything outside that plane is depicted more or less blurred.52

His first paper demonstrated images of the orbit and sella turcica in tomographic sagittal projections. Ziedes des Plantes applied the term planigraphy to his new technique and published his thesis "Planigraphy and Subtraction" in 1934.53 It contained detailed anatomic diagrams and accompanying radiographs of the spheno

Table 12.II

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1919</td>
<td>Jacobaeus of Stockholm describes his use of air myelography.</td>
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<tr>
<td>1922</td>
<td>Scard of Paris describes his use of myelography with iodized oil as a contrast medium, probably the first use of contrast media in the central nervous system. Scard was expert in the cytology of cerebrospinal fluid.</td>
</tr>
<tr>
<td>1924</td>
<td>Camp describes the radiographic anatomy of the sella turcica.</td>
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<tr>
<td>1925</td>
<td>Sosman publishes two classic papers in the A.J.R. on brain tumors and carotid aneurysms.</td>
</tr>
<tr>
<td>1927</td>
<td>Egas Moniz describes his use of strontium bromide and sodium iodide as contrast agents to achieve dramatic visualization of the arterial system of the brain.</td>
</tr>
<tr>
<td>1931</td>
<td>Egas Moniz publishes his first text on cerebral angiography.</td>
</tr>
<tr>
<td>1934</td>
<td>Caldas and Egas Moniz describe their development of a rapid film changer that greatly facilitates cerebral angiography.</td>
</tr>
<tr>
<td>1935</td>
<td>Lystholm describes his &quot;skull table&quot; for use in improved ventriculography.</td>
</tr>
<tr>
<td>1936</td>
<td>Hampton and Robinson assess ruptured intervertebral disks after injection of Lipiodol as a contrast agent.</td>
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<tr>
<td>1937</td>
<td>Davidoff and Dyle publish their classic text, The Normal Encephalogram.</td>
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<tr>
<td>1939</td>
<td>University of Minnesota gives a continuation course in &quot;Neurologic Roentgenology&quot; under the guidance of Harold O. Peterson, M.D.; fifty-two radiologists attend An International Conference on Cranial Radiology is held in Antwerp, Belgium; this would evolve into the Symposium Neuroradiologicum.</td>
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made of the superimposed radiograph and diapositive...I shall refer to this procedure as "subtraction."

In 1931 he applied this subtraction technique to arteriography and obtained strikingly detailed images of the carotid arteries in a cadaver. He commented:

The contrast medium had been injected into the left carotid artery, and it could therefore be expected that chiefly the capillaries of the left hemisphere would fill with contrast medium. It is difficult to establish this from a conventional radiograph, but it is quite evident after subtraction. This may give us a means of separating certain highly vascularized parts from others.54

Erik Lysholm

James Bull’s presidential address to the British Institute of Radiology in 1960 provides the best biographical data on this radiological giant.55 Lysholm was born in 1891 in Sweden, educated at Uppsala University, and continued his medical studies at the Serafimer Hospital in Stockholm, where he remained for the rest of his professional life. His M.D. thesis, submitted in 1931, was titled “Apparatus and Technique for Roentgen Examination of the Skull.”56 The apparatus was mounted on the head end of a flat table and consisted of a roentgen tube on two parallel semicircular tracks that were perpendicular to the long axis of the table and fixed to its sides. Regardless of where the tube was moved on the tracks, it was always angled toward the center of the patient’s head and was always the same distance from it and the film. Angles from the center of the track could be measured and recorded so that films could be obtained from both sides of the head at precisely the same angle and, if the patient returned for a follow-up examination, films could be obtained at the same angles for comparison. Later versions of this apparatus were separated from the table to allow more flexibility in positioning of the patient’s head and not only permit movement of the X-ray tube along the semicircular tracks, but also allow rotation of the tracks so that the tube could be placed anywhere on the surface of a virtual sphere and always be aimed at its center where the patient’s head was placed. This also assured a constant and reproducible “target-to-object” and “target-to-film” distance. This principle of an isocentric beam was later incorporated into the elegant instruments developed in Sweden in the 1960s and 1970s for isocentric pneumoencephalography.

By use of his table, Lysholm was able to perform “precision ventriculography.” He made multiple projections without moving the patient’s head, so that the air remained in constant position. When the head was moved, the same basic position could be reproduced. His use of the horizontal beam for the lateral projection was a revolutionary procedure but easily performed with his ingenious table.57

Bull notes that Lysholm was fortunate in having the assistance of a most able and dedicated engineer, Georg Schöndorfer, who, with the Stockholm School of Neuroradiology, continued to develop sophisticated neuroimaging apparatus which, forty years later, incorporated many of the principles contained in the original equipment of Lysholm and Schöndorfer.58

The First Symposium Neuroradiologicum

The first Symposium Neuroradiologicum was held in Antwerp, Belgium, in July 1939, and the initiative for the meeting came from Rudolph Thiennepont, an otorhinolaryngologist and ophthalmologist from Antwerp; the other main organizer was Dr. Chaussé of Paris. The two shared an interest in radiography of the temporal bone.59

Approximately fifty people participated in this initial symposium. Half of the twenty-one papers were devoted to otoradiology, and five of the thirteen speakers were radiologists. In addition to papers by Thiennepont and Chaussé, there were papers by Schüller, Lysholm, and Ziedses des Plantes. Also present at that meeting was James Bull, later to become director of neuroradiology at the Lysholm Department of Radiology at Queen Square, London. The symposium was limited to European participants and was felt to have been of such value that the participants decided to meet again within a few
years. Unfortunately, World War II intervened, and the next symposium was not held until 1949.

The Peterson Course at the University of Minnesota

The final noteworthy event in this era occurred from 13–15 November 1939. The University of Minnesota presented the first postgraduate course in neuroradiology in North America, under the direction of Harold O. Peterson. Peterson had just joined Leo Rigler in the department of radiology at the University of Minnesota as he put it, “thereby swelling the total number of radiologists in the department from one to two.” When Peterson informed Rigler that he was interested in chest and GI radiology, Rigler replied, “I want you to be interested in neuroradiology.” Over the next two years, Peterson reviewed all the cases of brain and spinal cord tumors ever seen at the University of Minnesota and produced a staff publication on the subject in 1939.

The president of the University of Minnesota had requested that all departments offer continuing education courses. With Rigler on sabbatical at the time, Peterson decided that the subject of his postgraduate course for physicians would be neuroradiology. He enlisted planning help from John Camp of the Mayo Clinic. The faculty also included Sosman; Dyke; Abe Baker, who was later to become professor and chairman of neurology at the University of Minnesota; James W. Kernohan, professor of pathology at the Mayo Foundation and noted for his classification of brain tumors; and Andrew T. Rasmussen, a famous neuroanatomist at the University of Minnesota.

The subject matter included plain films of the skull and spine, pneumoencephalography and ventriculography; clinical material by neurologists, neurosurgeons, and orthopedists; and neuroradiology and anatomy. Angiography was not discussed at the meeting. There was a symposium on the protruded intervertebral disk. Of the fifty-two people attending the course, fifteen were from Minnesota. The course ran eight hours per day for three days, and the tuition was $15.

Many postgraduate courses in neuroradiology would follow in the wake of Peterson’s. Their emergence signifies a growing body of neuroradiologic knowledge and signals a paradigm shift toward subspecialization, a shift that would be fueled by the rapid technological and educational developments to follow.

AMERICAN NEURORADIOLOGY, 1940–EARLY 1970s

The year 1940 marks the beginning of neuroradiology by neuroradiologists, the heyday of pneumoencephalography, cerebral arteriography, and myelography, and the appearance of myriad centers for training and practice.

New York

Cornelius Dyke assumed the directorship of roentgenology at the New York Neurological Institute in 1959 and was probably the first radiologist in the United States to devote his practice entirely to neuroradiology. In collaboration with the neurosurgeon Leo Davidoff, Dyke wrote a superb textbook on encephalography titled The Normal Encephalogram. The book is notable not only for the quality of radiographs but, more important, for its review of the history of the technique, its indications, the way it should be performed, and discussion of mortality and morbidity.

According to Davidoff, Dyke:

... never failed to be present at the operating table or in the postmortem room to verify his diagnoses or to benefit by his errors. As a consequence, his mistakes became fewer and his diagnostic acumen increased to the point where clinicians began to lean ever more heavily on his aid, and his reputation spread beyond the walls of the Institute.

Films were soon being mailed to him from all over the world, and he always "sent a prompt report, often with some kind word to soften the blow to the vanity of a hard-working colleague in Mississippi or Oregon who had failed to see for himself some obvious lesion." He was a founding member of the American Board of Radiology (ABR) and served as president of the Harvey Cushing Society from 1940–41. His death in
1942 at age forty-three deprived neuroradiology "of what surely would have been its most distinguished founder.\(^{71}\)

In 1946 Ernest Wood became director of radiology at the Neurological Institute, where he published numerous papers on a variety of neuroradiological topics as well as a book on myelography. In 1952 he became chairman of the department of radiology of the University of North Carolina. Wood's successor at the Neuroradiological Institute was Juan Taveras, who held that post until 1965.

Referred to as "the most dynamic spirit in neuroradiology in the USA" since World War II, Taveras assumed the directorship of radiology at the Neurological Institute at a time when the performance of invasive neurologic procedures was still the province of the neurologist and neurosurgeon.\(^{72}\) Of the 1950s, when the use of angiography increased, Taveras remarked, "In the few institutions where it was carried out, the injection and interpretation of findings invariably were performed by neurosurgeons, and sometimes by neurologists. Some radiologists were interested in learning something about the interpretation of angiograms and tried to generate intelligent reports.\(^{73}\)

Because there was no subspecialization within radiology at the time, there was no formal training in the United States in neuroradiology. When the National Institutes of Neurological Diseases and Blindness (NINDB) agreed to support fellowship training in neuroradiology, Taveras applied for a grant to cover the training expenses of the institution. On recommendation of the program director trainees could then apply for a special training fellowship. Taveras elected to establish a two-year program, accepting applicants who had completed their radiological training and were eligible to take the ABR examination. He commented, "I also thought it was necessary to have well-qualified applicants who were not apt to be distracted by other duties and who were likely to have made a career choice in this specialty of radiology."\(^{74}\) Taveras's program was the first to be approved and funded by NINDB. Shortly thereafter a similar program was organized at the Bronx Municipal Hospital and Albert Einstein College of Medicine by Mannie M. Schechter.\(^{75}\)

Neuroradiologic procedures began to consume increasing amounts of the neurosurgeon's time. Neurosurgeons who had visited Europe saw their colleagues becoming more and more dependent on neuroradiologists. Torgny Greitz spent a sabbatical year at Washington University in St. Louis during the late 1950s, and his presentations at a number of neurosurgical meetings throughout the United States "stimulated some neurosurgeons to ask the chiefs of radiology at their respective institutions to consider providing expert assistance in neuroradiology."\(^{76}\)

When Taveras's training program began, he was able to persuade some of the staff physicians to have the procedures on their patients performed under the supervision of a neuroradiologist. He commented:

Over a period of 12 to 18 months, it became apparent that the complication rate for cerebral angiography, when procedures were carried out by the radiologists, was noticeably lower than when procedures were carried out by others. Within a period of 2–3 years, the performance of angiography by neurological and neurosurgical residents was virtually eliminated.\(^{77}\)

One of the early members of Taveras's staff was D. Gordon Potts, who trained as senior registrar at the Atkinson Morley's Hospital in London where James Bulpin was a consultant. Potts saw approximately six hundred brain tumors and over one thousand subarachnoid hemorrhages per year. Bulpin recommended Potts to Taveras in 1959, and Potts joined Taveras's staff in 1960.

Potts recalled that although Taveras had no formal neuroradiology training, he did have a particularly strong background in anatomy, having taught it while a medical student at the University of Pennsylvania. "He had, for example, a better understanding of the anatomy of the middle cerebral artery and its branches than most neuroradiologists, and this helped to localize small supratentorial masses by angiography."\(^{78}\) Franklin roll-film changers were used at the Neurological Institute, and simultaneous biplane
filming caused considerable scatter and other artifacts. Because some of the procedures were carried out by neurologists and neurosurgeons with inadequate supervision, Potts was "amazed that Dr. Tavera was able to extract so much diagnostic information from such poor studies."79

David O. Davis, a fellow and later staff radiologist at the Neurological Institute, recalled that there were two small angiography rooms, barely 6 x 8 feet, and that most of the arteriography was done by direct percutaneous puncture. While some angiographers occasionally would perform catheter procedures, Gordon Potts felt strongly that the percutaneous method of arteriography was best. Catheter angiography gained slow acceptance because "the old Kifa catheters were stiff and dangerous, etc., and not very much progress was made, partly because of the fact that there was not enough room or fluoroscopic capability (just a little G-arm) and partly because no one was very interested because they were all needle experts."80

Davis recalled that one of the major events at the Neurological Institute was neurology rounds with H. Houston Merritt, a neurologist and dean of the medical school.81 Merritt supported Tavera’s goal of having neuroradiologists become more involved in performing procedures. By 1962 the bulk of the procedures were performed or closely supervised by neuroradiologists, and Merritt remarked, "a few years ago I thought of neuroradiology as the tail of the dog, but now I think the tail is starting to wag the dog."82

In 1964 Potts and Tavera developed a somersaulting chair for cerebral pneumography, a complex contraption resembling an electric chair, which allowed the patient to be somersaulted as many times as necessary in a forward or backward direction during pneumoencephalography or ventriculography, the point being to use gravity’s effects to diagnostic advantage. In 1965 Potts described a universal head unit—a gargantuan apparatus for skull roentgenography, pneumoencephalography, ventriculography, and angiography. It incorporated a chair that would somersault forward or backward with the head in isocentric position in relation to the X-ray beam. The film was always at 90 degrees to the central ray, and there were attachments for mechanical midline automography and linear luminography, which could be performed with a patient in any position.83

In 1964 Tavera served as president of the seventh Symposium Neuroradiologicum, which was held in New York City. Up to that time, North American participation in the symposia had been limited. The New York symposium offered the first chance for Europeans and others outside North America to appreciate the variety and quality of North American neuroradiology.

The program for the symposium contained the first advertisement for Diagnostic Neuroradiology, a textbook by Tavera and Ernest Wood, billed as the "first complete text in the English language on modern neuroradiology."84 Rather than a treatise on a limited part of neuroradiology, it was a true textbook of roentgenologic methods of diagnosis in the central nervous system. It included plain skull radiography, pneumography, angiography, and diseases of the spinal cord, including myelography. Other major sections dealt with the selection of diagnostic procedures and head injuries and their complications, chosen because, at the time, all of the diagnostic categories of neuroradiology were brought to bear in the work-up of central nervous system trauma.85 The book was an immediate success and the authors’ names became synonymous with neuroradiology to a generation of American radiologists and neuroscientists. Several years later a second edition was published. By this time Wood had returned to the Neurological Institute and Tavera had become director of radiology at the Massachusetts General Hospital. Wood died at his desk while working on the final revision of his contribution to the second edition.

Almost simultaneously with the development of neuroradiology at the Neurological Institute, another major New York program was being built by Mannie Schechter, who was among the first neuroradiologists to be given permission by neurosurgeons in the United States to perform cerebral angiography.
on their patients.\textsuperscript{87,88} A South African, Schechter trained in radiology at St. Bartholomew's in London under George Du Boulay and later at Queen Square with James Bull. C.T. Gutierrez, chief of neurosurgery at the St. Vincent's Hospital in New York, persuaded Schechter to take over neuroradiology at that institution. Gutierrez wrote:

It was a happy day for St. Vincent's and the U.S. when Mannie Schechter established the first completely independent neuroradiological unit in the U.S. Of course the NYNI, a hospital to which only neurologically affected patients were admitted, had a Department of Roentgenology, but not independent of the neurosurgeons.\textsuperscript{90}

In 1960 Schechter moved to the Albert Einstein College of Medicine, where he became director of neuroradiology. He developed a fellowship program and ran an excellent refresher course every one or two years. He and Tavera were members of the National Institutes of Health's (NIH) "Neurology Research and Training Committees A and B," which were the study sections reviewing applications for fellowship training programs in neuroradiology. Schechter served as secretary of the seventh Symposium Neuroradiologicum and was one of the founders and original editors of the journal \textit{Neuroradiology}.

Schechter's career was foreshortened by Alzheimer's disease, and he returned to South Africa, where he died in 1987 at the age of sixty-five. His colleague Lawrence Zingesser wrote, "Although today's American neuroradiologist will never have to struggle over the need to demonstrate the 4th ventricle pneumographically by using the techniques at which Mannie excelled, the acceptance of the role of the neuroradiologist by the neurosurgeon and neurologist is part of Mannie's continuing legacy.\textsuperscript{90}

\textbf{Giovanni di Chiro}

Although New York dominated neuroradiology in terms of sheer numbers during this era, there were other equally important academic centers participating in the development of this specialty. Notable among these was the National Institute of Neurological Disorders and Stroke (NINDS) in Bethesda, Maryland; Giovanni di Chiro was appointed chief of its neuroimaging section in 1958 and undertook research in virtually every aspect of neuroradiology. Known for his keen intellect, fiery oratory, and unimpeachable honesty, he applied every imaging technique to the study of the central nervous system, having seen early on that the traditional anatomic ways of imaging the brain would soon give way to "functional imaging and the wealth of non-pictorial, quantitative information about tissue characteristics and body chemistry it would provide."\textsuperscript{91} He brought nuclear medicine into the armamentarium of the neuroradiologist and goaded his reluctant colleagues to expand their horizons beyond traditional aspects of neuroradiology. He beguiled and educated through his incisive comments on papers presented at national and international meetings.

His early work was devoted to a study of the flow of human cerebrospinal fluid using Iodine-131 serum albumin, which laid the groundwork for subsequent studies of communicating hydrocephalus and cerebrospinal fluid (CSF) rhinorrhea.\textsuperscript{92} He wrote \textit{Atlas of Detailed Normal Pneumoencephalographic Anatomy} in 1961 and a companion volume in 1967.\textsuperscript{35,94} When CT was suddenly sprung upon unsuspecting neuroradiologists in 1972, they turned to these two volumes in order to make some sense out of the cross-sectional images they were suddenly called upon to interpret.

His other important contributions were in the field of spinal cord arteriography where, with Dopman and Ommaa, he reported the obliteration of spinal cord arteriovenous malformations (AVMs) by percutaneous embolization. He used positron emission tomography (PET) scanning to distinguish between recurrent tumor and radiation necrosis and later studied CSF and spinal cord motion using magnetic resonance (MR) imaging. He was president of the American Society of Neuroradiology (ASNR) and president of the 12th Symposium Neuroradiologicum held in Washington in 1982.
The Mayo Clinic, 1940–1970

John Camp was the first neuroradiologist at the Mayo Clinic. He achieved fame for his paper on the normal and pathologic anatomy of the sella turcica, an atlas of lateral skull films, and an all-encompassing article on tumors of the spinal column, spinal cord, and associated tissues. Camp was the inspiration for a generation of neuroradiologists at the Mayo Clinic, and forty-seven of the one hundred papers in his bibliography were on neuroradiologic subjects. He was president of the Radiological Society of North America (RSNA), as were two other prominent neuroradiologists at the Mayo Clinic, Hillier Baker, Jr., and O. Wayne Houser.

Camp was succeeded at the Mayo Clinic by Colin B. Holman, who was joined in 1956 by Hillier Baker, Jr. Under Holman and Baker, neuroradiology flourished at the Mayo Clinic. An angiographic room with state-of-the-art equipment was installed for cerebral angiography, fractional pneumoencephalography was introduced, and neuroradiologists soon gained control of neuroradiologic procedures. Holman was something of a gadgeter and, with F. Ballard of the Motorola Corporation, developed a method of electronic subtraction of angiographic film based on positive and negative TV cameras used to produce a subtraction image.

In 1962 Holman helped found the ASNR. In 1965 the training program at the clinic was formalized with the creation of a neuroradiology fellowship program, the two-year variety of which led to a master of science degree in radiology from the Mayo Graduate School.

O. Wayne Houser joined the neuroradiologic staff in the 1960s. The volume of neuroradiologic procedures steadily increased, and the importance of the neuroradiologic staff grew accordingly, both within the clinic and on the national and international scene. Holman, Baker, and Houser all served as presidents of the ASNR.

The West Coast

Two major centers were developing on the other side of the continent. One of these was at the University of California, Los Angeles (UCLA), where William Hanafee started the program in neuroradiology. He had spent a sabbatical year in Göteborg studying neuroradiology with Ingmar Wickbom. He had also spent some time in Oslo with Per Amundsen learning catheter angiography. The fluoroscopic unit with which Amundsen worked was of such poor quality that he was virtually catheterizing arteries blindly. Amundsen would puncture the common carotid artery and then, by means of a catheter, selectively inject the internal or external artery. Because of the inadequate fluoroscopy, however, he would inject saline and closely observe the patient. If the patient’s face blanched, he knew he was in the external carotid artery; if a little triangle over the supraorbital ridge blanched, he knew he was in the internal carotid artery.

At this time morbidity from cerebral arteriography in the United States ran about 20 percent. Hanafee noted that Wickbom had a complication rate of 3 to 7 percent, and when Hanafee returned to UCLA, using carotid catheter techniques, the combined morbidity at his institution and in San Francisco (where Thomas Hans Newton had begun to introduce catheter angiography) using needles or catheters was approximately 0.3 percent.

During his first two years back at UCLA Hanafee was on call every night. Procedures were still done mostly by neurosurgeons, but he made himself available to help and slowly demonstrated his expertise at the procedure. In the mid-1970s he took a year’s leave of absence and, returning to the department, was asked by the chairman, Gabriel Wilson, whether he would do the head and neck radiology. For the next five years the chief resident in otolaryngology was assigned to sit at Hanafee’s side and provide him with clinical information and operative findings in all of the head and neck cases that he interpreted. Hanafee thus entered a second career as a head and neck radiologist, later becoming one of the founding members of the American Society of Head and Neck Radiology.
In the early 1960s Newton adopted the transfemoral approach for cerebral angiography, using hand-shaped polyethylene catheters and injecting the contrast material by hand. Catheters and guidewires were reused after ultrasonic cleansing and autoclaving. In 1964 Newton visited Stanford University Medical School to observe selective bronchial arteriography. He learned to maneuver catheters within the aorta and shortly thereafter began to perform spinal angiography. He attempted an embolization of a spinal vascular malformation in 1967, carried out a preoperative embolization of a juvenile angiofibroma, and began treating patients with large intracranial AVMs using a variety of embolic materials including gel foam, muscle plugs, cotton, and lead pellets.

In 1964 Richard Kramer became the first fellow in neuroradiology at UCSF. Shortly thereafter Newton applied to NIH for a training grant, which enabled him to start a formal neuroradiology fellowship program which became very popular. It was particularly known for its teaching and technical excellence in transfemoral cerebral angiography. Gordon Potts said that Newton "has probably done more than any other neuroradiologist to develop selective catheter angiography techniques for brain diagnosis, and has played a significant role in the use of interventional techniques."105

Perhaps his crowning achievement was the publication, with Potts, of Radiology of the Skull and Brain.101 According to Newton, Mannie Schechter originally encouraged him to edit a comprehensive textbook of neuroradiology in 1968. Newton was familiar with neuroradiologists on the west coast of North America and Scandinavia, and Potts was more familiar with those on the east coast of North America and the British groups. Between 1971 and 1990 they produced thirteen books, nine with C.V. Mosby and the rest with their own publishing firm, Clavadel Press. Radiology of the Skull and Brain is clearly the most comprehensive textbook of neuroradiology as it was practiced before the era of CT. Volume II, in particular, is probably the most comprehensive treatise on cerebral angiography that has ever been written.

Canada

During this time neuroradiology was developing concurrently in Canada, and among the most important institutions fostering this discipline was the Montreal Neurological Institute (MNI), where Arthur E. Child served as its first neuroradiologist. But Child's successor, Donald McRae, is considered by many to be the father of Canadian neuroradiology. McRae was known for "his attention to detail, and with his great knowledge of neuroanatomy, embryology, and neuroradiology produced well-disciplined and well-trained residents."105,106

McRae's greatest interest was pneumoencephalography, but his efforts extended to echencephalography and isotopic brain scanning. Most notable was his work on the cervical spine, including asymptomatic intervertebral disk protrusions and abnormalities of the craniovertebral junction.107 He was a founding member of the ASNR and served as its
president in 1965 and 1966. In 1957 he was president of the fifth Symposium Neuroradiologicum held in Brussels.

THE MATURATION OF ARTERIOGRAPHY IN NORTH AMERICA, 1940–EARLY 1970S

Refinements in arteriographic technique span the years from 1940 to the mid-1970s, after which CT replaced much of the localizing functions of arteriography. Angiography became the most accurate method of cerebral imaging because of the parallel developments in radiographic technique, improved selectivity of arterial injection, improved contrast materials, and an expanding body of knowledge about normal and abnormal physiology and radiographic anatomy of the most minute arteries and veins of the cerebral circulation.

Rapid serial film changers were developed that could take up to six exposures per second, along with innovative developments such as vacuum cassettes to improve film-screen contact. Biplane simultaneous or alternating rapid serial angiograms could be obtained with pairs of three-phase generators coupled with high heat capacity tubes having focal spots as small as 0.1 square millimeters (mm.). These enabled the visualization of even smaller vessels by the use of magnification techniques. Femorocerebral angiography, using the Seldinger technique, shortened the time for examination of the brachiocephalic vessels and began replacing direct carotid and vertebral puncture as the standard technique.109,110 The safety of contrast media greatly improved. Use of Thorotran diminished; it was initially replaced by Diodrast and ultimately methylglucamine salts of iothalamate and diatrizoate.109,110

New narrow diameter, disposable catheters were developed which simplified navigation of even the most tortuous arteriosclerotic brachiocephalic vascular trees from either the axillary or femoral artery approach.111,112 Fluoroscopic tables with guiding tops and image amplification fluoroscopy further simplified the technique and enhanced its safety. Permanent neurological complication rates from cerebral angiography in the early 1970s had come down to well below 1 percent. Given this degree of safety, arteriography was routinely extended to patients of all ages and states of health, from neonates to the aged, because the likelihood that the neuroradiologist would gain useful information far outweighed the possibility of further harming the patient by the procedure.113

As surgical and medical therapeutic techniques improved, there was demand for greater precision in neurologic diagnosis. Brain tumors could be treated stereotactically, and precise localization and definition of the blood supply of tumors and venous drainage was needed. The technique of carotid endarterectomy required preoperative identification of stenoses and ulceration, and mapping of collateral circulation, not only in the brain, but also in the brachiocephalic vessels in such entities as "subclavian steal."

Angiography achieved preeminence in the diagnosis of stroke and head trauma. Subdural and epidural hematomas, as well as hypertensive hemorrhages, were diagnosed by angiography because extravasated blood in the brain was invisible on conventional radiography in the era before CT. American neuroradiologists of this era kept irregular hours and were subject to frequent emergency calls to perform angiography in patients with suspected intracranial bleeding. If the diagnosis was subarachnoid hemorrhage, the neuroradiologist determined whether there was an aneurysm or an AVM, whether there was vasospasm and, if an aneurysm was present, whether it had a surgically clippable neck.

With the advent of magnification angiography, the neuroradiologist could meaningfully comment on the presence of arteritis and generalized cerebral arteriosclerosis. This was a fruitful time for the study of the radiographic anatomy of the cerebral circulation in health and disease.

Nothing epitomized this era more than the magnum opus of Yun Peng Huang and Bernard S. Wolf—a series of radiologic-anatomic and radiologic-pathologic correlations of the Galenic venous system and later the veins of the posterior fossa, published as a series between 1963 and 1970. Each article was a voyage through intricately labeled
drawings in all possible projections with corresponding radiographs. In addition to anatomic studies, there were monographs on how these structures could be used to study the vascular shifts produced by various posterior fossa and brainstem masses. To decipher their twenty-one-page monograph on the vein of the lateral recess of the fourth ventricle requires the patience of a Talmudic scholar.¹¹¹ The subject of "veins of the posterior fossa" struck fear in the hearts of a generation of radiologists preparing for the ABR examination. The work of Huang and Wolf was truly monumental and yet, within five years of its completion, was of only academic interest because its use in the localization of brainstem and posterior fossa masses was rendered irrelevant by the advent of CT.

THE ERA OF SECTIONAL IMAGING, 1972 TO THE PRESENT

Computed Tomography

The development of CT was a quantum leap forward in the ability to diagnose diseases of the brain parenchyma, the spinal canal, and regions of the head and neck. The prototype instrument developed by EMI Ltd. in Britain had a small aperture suitable for holding a round or ovoid structure, such as the human head, inside a large rubber membrane that separated it from water contained in a large plastic box. As a result, the first year or two of CT applications were totally neuroradiologic. For the first time, instead of looking at displacements of ventricles and sulci and shifts of arteries and veins caused by masses in the brain, the neuroradiologist could look directly at the parenchymal abnormality and obtain quantitative information about different tissues. Although no one had experience in interpreting such images, the neuroradiologist was a natural because of familiarity with integrating tomographic images, with tomography of the ventricles and sulci during pneumoencephalography, and with cerebral arterial anatomy.

Therefore, when Godfrey Hounsfield, inventor of CT (for which he would later receive the Nobel Prize) visited the United States in May 1972, it was appropriate that he made a presentation before a group of neuroradiologists. This took place at the postgraduate course in neuroradiology at the Albert Einstein Medical Center conducted by Mannie Schechter. Giuseppe Scotti of Milan was, at the time, a fellow in neuroradiology at the MNI and had been sent to the course. He has recalled that a loose page was inserted in the program announcing:

NOTE: There has been a change in our printed program for Monday, May 15th, only! It is our pleasure to introduce Godfrey Hounsfield, from England, who, together with Dr. James Bull, will speak to us on a new and exciting radiologic system designed by EMI.

Bull, a member of the faculty, introduced Hounsfield, who proceeded to show a series of 80 x 80 pixel images (a standard TV set displays images at a resolution greater than 300 x 300 pixels) demonstrating tumors, hemorrhages, infarcts, and hydrocephalus. Scotti writes "I remember vividly the impression that I had at that presentation; I also remember that it was quite difficult for me to understand precisely the technical and physical aspects of that 'new technique.' While I returned to Montreal, I tried to explain it to Dr. Romeo Ethier who, despite my confused explanation, immediately understood the importance of the EMI scanner."¹¹⁵

Hillier Baker recalled the events that immediately followed the presentation.¹¹⁶ His colleague at the Mayo Clinic, Colin Holman, prevailed upon Bull to allow him to take some of the slides back to Rochester to share with his colleagues at the clinic. It must be remembered that the economic state of the national health system in Britain made it unlikely that many of these instruments would be sold in Britain at the asking price of $350,000 (which, Baker notes, was enough money at that time to "furnish several regular radiographic rooms with standard equipment or one or two angiographic rooms with more sophisticated equipment"). Convinced that this was the future of radiology, John Hodgson, chairman of radiology at the Mayo Clinic, asked Baker to go to England to evaluate the machine.
Unknown to the executives at EMI, Baker had authority from the Mayo Board of Governors to place an order for the scanner on the spot if it met his expectations.

In July 1972 Baker visited the central research laboratories and corporate headquarters of EMI and the Atkinson Morley’s Hospital, where he saw the scanner in action. After three days in London, Baker was convinced; to the amazement of the EMI executives, he placed an order that would give the Mayo Clinic the first CT scanner in North America; it began operation on 19 June 1973.

By 1972, Juan Tavera had become director of radiology at the Massachusetts General Hospital and was in the audience the day that Hounsfield made his presentation in New York. He also immediately recognized the potential of CT, and in July 1973 his institution became the second in the United States to operate one. Tavera appointed Paul F. J. New to take charge of the scanner. New took to his work with gusto, presenting his first results at the Harvard Postgraduate Neuroradiology Course in September 1979.17

In January 1974 both the Mayo and Massachusetts General Hospital groups

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Table 12.31

Neuroradiology Highlights
1940 to early 1970s

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1940</td>
<td>Pancoast, Pendergrass, and Schaeffer publish <em>The Head and Neck in Roentgen Diagnosis</em>.</td>
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<tr>
<td>1942</td>
<td>Iodinated contrast agents begin to be used with increasing frequency in myelography.</td>
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<td>1948</td>
<td>Moore describes the use of radioactive isotopes in diagnosis, specifically in the localization of brain tumors.</td>
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<td>1950</td>
<td>Lindblom of Stockholm introduces discography, debates over its usefulness begin almost immediately.</td>
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<tr>
<td>1950</td>
<td>Cerebral pneumography will continue to improve over the next few years thanks to Lindgren and his Swedish colleagues and their development of fractionated technique in pneumoencephalography.</td>
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<td>1952</td>
<td>Wood and Tavera foster neuroradiologic specialization at New York’s Columbia-Presbyterian Medical Center.</td>
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<tr>
<td>1953</td>
<td>Wood and Tavera foster neuroradiologic specialization at New York’s Columbia-Presbyterian Medical Center.</td>
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<tr>
<td>1955</td>
<td>Woods and Sweet localize brain tumors using position emitters.</td>
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<td>1959</td>
<td>Viallet shows that he can visualize the extracranial portions of the carotid and vertebral arteries using intravenous angiography rather than direct puncture of the carotid.</td>
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<td>1956</td>
<td>Leksell describes his use of echoencephalography to determine the position of the midline of the brain.</td>
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<tr>
<td>1958</td>
<td>Tavera establishes a general postgraduate course in neuroradiology at the Neurological Institute.</td>
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<tr>
<td>1959</td>
<td>Appearance of Greitz’s classic description of brain circulation using rapid serial angiography.</td>
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<td>1958</td>
<td>National Institutes of Neurological Diseases and Blindness agrees to support trainees in neuroradiology.</td>
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<tr>
<td>1960</td>
<td>Guettard and Spence perform an open arteriography of a carotid artery to introduce methy methyl methacrylate emboli that are carried by blood flow to the treatment target, i.e., an AVM.</td>
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<tr>
<td>1961</td>
<td>Schechter’s efforts with angiotomography lead to improved visualization of the ventricular system.</td>
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<td>1962</td>
<td>Ziedessl des Plantes successfully uses subtraction angiography neuroradiologically.</td>
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<tr>
<td>1962</td>
<td>Beginnings of the American Society of Neuroradiology with fourteen founding members.</td>
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<tr>
<td>1963</td>
<td>Amplatz develops an improved chair for pneumoencephalography.</td>
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<tr>
<td>1963</td>
<td>Amundsen uses and describes a neuroradiologic use of the Seldinger technique.</td>
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<td>1964</td>
<td>Wilson publishes his <em>Anatomical Foundation of Neuroradiology of the Brain</em>.</td>
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<tr>
<td>1964</td>
<td>Tavera and Wood publish <em>Diagnostic Neuroradiology</em>.</td>
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<tr>
<td>1964</td>
<td>Kuhn and Edwards’s “Cylindrical and Section Radiosotope Scanning of the Liver and Brain” will provide grist for Hounsfield’s mill.</td>
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<tr>
<td>1966</td>
<td>Brinker’s “Ultrasound in Neuroradiology” is apparently the first refresher course on ultrasound (RSNA).</td>
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<tr>
<td>1968</td>
<td>Doppman, di Chiro, and Omaya embolize a spinal cord angioma percutaneously.</td>
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<tr>
<td>1969</td>
<td>Founding of the European Society of Neuroradiology.</td>
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Huckman • Stewart

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presented their first results in print, the Mayo group reporting results in the first five hundred patients examined. Though their error rate was half that of angiography, they felt that the most striking indication of the value of CT was in instances where unsuspected conditions were revealed. The Massachusetts General group gave the results in the first three hundred cases. They encountered no errors in diagnosis of cerebral hemorrhage or in differential diagnosis of atrophy versus obstructive hydrocephalus.

The first EMI scanner in Canada was installed at the MNI. Its director of radiology was Romeo Ethier, who had been appointed in 1967, and who organized the first International Symposium on Computed Tomography, held in Montreal from 31 May to 1 June 1974. Fifteen papers were presented, including one on infarction by Tavera and colleagues, one on hydrocephalus by David O. Davis, and one on meningiomas by David Reese and Hillier Baker of the Mayo Clinic. A group from the Cleveland Clinic reported on its first five hundred cases, and the group from Montreal presented papers on CT use in focal epilepsy, as well as a paper by Ethier on the use of iodinated contrast material in CT scanning, a technique he referred to as computerized angiotomography. A group from Queen Square presented a paper on the use of CT in diagnosis of brain tumors. Messina, Potts, and Sackett of Cornell presented a correlation of CT findings and the findings of other neuroradiologic techniques. Robert S. Ledley of Georgetown University presented his device, the ACTA scanner, which was capable of head and body scanning because it did not employ the "water bag." Laurens Ackerman of Rush-Presbyterian-St. Luke's Medical Center in Chicago presented a paper on frontal and lateral projections of EMI scans, introducing the concept of the reformatted scan, which would subsequently become a highly refined technique in modern CT and MR imaging.

In 1975 Computed Tomography of the Brain and Orbit (EMI Scanning) by Paul F. J. New and William R. Scott was published. This contained mostly 80 x 80 pixel images (and a few 160 x 160 pixel images) and comprised anatomic-radiologic correlations as well as chapters on historical developments in the field and on the operation of the EMI scanner. In 1975 New and Tavares sponsored an international symposium and course on CT in Bermuda which became an annual event for many years to come.

In 1976 Raven Press began publication of the Journal of Computer Assisted Tomography. It has remained one of the major journals in this field including articles on CT, MR, and a variety of cross-sectional radionuclide imaging techniques applied to neuroradiologic and nonneuroradiologic topics. The founding editor of the journal was Giovanni di Chiro.

The fifteen years between the advent of CT and the introduction of MR were marked by a tremendous volume of descriptive literature by neuroradiologists who recounted the application of CT scanning to a variety of neurologic, orthopedic, otolaryngologic, and ophthalmologic problems. When CT scanners appeared throughout the United States and Canada the number of pneumoencephalograms performed fell to virtually zero. The volume of arteriography fell less precipitously because it was still essential for the evaluation of extracranial vascular disease of the brachiocephalic arteries, for the evaluation of subarachnoid hemorrhage, and as part of the development of the emerging superspecialty of interventional neuroradiology.

It is impossible to list all the papers and authors who made significant contributions in this era. CT allowed us to recognize extravasated blood in the brain and subdural or subarachnoid space; it became the first, and often only, preoperative imaging study in subdural and epidural hematomata. Malignant primary and secondary tumors of the brain and meningiomas had characteristic patterns that could be demonstrated by the use of iodinated contrast materials, obtaining precontrast and postcontrast scans. Inflammatory diseases and abscesses, as well as certain stages in the evolution of infarcts, also showed characteristic patterns of enhancement.

CT changed the work-up for demyelinating diseases such as multiple sclerosis.
Not only did it provide a direct look at the periventricular plaques and characteristic patterns of atrophy, but it also proved useful in ruling out the mimics of multiple sclerosis, such as meningiomas of the tentorial edge and foramen magnum, which previously would have required arteriography or myelography.

Demented and elderly confused patients could now be humanely examined. Congenital anomalies in children could now be assessed without an invasive study. Hydrocephalus was readily apparent; characteristic patterns of these anomalies were described and shunts could easily be evaluated for their positions and patency. It became apparent that the scanning of infants, children, and newborns had a unique set of problems related to sedation, hypothermia, and radiographic technique, and while there had been a fledgling superspecialty of pediatric neuroradiology, important training programs in this field now emerged.

With the development of high-resolution scanners capable of obtaining sections as thin as 1 mm. and having large apertures and a wide range of gantry angles, CT was applied to scanning of the spine, skull base, temporal bone, orbit, sinuses, temporomandibular joint, and the soft tissues of the neck. By the late 1970s high rates of accuracy were reported in the diagnosis of lumbar disk disease by CT scanning; in addition, it became the examination of choice for the diagnosis of spinal stenosis.

The application of intravenous contrast and the use of ultrathin sections also made CT ideal for the diagnosis of cervical disk disease. Myelography diminished somewhat in volume as a result, because pantopaque was too dense to be a useful CT contrast material. In the late 1970s, after the introduction of nonionic contrast materials for myelography, the postmyelographic CT scan became the optimum examination for diagnosing disk disease, syringomyelia, diastematomyelia, and other dysraphisms by allowing visualization of the thecal sac, spinal cord and its cavities, epidural soft tissues, and the vertebral canal in cross section. Techniques were also described to distinguish postoperative scar of "failed back syndrome" from recurrent or residual disk by the use of intravenously administered contrast material that selectively enhanced scar tissue. In the mid-1980s software was developed for reformattting the raw data of spine scans and displaying them in a multitude of projections and window widths.

The CT scanner replaced conventional tomography in diseases of the temporal bone, particularly with the development of scanners that could obtain 1 mm. thick sections and acquire them with a bone-edge enhancing algorithm, enabling the visualization of ossicles, the facial nerve canal, and the tympanic membrane. Pantopaque cisternography, an invasive procedure, virtually disappeared. With the development of scanning of the sinuses and facial bones, salivary glands, larynx, thyroid gland, and other soft tissues of the neck, there arose a superspecialty of head and neck or otolaryngologic radiology.

This era witnessed many attempts to obtain dynamic or functional CT images. Time-density curves obtained by rapid, repeated scans in a single plane and after injection of iodinated contrast material were used to determine curves for specific pathologic entities; these subsequently proved to be of little practical value. The use of stable xenon inhalation followed by sequential scanning has provided accurate measurement of cerebral blood flow; however, the logistical and personnel problems involved in this technique have limited its use to only a few centers.

Magnetic Resonance Imaging

The introduction of MR imaging into neuroradiology was somewhat less sudden than that of CT; everyone knew it was coming, but no one was certain when. Chemists have used nuclear MR spectroscopy for many years to determine the chemical composition of substances and tissues. The history of the development of MR imaging into a clinically usable tool is nicely recounted by Macneal in this volume and by Hendee. As with CT scanning, the brain was an ideal subject for examination because of the relative lack of motion from respiration and vascular pulsation. When scanners became wide-
ly distributed in the United States in the
mid- and late 1980s, most of the early
clinical indications for this examination
were neuroradiologic.

Although the original MR scanners
acquired each section individually, soon
there were commercially available scan-
ers with multisecton acquisition capa-
bility and an almost infinite variety of pulse
sequences, gating capabilities, surface coil
designs, and increases in scanning speed,
matrix sizes, and field strength of the mag-
nets.

In the mid-1980s large clinical studies
came from the UCSF, the Mayo Clinic,
Massachusetts General Hospital, New York
Hospital-Cornell Medical Center, the
Cleveland Clinic, the University of Pennsyl-
vania, and Duke University, among others.
Many early studies tried to characterize the
density and composition of tissues by relax-
ation times similar to the way tissues had
been characterized by attenuation num-
bers on CT. It soon became apparent that
substances such as extravasated blood had
a variety of appearances depending on the
state of oxidation, whether the hemoglo-
bin was intra- or extra-cellular, and whether
the MR study had been done on a low-field
or high-field scanner. Neuroradiologists
were instrumental in sorting out the com-
plexities of imaging blood, determining
relaxation times for gray and white matter,
relating signal intensities in various parts of
the pituitary gland to its function, and
mapping normal and abnormal distribu-
tions of iron throughout the brain.

Important anatomical studies were
undertaken to map the surface anatomy
of the brain, and especially the anatomy
of the hippocampal formation; the
information gained was subsequently
applied to the study of complex partial
seizure disorders. The exquisite ability
of MR to differentiate gray and white
matter enabled accurate diagnosis of
heterotopias and other migration anom-
alies, and MR completely replaced CT in
the diagnosis of demyelinating disorders
such as multiple sclerosis. Neuroradiolo-
gists encountered a new mystery, the
"unidentified bright object" (UBO) and
have undertaken hundreds of studies to
classify and age-related ubiquitous
denizen of the brain which may or may
not represent disease or be associated
with symptoms. During the search the
imaging correlate of the Virchow-Robin
space was discovered.

Flow voids in the MR scan of the
brain became important. When absent
they could indicate normal vascular
anatomy and its variants; when present as
a serpentine lattice they might represent
AVMs or indicate the presence of
aneurysms and abnormal tumor vascular-
ity. The picture of the occult vascular
malformation combined the presence of
a flow void and hemosiderin from an old
hemorrhage. Recognizing that flowing
blood and CSF created flow voids led to
studies of the movement of fluid through
the aqueduct, through CSF leaks, and
through shunt tubes, providing a non-
vasive way to study their patency. Mak-
ing use of phase contrast sequences
allowed study of the pulsations of the
CSF and movement of the spinal cord.

Even absence of the normal vascular
flow voids became important signs, being
present in certain vascular occlu-
sions, especially in the carotid arteries,
in branches of the circle of Willis, and in
the dural sinuses indicating thromboses.
Absence of a flow void in an artery, such
as the middle cerebral, became pre-
sumptive evidence of an infarct in its ter-
ritory, and was often present before the
infarct itself could be visualized radi-
ographically. This led to very rapid diag-
nosis of ischemic stroke; the application
of diffusion weighted scanning, first in
experimental animals and later in
humans, promises to be a powerful tool
for early stroke diagnosis, allowing the
interventional neuroradiologist to apply
techniques to reverse the process before
the stroke is completed.

The race was on to develop paramag-
netic contrast materials that could be
injected and would cross a damaged
blood-brain barrier. Gadolinium-DTPA
was the first such product successfully
brought to market, and neuroradiologists
conducted trials of its safety and efficacy.
Its usefulness was demonstrated in the
detection of brain metastases, menin-
giomas, pituitary microadenomas, in the
opportunistic infections of AIDS, and in
the detection of metastatic and inflam-
matory diseases of the meninges.
Suddenly, congenital anomalies were easily diagnosed by MR because of its ability to image in the sagittal and coronal projections, views that had been difficult to obtain with CT. Pediatric and other neuroradiologists reported significant studies on the diagnosis of agensis of the corpus callosum, and there was suddenly an increased detection rate of the asymptomatic Chiari I malformation.

The spinal canal and cord lent themselves readily to MR imaging because of the inherent MR contrast between the marrow in vertebral bodies, epidural fat, CSF, and the cord itself. Sagittal imaging allowed a noninvasive method of screening for cord compression. Intervertebral disks, because of their water content, were readily visualized, as were changes in the vertebral bodies produced by degenerative disk disease. Although MR is useful in examining patients with radiculopathy, the greatest value of MR in the spine is in the myelopathies, especially in the evaluation of cord tumors, vascular abnormalities, and multiple sclerosis. The introduction of gadolinium-DTPA for spine scanning enabled the visualization of meningial carcinomatosis and meningeval inflammation and became useful in distinguishing between postoperative scar and recurrent disk herniation.

MR angiography, still in its infancy at this writing, has been used to screen for extracranial carotid occlusive disease, for aneurysms and arteriovenous malformations, and for occluded intracranial vessels. In addition, it has been useful in examining the dural sinuses for evidence of thrombosis or impingement by tumors. Three-dimensional images of the cerebral circulation obtained by MR have become a useful tool for surgeons who use maps of the venous anatomy of the brain for localizing lesions on its surface.

The MR spectra of hydrogen (and sometimes sodium and phosphorus) have been used to attempt characterization of lesions such as brain tumors and degenerative diseases in children. Typical spectral changes have also been described for cerebral ischemia and infarction. Although still in the investigative stages, in vivo spectroscopy is expected to greatly enhance the neuroradiologist's ability to characterize abnormal areas of the central nervous system accurately.

MR imaging has been applied to the temporal bone, which was initially thought to be invisible to MR; in particular, it has become the examination of choice for investigation of the soft tissues in the internal auditory canal. In addition, structures such as the cochlea, vestibule, and facial nerve have characteristic MR appearances in health and disease.

Finally, the development of rapid MR imaging has enabled the development of functional MR imaging. Techniques have been developed for the detection of changes in the oxidative state of hemoglobin in localized areas of the brain produced by tasking and sensory stimulation. It is expected that such functional techniques will supply some of the information now provided by electroencephalography and such functional radionuclide techniques as positron emission transverse tomography (PETT), single photon emission computed tomography (SPECT), and CT scanning after inhalation of xenon.

The potential benefits of MR imaging in neuroradiology are seemingly limitless, and most neuroradiologists of the 1990s look upon it as the single most important tool in their diagnostic armamentarium. Effective application of new developments in MR angiography, spectroscopy, and functional MR imaging will be the major challenges faced by neuroradiologists in this decade.

Interventional Neuroradiology

The discipline of interventional neuroradiology (often referred to as endovascular neuroradiology, therapeutic neuroradiology, and surgical neuroradiology) also has its roots in neurosurgery and in European neuroradiology, but much of its development in both technique and equipment took place in North America between the mid-1960s and the present. It parallels the development of refinements in angiographic technique by neuroradiologists, the development of biocompatible materials for the manufacture of catheters and embolic materials, and the development of
high resolution digital fluoroscopic systems that enabled catheterization of truly minuscule cerebral vessels.

Credit for the first interventional procedure in North America goes to Barney Brooks. By directly exposing a carotid artery in 1930, he was able to inject a chunk of autologous muscle into the internal carotid artery in a patient with a carotid cavernous fistula. Because of the pressure gradient, the embolus was carried to the fistula and occluded it.

In 1960 Alfred Lusshenhop, a neurosurgeon at Georgetown University Hospital in Washington, embolized (i.e., purposely occluded) a cerebral AVM with methyl methacrylate spheres. In the late 1960s and early 1970s Rene Djindjian carried out a number of studies primarily embolizing lesions of the external carotid territory and spinal arteries using gelfoam particles. Djindjian trained and inspired a generation of French interventional neuroradiologists who have made major contributions to the field and elevated the discipline to a fine art, not only in France but throughout the world. The scope of this chapter does not allow listing their individual accomplishments, but among them are such famous names as Jacques Theron, Jean Jacques Merland, Jacques Moret, Luc Picard, Gerard DeBrun, Claude Manelfe, and Pierre Lajouanias.

In 1968 Newton and Adams selectively catheterized two intercostal arteries supplying a spinal AVM and injected lead pellets and autologous muscle, which resulted in ablation of the lesion. In 1971 di Chiro, Doppman, and Ommaya also reported successful embolization of a spinal AVM by injecting stainless steel particles.

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Table 12.IV

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<thead>
<tr>
<th>Neuroradiology Highlights</th>
<th>1972–present</th>
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<tr>
<td>1972 Hounsfield and Ambrose announce the development of computerized axial tomography at the annual meeting of the British Institute of Radiology. First catheter embolization of an intracranial AVM accomplished by Kricheff, Madayag, and Braunstein.</td>
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<td>1974 Serbinenko of Moscow uses microballoons to achieve control of catheter advancement and placement. Appearance of New's &quot;Computerized Axial Tomography with the EMI Scanner&quot; in Radiology, apparently the first CT paper in that journal.</td>
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<td>1975 Skalpe describes his use of metrizamide in lumbar radiography and thoracic and cervical myelography. Appearance of New and Scott's Computed Tomography of the Brain and Orbit.</td>
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<tr>
<td>1978 Apparently the first MR images of human brain are obtained at the Research Laboratories of Thorn-EMI Ltd. A committee under the direction of Norman Leeds, M.D., meets at the Sheraton-LaGuardia on 27 July to discuss whether ASNR should publish a journal.</td>
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<td>1979 Christensen and associates show the feasibility of using digital subtraction techniques to obtain good images of the extracranial vessels after IV injection of contrast media.</td>
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<td>1982 Alfidi and colleagues surmise that 3-D MR images of blood vessels could be obtained using appropriate software; a harbinger of MRA.</td>
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<td>1984 Appearance of Head and Neck Imaging (Excluding the Brain) by Bergeron, Osborn, and Som.</td>
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<td>1985 Zimmerman and colleagues report on phosphorus MR spectroscopy in a malignant glioma.</td>
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<td>1986 ASNR assumes ownership of its official journal, A.J.N.R.</td>
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<td>1990 Huckman assumes the editorship of A.J.N.R.</td>
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<td>1992 The ABR approves examination for added qualifications in neuroradiology.</td>
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<td>1994 A.J.N.R. moves to ten issues per year.</td>
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pellets. In 1972 Kricheff and others reported therapeutic embolization of cerebral and cerebellar AVMs with opaque silastic pellets introduced using a catheter via the transfemoral route. The advantages of this technique over the use of a surgical incision marked a turning point in this field.

In 1974 a Russian neurosurgeon, F. A. Serbinenko, devised a balloon catheter that could occlude a vessel and be detached from the introducing catheter. In 1975 Gerard Debrun, a French neuroradiologist who would later direct interventional neuroradiology at the University Hospital in London, Ontario, at the Massachusetts General Hospital, and at the Johns Hopkins Hospital, pioneered the use of a latex detachable balloon, which has since been in extensive worldwide use. In 1976 Kerber developed a "calibrated leak" balloon which allowed liquid contrast material or tissue adhesive to escape while the balloon remained inflated.

Interventional neuroradiologists have made great efforts to minimize the hazards of the procedures they perform. Berenstein and his colleagues made use of somatosensory evoked potentials to determine spinal conductivity during spinal angiography and embolization, and Horton introduced the use of xylocaine to predict whether cranial nerve deficits would occur from cerebral embolization.

Grant Hieszima, together with colleagues Van Halbach and Randall Higashida, promoted the use of silicone detachable balloons for the treatment of intracranial aneurysms. This group has also developed a silicone balloon that elongates and conforms to the blood vessel lumen, so that it may be used for transluminal angioplasty of vessels narrowed by intracranial arterial vasospasm.

Microcatheters of variable stiffness have been developed to combine high tensile strength, flexibility, and ease of manipulations. These have become the mainstay of the interventional neuroradiologist, allowing access to vessels that were heretofore unreachable.

Among the newer developments in this field is the use of coils for the treatment of aneurysms. Thrombogenic materials usually coat these platinum coils which, when introduced into an aneurysm, will promote thrombosis. The recent development of the Guglielmi detachable coil (GDC) promises to be an effective tool for aneurysm therapy. This technique deposits a platinum coil in an aneurysm, after which an electric current is applied to the coil. The platinum in the aneurysm becomes positively charged and attracts the negatively charged blood cells, platelets, and fibrinogen, thereby inducing thrombus formation in the aneurysm. The electrical current also promotes detachment of the coil from the delivery system inside the aneurysm.

One of the most exciting areas of interventional neuroradiology is in cerebrovascular occlusive disease. Interventionalists are already doing angioplasties of some of the brachiocephalic vessels in lieu of surgery. With the early diagnosis of ischemic stroke by MR and CT techniques, large trials are under way to evaluate the effectiveness of localized superselective intracerebral thrombolysis, using urokinase or recombinant tissue plasminogen activator (TPA) in attempts to reverse ischemic stroke in its early stages. Interventional neuroradiologists will certainly play a pivotal role in these efforts.

Interventional neuroradiologists today have invariably had training as diagnostic neuroradiologists, but generally limit their efforts to this discipline. Although there are many practitioners of this art, the earliest North American centers arose in the late 1970s and early 1980s. Centers of excellence arose at UCLA under the direction of Hieszima who, with Halbach and Higashida, later established an outstanding center at the UCSF. One of the early practitioners on the east coast was Sadek Hilal, who introduced imaginative devices such as a magnetically-guided catheter and a variety of thrombogenic coils. Alex Berenstein was the first in New York to exclusively practice interventional neuroradiology, and his trainees are found practicing throughout North America. With Pierre Lasjaunias he has authored a multivolume textbook of interventional neuroradiology, which contains a comprehensive treatise on the microanatomy of the intra- and extracranial circulations and their variations. Gerard Debrun,
Allan Fox, and Fernando Viñuela have developed interventional neuroradiology at University Hospital in London, Ontario, a major Canadian center for the treatment of aneurysms and AVMs. Viñuela later moved to UCLA, where he has created an excellent program, and where he was joined by Guido Guglielmi to conduct early trials of his electro-detachable coils. Gerard Debrun performed the interventional studies at the Massachusetts General Hospital and in recent years established a fine program at Johns Hopkins; Charles Strother has established an excellent program at the University of Wisconsin.

Interventional neuroradiology has become a labor intensive specialty demanding not only that its practitioners be diagnostic neuroradiologists, but also that they have considerable knowledge about such things as biocompatibility of materials, pharmacology, coagulation disorders, general critical care, and monitoring of neurologically affected patients. Most programs now demand a minimum of two years of training beyond a neuroradiology fellowship.

For many years an informal meeting of interventional neuroradiologists took place in Val d’Isere, France. This conference was first organized by Luc Picard of Nancy. The friendships and cooperation created by the free exchange of ideas led to the formation in 1991 of the World Federation of Interventional and Therapeutic Neuroradiology, of which Alex Berenstein was the first president and, in 1993, the American Society of Interventional and Therapeutic Neuroradiology (ASITN), of which Charles Strother was elected first president. The American Journal of Neuroradiology (A.J.N.R.) is the official journal of ASITN.

Head and Neck Radiology

The radiology of otolaryngologic and ophthalmologic diseases was for many years a stepchild, falling between the provinces of the general radiologist and the neuroradiologist. The tools in the radiologic armamentarium were limited; they generally consisted of plain radiography of the skull, orbits, larynx, and paranasal sinuses. There were some additional procedures developed such as sialography, positive contrast orbitography, and laryngography, but the development of pluridirectional tomography gave a major impetus to this discipline, especially because of the possibility of examining the temporal bone in detail with sections as thin as one mm.

In 1968 Galdino Valvassori organized a course on radiology in otolaryngology and ophthalmology under the auspices of the Eye and Ear Infirmary of the University of Illinois College of Medicine in Chicago. Valvassori had developed great expertise in radiology of the temporal bone, particularly in the diagnosis of otosclerosis and Meniere’s disease. A highlight of the course was a millimeter-by-millimeter walk through the temporal bone by tomography in various projections, with Valvassori pointing out the anatomy on comparable microtome sections of dried temporal bones. The course was an immediate success and ran until 1976, the name being changed in 1973 to “Radiology of the Head and Neck.”

With the advent of CT scanning, major changes took place in head and neck imaging, and the birth of new examinations made this a highly specialized field. It became possible to distinguish pathologic and nonpathologic lymph nodes in the neck, and characteristic patterns were described for such non-nodal masses as branchial cleft cysts, ranulas, thyroglossal cysts, and hygromas. Primary lesions of the salivary glands, tongue, tonsils, and vocal cords could be more specifically characterized than just being called “soft tissue masses in the neck.” Anatomic papers were published on the radiographic anatomy of the various fascial planes in the neck. Thin-section CT gradually replaced pluridirectional conventional tomography in the examination of the sinuses, facial bones, larynx, temporal bone, and base of the skull. Detailed studies of the orbits became possible without invasive measures. After the introduction of CT two superb textbooks of head and neck radiology were published, one by Mancuso and Hanafee and another by Bergeron, Osborn, and Som.138, 139

In 1976 Valvassori organized a meeting during his course in Chicago which was attended by Hanafee of Los Ange-
ies, Guy Potter of New York, and Daniel Johnson of New Orleans. These men established the American Society of Head and Neck Radiology (ASHNR), which was officially incorporated in February 1977. Valvassori was elected first president of the society, Johnson was secretary-treasurer, and Hanafee was vice president. Hanafee organized the first meeting in Los Angeles in 1977; Potter organized the second in New York in 1978. According to Valvassori, the group of earliest head and neck radiologists also included the late Judah Zizmor (New York), Kenneth Dolan (Iowa City), Robert Scanlon (Los Angeles), and Barbara Carter (Boston).

MR scanning brought about major advances in the field and has become the examination of choice for the internal auditory canal, providing exquisite definition of the neurovascular bundle, and occasionally allowing direct visualization of abnormalities of the cochlea, vestibular apparatus, and the facial nerve. Head and neck radiologists have developed invasive techniques that include CT-guided biopsies. Many interventional neuroradiologists devote large portions of their practices to interventional radiology of the head and neck, which includes embolization of vascular tumors (angiobromas and chemolectomas), embolization for severe epistaxis, and preoperative balloon occlusion testing to determine the safety of carotid artery sacrifice at surgery.

In 1993 the ASHNR listed more than four hundred members in its directory. The annual meetings of the RSNA and the ASNR have several sessions devoted solely to head and neck radiology. The ASHNR annual meeting continues to include a didactic course, which is attended by many members and nonmembers of the society. In 1992 the A.J.N.R. was designated as the official journal of the ASHNR.

**PEDIATRIC NEURORADIOLOGY**

Although neuroradiologic procedures were performed on pediatric patients as far back as the time of Dandy, the devotion of a group of neuroradiologists to pediatric patients and the neurological diseases that afflict them is a recent phenomenon. Like the rest of neuroradiology, the procedures were most often performed by surgeons. The evolution of the role of the neuroradiologist in this field was chronicled by Derek Harwood-Nash in the 1993 Edward B. D. Neuhauser Lecture.

Around 1968 several neuroradiologists began to devote their practices solely to children. Fellowship programs devoted to this area were established under Harwood-Nash and Charles Fitz at the Hospital for Sick Children in Toronto and under Roy Strand at the Children's Hospital of Boston. As the specialty grew, no infant was too small to undergo angiography if it was indicated. As CT and MR came along, important lessons were learned about providing warmth for infant patients during procedures and about techniques of sedation that were sufficient to immobilize a child but pose no risk to health. Pediatric neuroradiologists rigorously evaluated trials of various newly developed contrast materials such as metrizamide, which were subsequently marketed for use in children.

CT and MR opened the gates to the understanding of many congenital brain anomalies. Thomas Naidich at the Children's Memorial Hospital in Chicago, James Scadiff at the University of North Carolina, and A. James Barkovich at UCSF have contributed significantly to the understanding of congenital hydrocephalus, dysraphisms, and migration anomalies. At Children's Hospital of Philadelphia, Robert A. Zimmerman has begun the promising use of in vivo MR spectroscopy for the evaluation of pediatric brain disorders.

For many years Harwood-Nash and Naidich hosted an informal early morning session at the ASNR annual meeting where attendees were encouraged to bring their difficult cases for discussion. The number of participants soon outgrew the small space allotted for the sessions. At the 1998 meeting the American Society of Pediatric Neuroradiology was formed, with A. J. Barkovich elected as its first president. The society's official journal is the A.J.N.R., and William S. Ball was chosen as the first assistant editor for pediatric neuroradiology.
THE AMERICAN SOCIETY OF
NEURORADIOLOGY AND THE AMERICAN
JOURNAL OF NEURORADIOLOGY

In 1960 at the sixth Symposium Neuroradiologicum in Rome, Juan Taveras was elected president of the seventh symposium to be held in New York city in 1964. On 19 April 1962 he convened a meeting of fourteen neuroradiologists from around the United States to form an organization to integrate efforts to establish neuroradiology in all neurological centers in North America, to exchange ideas, to support standards for training in the practice of neuroradiology, and to foster research. The meeting was attended by Chase, di Chiro, Hanafee, Hodges, Holman, Leeds, Leslie, McRae, Newton, Peterson, Potts, Schechter, Taveras, and Wood. Years later, Potts remarked that he "had no appreciation of the historic importance of the meeting. The fourteen people in the room represented all of the fully trained or experienced neuroradiologists in North America at that time."142

The ASNR, the oldest subspecialty society within radiology, has continued to grow in size since 1962. The addition of categorical courses and joint meetings with other societies have increased the budget for its annual meeting to well over $1 million.

In 1978 Samuel Wolpert proposed to the ASNR that the time was ripe to publish its own journal. He recalled that there was considerable resistance from members, and one past president, contemplating the prospect of yet another journal, remarked, "The American Journal of Neuroradiology is doomed to succeed."143 The society approved the idea and an arrangement to have the journal published by the American Roentgen Ray Society (ARRS) was worked out. As part of the agreement, the American Journal of Roentgenology had the right to publish a limited number of AJNR articles one month after they appeared in AJNR.

The ASNR publications committee selected Taveras as the first editor. The first bimonthly issue appeared in January 1980. The goals of the new publication were to publish outstanding clinical and laboratory studies in neuroradiology, to stimulate research in the field, to advance the identity of the ASNR and the identity of neuroradiology as a subspecialty, and to act as an authoritative voice for neuroradiology in North America.144

The journal was an immediate success and quickly gained listing in the Index Medicus. In 1986 Tom Bergeron, president of ASNR, and Jim Stull, publications chairman, negotiated the purchase of AJNR from ARRS, although the close relationship between the two publications continued.145 A survey of thirty radiology journals, published in Radiology in 1988, showed that AJNR ranked eighth in the number of times it was cited in other radiology journals. It ranked fourth in "impact factor," a method of comparing large and small journals.146 With a circulation of approximately seven thousand, AJNR is the most widely circulated neuroradiology journal in the world.

In the mid-1970s the society petitioned the ABR to grant subspecialty certification in neuroradiology. The ABR and the bulk of organized radiology opposed this position. In the meantime, to standardize training in the field, ASNR petitioned the Accreditation Council for Graduate Medical Education (ACGME) to approve fellowships in neuroradiology; this approval was granted in 1990. In 1992 the ABR agreed to award a certificate of added qualification in neuroradiology. This proposal was subsequently approved by the American Board of Medical Specialties and the first examinations and awards of certificates took place in 1995.

In the meantime, ASNR continues to grow, with membership in all categories totaling 2,300 in 1993, making it the largest neuroradiological society in the world. Its members chair many academic departments of radiology, and many have been active in the highest echelons of organized radiology. In September 1994, at the quadrennial international twenty-fifth Symposium Neuroradiologicum in Kumamoto, Japan, the World Federation of Neuroradiological Societies (WFNRS) was inaugurated. Derek Harwood-Nash of Toronto was elected its first president, and Anton Hasso of Loma Linda, California,
was elected treasurer. The twenty-sixth Symposium Neuroradiologicum will be held in Philadelphia in 1998 under the auspices of the WFNR and in conjunction with the annual meeting of the ASNR. This will be the third time since 1939 that this congress will have been held in North America. The president of the symposium is Sadek K. Hilal of Columbia University.

CONCLUSION

Alfred North Whitehead began his seminal work, Science and the Modern World, with the sober admonition that the "progress of civilisation is not wholly a uniform drift toward better things," and each of us in our lifetime can point to areas of scientific endeavor that have produced fruits with high-tech husks and less than nourishing pulp. "Variation," "multiplicity," and "change" are not magical words; our age includes them in discourse about scientific "advances," but with annoying monotonity and increasingly muted effect.

Nevertheless, the record of neuroradiologic achievement over the past one hundred years does indeed appear as a "uniform drift toward better things," particularly for the large segment of humanity that at some time experiences disruption of homeostasis in the central nervous system. Neuroradiologists have made it their work to visualize and assess the central nervous system using the most effective, accurate, and least injurious imaging tools at hand. Because of these efforts the corpus of diagnostic insights and methods of intervention has grown exponentially, as is well chronicled in the medical literature. Unless the record is ignored, it is difficult to see how future historians can view the era spanning the time from Röntgen's first experiments to the present as anything other than an unbroken, giddily-paced renaissance in medical diagnosis.

However, this renaissance was not sparked by the recovery and explication of ancient Greek texts, but rather by the discovery and innovative use of existing energy in our physical universe, by the realization that the "digital" concept can revolutionize visual thinking and the management and manipulation of visual information, and by the electromagnetic triage and repository of such information—the computer.

It has been a long trip from Pfahler's skigram to MR angiography and in vivo spectroscopy—but the journey continues and the end is hardly in sight.

REFERENCES

The authors wish to acknowledge and extend thanks to a number of individuals who supplied valuable documents and personal memoirs which, because of space limitations, could not be included in this chapter. Their contributions were of great value and their names are here listed: Torgny Greitz, Sten Cronqvist, Michael Sage, Jean Paul Braun, Pierre Lasjaunias, Trygve Gabrielsen, Marco Leonardi, Ian Isherwood, Kaj Ericson, W.S.C. Hare, Eric Gifford, H. Trevor ApSimon, Benjamin Kaufman, Robert Waldron, Norman Chase, E. Ralph Heinz, Norman Leeds, and Sadek Hilal.
