Cross Sectional Medical Imaging: A History

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Introduction

The history of cross sectional imaging is in many ways a history of radiology in microcosm. Explorations into the theory of analog tomography began shortly after the turn of the century, and devices to actually produce tomograms were constructed in the 1930's. In the same decade work was initiated on the possible clinical applications of ultrasound and radioisotopes. This work came to fruition in the 1950's and 60's as the disciplines of ultrasonography and nuclear medicine became established as substantive contributors to clinical medicine.

A major advance in diagnostic imaging occurred in the early 1970's with the introduction of computed tomography. This technology made cross sectional imaging with x rays a reality, and greatly enhanced the ability of the physician to see abnormalities in a variety of body structures, especially the brain and spinal cord. Then, the early 1980's witnessed magnetic resonance imaging, a second major advance in cross sectional imaging. Many researchers believe that the potential of this method has been explored only superficially so far, and that ultimately magnetic resonance will be acknowledged as the most important development in medical diagnosis since the discovery of x rays.

Analog Tomography

Sectional images of the body were first produced by the technique of analog tomography, also termed planigraphy, stratigraphy, laminography, body section radiography, and sonography. In this technique, the x-ray tube is moved during exposure in synchrony with, but in the opposite direction to, a film cassette on the other side of the patient. Only one section of tissue remains in focus on the film; tissues above and below the tomographic section are blurred by the motion of the tube and cassette.

The first attempt to describe a method to produce tomographic images was that of the Polish radiologist Mayer in 1914. In 1915, an Italian radiologist, Baese, filed a patent application for the design of a rudimentary tomographic x-ray unit intended principally for foreign body localization. The French physician, Bocage, applied for a patent for an improved tomographic unit in 1921. Bocage's design was the prototype of modern analog tomographic units. Most of the physical principles of tomography were described in his patent application. Two French physicians, Portes and Chausse, applied for a French patent in 1922 for a device similar to that outlined in Bocage's application, and five years later, the German radiologist Pohl was granted a patent for a tomographic device. In 1929 Kieffer, an American radiologist, described a tomographic unit for chest imaging. None of these descriptions acknowledged the ideas of other investiga-
tors, and none was developed into a working unit until the 1930's. Nevertheless, the concept of analog tomography arose naturally out of the state of development of x-ray imaging at the time.

In a 1930 paper, the Italian, Vallebona, described a tomographic unit in which the x-ray tube and film remained stationary and the patient rotated between them. In 1933, Vallebona built a unit in which the x-ray tube and film rotated around the stationary patient. In these devices, only the structures along the axis of rotation in the patient remained in focus.

The Dutch physician Ziedses des Plantes is recognized today as the founder of modern analog tomography. He developed his ideas in the 1920's, but waited until the early 1930's to publish them. Ziedses des Plante introduced linear, pluridirectional and multisectiion tomography in 1931, and air encephalography and lipiodol myelography with tomography in 1934. About the same time, another Dutch radiologist, Bartelink, developed a fixed-fulcrum tomographic unit that employed sinusoidal motion of the x-ray tube and film.

The first American tomographic unit was constructed in 1936 by Andrews of the Cleveland Clinic working in collaboration with Stava of the Picker Corporation. Shortly thereafter, Kieffer and Moore constructed the tomographic laminagraph at the Mallinckrodt Institute in St. Louis.

From the onset, it was apparent that pluridirectional tomographic motion yielded fewer image artifacts than did linear motion. A versatile pluridirectional unit developed by Sans and Porcher in 1949 was reproduced commercially by Massiot in 1951 under the name "Poly-tome". Eventually, hypocycloidal motion was added to this unit, and through marketing by Philips, it became the gold standard of analog tomography. In many of its original applications, analog tomography has now been supplanted by computed tomography. It still remains useful as a confirmatory test for lung lesions and in certain urologic and other applications.

With traditional analog tomographic units, cross sectional images of most regions of the body are difficult to achieve. In 1936, a radiologic technologist named Watson described the transverse axial tomograph as a method to achieve cross sectional images. In this approach, the x-ray tube remains stationary, while both the seated patient and film rotate in synchrony (Figure 1). During exposure, the x-ray beam impinges on the film at an acute angle. Only structures within the cross-section of interest remain in focus on the film. The thickness of the tomographic section is varied by changing the angle of incidence of the x-ray beam on the film. The resolution of transverse axial tomograms was never satisfactory for most diagnostic applications. It did, however, find limited use as an aid to treatment planning in radiation therapy.

Figure 1
Transverse axial tomography (from C. L. Morgan, Basic Principles of Computed Tomography, University Park Press, Baltimore. 1983).
Sonography

Medical diagnosis with ultrasound originated in the work of physicists exploring energy propagation by sound waves before the turn of the century. The phenomenon of piezoelectricity was revealed by Jacques and Pierre Curie in the 1880's, and France was the site of much of the work in sound propagation over the next few decades. During World War I, Langevin and others explored the use of pulse-echo ultrasound to detect submarines, map the ocean floor, and communicate underwater. By 1928, the ocean liner Ile de France had a device to monitor the ocean bottom, and communication among ships and between ships and a stationary transmitter occurred underwater with reasonable precision.

In the late 1930's and early 1940's, Dussik pursued a suggestion of the Russian scientist Sokolov that ultrasound might be useful in tumor detection. With transducers mounted on opposite sides of the head, he measured ultrasound transmission profiles (which he termed hyperphonograms) and claimed to detect tumors and other intracranial lesions. The interest of others in the technology was fleeting at best, however.

Major advances in underwater detection and communication with ultrasound occurred during World War II with the development of pulse-echo SONAR (Sound Navigation and Ranging). Also during the period, Firestone in the United States and Sproule in England developed pulse-echo equipment for detecting flaws in metals. After the war, some of the military instrumentation became available to biomedical researchers.

At the Naval Military Research Institute, the velocity of sound was measured in various biological specimens. At the University of Minnesota, Wild used ultrasound to determine bowel wall thickness and to evaluate differences in echo patterns from normal and cancerous stomach tissue. His work, performed partly in collaboration with Reid, suggested that ultrasound might be useful for tissue characterization, as well as for imaging. In one study, Wild and Reid examined 147 breast cancer patients and reported an accuracy of 94 percent in detecting breast tumors. Unfortunately, other investigators were unable to reproduce these results.

One investigator, Howry of Denver, showed in 1947 that soft tissues produce a variety of echo patterns representing different interfaces between soft tissues. Over the next 2 years, Howry and Bliss, working in Howry's basement, constructed the first B-mode scanner from surplus naval sonar equipment, a Heath oscilloscope, and a quartz transducer with a pulse repetition frequency of 400 pulses/sec. The transducer and object to be studied were submerged under water first in a laundry tub, and later in a metal stock tank (Figure 2). The quartz transducer soon was replaced with a succession of transducers fabricated by Paskony, who joined with Howry to form a small company called ElectroAcoustics. Within the year, the company was sold to Automation Industries, a corporation that ultimately became the principal source of transducers for sonography.

Figure 2
In 1954, Howry and Holmes, the latter an internist at the University of Colorado, used a B-29 gun turret to construct a B-mode scanner which they called the Somoscope (Figure 3). Patients were examined while in water, with a lead weight tied to the abdomen to prevent them from floating. The transducer carriage rotated 360 degrees around the patient while a submerged focused transducer moved laterally across the carriage. In this manner, the first compound scans were obtained as a combination of linear and circular movements of the transducer. Images were displayed on an oscilloscope with a persistence phosphor. Variations in echo intensity were depicted by the degree of fading of different regions of the image over time, yielding a rudimentary type of gray-scale image. A typical result is shown in Figure 4.

Figure 3
Compound scanner (Somoscope) developed by Howry and co-workers from a B-29 gun turret (from Am J Digest Dis 1963; 8:12. Harper and Row, Hoeber Medical Division).
Examining the anatomical region of interest under water was a nuisance for the investigators and an inconvenience for the patients. Eventually, the water tank was replaced by a semicircular pan with the bottom removed and a plastic sheet inserted in its place. The patient was pressed against the sheet, with mineral oil used as a coupling agent. The transducer was moved in a semicircular path through a water bath on the opposite side of the sheet. Reasonably good images were obtained for the breast and various abdominal and pelvic organs, including the liver, spleen, kidneys and bladder.

By the early 1950’s, several other investigators were exploring the clinical applications of ultrasound. In Sweden, Edler and Hertz used an ultrasonic flaw detector obtained from the Malmo Shipyards to develop an A-mode device for echocardiographic studies (Figure 5). Edler was the first to demonstrate motion of the anterior leaflet of the mitral valve and the effects of mitral valve stenosis. This work laid the foundation for echocardiography with a time-motion (T-M) display. Leksell borrowed an A-mode device from Edler and Hertz and demonstrated the displacement of midline intracranial structures caused by tumors and hemorrhage.
Ophthalmologic applications of ultrasound were explored in Europe, mainly through the work of Oksala, Buschmann, and Ossoinig. The latter used calibrated A-mode equipment to distinguish melanomas from other orbital tumors with an accuracy of 95 percent. One of the first compound scanners for ophthalmologic studies was developed in 1958 by Baum and Greenwood. With this scanner, intraocular and orbital tumors were revealed, and foreign bodies and retinal detachments could be seen. One drawback of the Baum and Greenwood scanner was that the patient had to wear water-filled goggles. Other scanners were soon developed that removed this inconvenience.

In 1954 Donald, an obstetrician in Glasgow, took pathological specimens to a nuclear plant to be examined with an ultrasonic unit used for metal flaw detection. He then borrowed an A-mode unit from Mayneord at the Royal Marsden Hospital and demonstrated ovarian cysts, ascites and hydramnios. Later, Donald and Brown constructed a compound contact scanner that was mounted on an examination table and suspended over the patient. The transducer was moved manually under the table, and rather crude images were obtained. This scanner was the first to work without a water bath and greatly facilitated the ultrasonic study of pregnant patients. In 1959, Donald recorded the first ultrasonic images on Polaroid film. Among Donald’s accomplishments, he was the first to measure biparietal diameters and use them as indices of fetal growth.

In the United States, the first compound contact scanner was built in 1962 by Thompson, Holmes and colleagues at the University of Colorado. This unit included an overhead track with a transducer that could be moved across the patient’s abdomen (Figure 6). As the transducer moved, it was rocked 30 degrees to each side, with potentiometers indicating the exact location and orientation of the transducer at each instant. These researchers were the first to demonstrate the echo pattern of the placenta. Their scanner removed most of the remaining skepticism about the ultimate clinical utility of ultrasound in obstetrics.

The compound contact scanner developed in Colorado had obvious commercial potential. Wright and Meyer, two engineers associated with the project, formed a small company named Physionics in Longmont outside of Denver. Their first contact scanner employed a three-jointed arm for transducer movement, as shown in Figure 7. It provided a facile and portable scanner that yielded superb (for that time) images, and served as the prototype for commercial B-mode scanners to come. Eventually, Physionics Inc. was purchased by Picker X-Ray Corporation as a mode of entry for this large company into the fledgling ultrasonics market.
Contact scanners greatly facilitated the clinical use of sonography. Some investigators felt, however, that the distortion and loss of spatial resolution were too great a price to pay for contact scanning, and continued to use a water bath. Among these investigators were Kossoff and his colleagues at the Commonwealth Acoustic Laboratories in Australia. The Laboratories were established after World War II to help veterans who had lost their hearing. In 1959, Kossoff began work on medical ultrasonics, and his first scanner is shown in Figure 8. This unit was designed for obstetrical examinations and used a large water tank with a polyethylene window positioned against the patient’s abdomen. The transducer carriage moved on curved rails, and the transducer was sector-scanned by a small motor attached to the carriage. This unit was the forerunner of the major development of the Laboratories, the multi-transducer and commercially available Octoson ultrasonic scanner (Figure 9).
During the 1960’s, contact compound B-mode scanning was refined, and its clinical applications were explored. Over this period, sonography became recognized as a primary imaging technology in obstetrics, and echocardiography was acknowledged to be important for detecting abnormal cardiac conditions. In addition, sonography was considered an adjunctive diagnostic technique in the abdomen. But still there were problems. In the first place, scanning times were several seconds, and loss of spatial resolution because of motion was a constant problem.

Furthermore, the quality of the image depended as much on the skill of the operator as on the sophistication of the equipment. In fact, sonography was considered more an art than a science. Technologists who could reproducibly obtain decent images were hard to find, and image quality often varied widely from examination to examination and institution to institution. Also, persistence oscilloscopes provided little gray-scale information, and ultrasonic images were termed “bistable” images—each part of the image was either black or white.

In the early 1970’s a major improvement was added to ultrasonic instrumentation. First analog, and then digital, scan converters were introduced as image display devices.
These devices could record and display gray scale information, and led to substantive improvements in the ability of ultrasonic images to reveal subtle differences among tissues. The scan converter was a significant advance in ultrasonic imaging and greatly improved its clinical usefulness, especially for obstetrical and abdominal applications. Typical gray scale and bistable ultrasonic images are compared in Figure 10.

The time required to compile the data for an ultrasonic image was determined primarily by the need to move the transducer across the patient's body in a series of complex motions. Two approaches were envisioned to reduce the imaging time. One involved replacement of manual motion by mechanically controlled, automated motion of the transducer. This approach is used in mechanical sector scanners developed commercially to produce "real time" ultrasonic images.

**Figure 10**
Bistable (A) and gray scale (B) ultrasound images.
A second approach involved the use of multiple transducers operated as a linear or phased array. These systems also became available in the late 1970's and have proved especially popular for obstetrical and cardiac imaging. With these developments, real time ultrasound scanning became a reality, and static B-mode scanners have gradually been replaced by real time units over the past decade. This replacement partially automated the scanning process and reduced the dependence of image quality upon the skill of the operator.

The transition of ultrasonic imaging to real time, together with the development of Doppler techniques for measurements of blood flow, have propelled sonography to a level of clinical importance unanticipated by even its strongest advocates 3 decades ago. With its relatively inexpensive instrumentation, sonography is sure to remain an important part of diagnostic imaging for many years to come. This technology required over 4 decades to mature into a clinically useful diagnostic tool. One wonders whether this level of patience would be available today for a fledgling new imaging technology with an uncertain return both clinically and financially.

**Computed Tomography**

In science, a development often is characterized as a "breakthrough" or "discovery" when actually it is more of an "advance" or "step forward." The latter terms are more descriptive than the former in understanding the development of computed tomography (CT). The principle of computed tomography evolved from the work of an Austrian mathematician, Radon, who demonstrated in 1917 that the image of a 3-dimensional object could be reconstructed from an infinite number of 2-dimensional projections of the object. Radon's work had nothing to do with medical images; he was working with equations that described gravitational fields. In the 1950's and 60's, Radon's mathematics, modified for a finite number of projections, were applied to several imaging problems including solar astronomy, electron microscopy, and holographic interferometry. In 1961, Oldendorf, a nuclear physician in San Diego, explored the potential of producing images from transmission projections produced with gamma rays from an I-131 source. He constructed the miniature tomographic scanner shown in Figure 11. Oldendorf used a scintillation detector to measure the intensity of radiation transmitted through an object rotating between the source and the detector.

In the 1950's, Cormack, a native South African and physicist at Groote Schuur Hospital in Capetown, became interested in the changes in radiation therapy dose distributions caused by inhomogeneous regions of the body. He realized that these changes could be predicted if the distribution of attenuation coefficients were known across the body region of interest. He also realized that such a distribution could be displayed as a gray-scale image. Cormack's pursuit of methods to determine these coefficients led to independent solutions of many of the mathematical challenges addressed decades earlier by Radon. He assembled a 7 mCi Co-60 source and a Geiger-Mueller detector on opposite sides of an aluminum and wood specimen, and showed that the resulting projection data yielded computed attenuation coefficients in good agreement with those measured directly.

In 1957, Cormack moved to Tufts University in Boston. His work on projection imaging was set aside until 1963, when he repeated his measurements using an apparatus with an asymmetrical test object (Figure 12). Data obtained at 7½ degree increments were processed by computer to yield a highly accurate cross sectional distribution of attenuation coefficients. The results were published in Physics Review, where they remained relatively unnoticed for several years. These results surfaced and were acknowledged as prescient, after projection imaging was introduced into clinical medicine. In 1979, Cormack shared the Nobel Prize in Medicine and Physiology with Hounsfield for the development of computed tomographic scanning as the clinical realization of projection imaging.
Figure 11
The experimental apparatus designed by Oldendorf to test the principles of projection imaging (from the Quest for an Image of Brain, C. V. Mosby, 1980:83).

Figure 12
1963 Model CAT-Scanner. Cost ~ $100
Equipment used by Cormack in 1963 to obtain x-ray attenuation data for a nonsymmetric test object (from Medical Physics of CT and Ultrasound, Am Assn of Physicists in Med 1980).
In the late 1960's and early 1970's, several groups were investigating tomographic imaging from projections as a possible diagnostic tool or potential aid to treatment planning in radiation therapy. For example, Kuhl and the nuclear medicine group at the University of Pennsylvania explored applications of projection tomographic imaging to nuclear medicine. Projection imaging was a technology whose time had arrived, principally as a consequence of the emergence of scintillation detectors, fast electronics and computers powerful enough to process immense amounts of data. Evolution of the technology from experimental curiosity to clinical reality was due largely to one individual, Godfrey Hounsfield, an engineer at the Central Research Laboratories of Electro-Musical Instruments (EMI) Ltd. in England.

Hounsfield was born on a farm in Nottinghamshire in central England. As a boy he was fascinated by mechanical devices and electronics. He was a radar instructor during World War II, and joined EMI after receiving his engineering diploma following the war. The first transistorized digital computer was among his accomplishments at EMI, after which he became interested in the challenge of automated pattern recognition and its applications to problems such as handwriting analysis, fingerprint and facial recognition, and evaluation of cervical smears. This interest led Hounsfield to projection imaging and its mathematical challenge. He solved this challenge without knowing of Radon's and Cormack's work, and began experimental verification in 1968. This research ultimately paid handsome dividends for EMI, as the CT scanner became a clinical reality in the early 1970's.

Hounsfield's first experimental apparatus consisted of an Am-241 source and a sodium diode detector mounted on a motorized lathe bed that provided both translational and rotational motion. This device yielded reasonable images of a symmetrical object. However, the time required was excessive. For example, 9 days of data acquisition and 2(3/4) hours of data processing were required for the image shown in Figure 13. The major limitation was the low intensity of the radiation from the Am-241 source.

To obtain higher intensity radiation, Hounsfield replaced the Am-241 source with an x-ray tube to form the device shown in Figure 14. The influence of the heterogeneous nature of the x-ray beam on the values of the attenuation coefficients was reduced by using high tube voltage and heavy filtration of the x-ray beam. In this manner the x-ray beam was attenuated almost exclusively by Compton interactions. The x-ray beam was tightly collimated to reduce scatter and radiation dose, in anticipation of the potential clinical applications of the technology. With an x-ray tube as the radiation source, the imaging time was reduced from 9 days to 9 hours.

Hounsfield produced images of several biological specimens provided by the London radiologists Lennon, Ambrose and Kreei. These images clearly demonstrated superior resolution of subtle differences in tissue density (attenuation), when compared with traditional radiographic methods. They also provided the initiative to build a prototype CT scanner for humans. Because of the long imaging times and the problem of motion in the abdomen, Hounsfield chose the brain as the target organ for the first scanner. The intractability of this organ to more traditional methods of imaging undoubtedly contributed to his decision.
Figure 13

Figure 14
Early laboratory prototype of x-ray transmission CT scanner developed by Hounsfield (from EMI Ltd.).
The prototype CT scanner was assembled in virtual secrecy in an annex to the x-ray department at the Atkinson Morley Hospital in London. The first image was obtained in October, 1971, and had a slice thickness of 1 cm and a data acquisition time of 41/2 min. The scan clearly revealed a frontal lobe tumor in a 41-year-old woman. By April, 1972, 70 patients had been examined, and the results were presented at the Annual Congress of the British Institute of Radiology in London. The prototype scanner, and an announcement in the London Times the day after the results were described, are shown in Figure 15. The enthusiasm that greeted the results, both in England and the United States during a lecture tour a month later, led to a decision by EMI to produce 5 commercial scanners. These scanners were purchased almost immediately by hospitals in London, Manchester, Glasgow, Rochester MN (Mayo Clinic), and Boston (Massachusetts General). All 5 units were installed in the summer of 1973. By this time EMI had received several more orders, mostly from the United States following a presentation at the annual meeting of the Radiological Society of North America in Chicago, the preceding November.

Figure 15
Press announcement of first clinical results of computed tomography (from The London Times, April 21, 1972).
The EMI scanner was designed for brain scanning, and its applications were limited to the head. At Georgetown University in the United States, a dentist named Ledley became intrigued with the possibility of applying the technique to other regions of the body. He parlayed this interest into funding for construction of the first whole-body scanner, entitled the ACTA scanner. The first clinical ACTA scanner was installed at the University of Minnesota in 1973 (Figure 16). It employed the same combination of translational and rotational motion used by EMI, and required several minutes for data acquisition. Anatomical motion was a significant problem in applications of this scanner to regions other than the head and extremities.

To reduce motion artifacts in images of the chest and abdomen, CT imaging times had to be substantially reduced. One approach to this problem was the scanner built at the Cleveland Clinic by Ohio Nuclear, a company that previously had concentrated on devices for nuclear imaging. In the EMI scanner, two scintillation detectors were used to acquire projection data simultaneously for adjacent slices of anatomy, as shown in Figure 17. Ohio Nuclear acquired data for one slice at a time by using an array of detectors and multiple pencil-beams of x-rays, and later a small fan-shaped x-ray beam (Figure 18). The Ohio Nuclear scanner, known as the "Delta" scanner, reduced imaging time from 4½ minutes to about 20 seconds, and produced whole body images superior to those from the ACTA scanner. The first Delta scanner became operational in 1974, and was termed a "second generation" scanner because of the significant reduction in scan time.

Figure 16
First generation ACTA scanner.

Figure 17
Diagram from the first Hounsfield publication on computed tomography. (from Brit J Rad 1973; 46:1016).
It is one thing to do the research and development work necessary to bring a new technology such as computed tomography to the stage of commercial marketability. It is quite another to market, install and service the product, especially when the market is an unfamiliar arena. This was the dilemma confronting EMI in 1972; the company had considerable experience in commercial entertainment, but essentially no products in medicine. EMI officials approached the International General Electric (GE) Company of the United States with a proposal that GE distribute and service EMI scanners in the United States. Officials of GE decided that the US market was too limited to justify a new sales and service arm just for computed tomography. So they declined EMI’s offer. EMI then decided to establish a sales and service organization in the United States, and experienced success almost overnight.

By early 1974, GE realized that they had seriously underestimated the CT market. They convened a small group of advisors over a weekend in the Bahamas to develop a strategy for entering the CT market. The advisors recommended that GE devote its resources to the development of a purely rotational whole-body CT scanner that could scan a patient in 5 seconds or so. This recommendation was a major challenge, because the mathematics of purely rotational projection imaging had not been developed. But by late 1975, a prototype had been developed, and a year later, it was producing respectable images at the University of California in San Francisco. The unit employed an array of pressurized gas-filled ionization chambers in place of scintillation detectors, and a pulsed x-ray tube on the opposite side of the patient. Because of the further reduction in data acquisition time from 20 to 5 seconds, the GE scanner was described as a third generation unit.

By the time the GE unit was being tested, over 20 companies, some large and others small, were pursuing designs for CT scanners. Federal agencies became concerned that many of these scanners would quickly become antiquated and would have to be replaced by institutions that purchased them. This would be a costly process that would increase health care costs, including those borne by Medicare. Hence, a “Request for Proposal” was issued to solicit designs for the “optimum” CT scanner. Many proposals were submitted, and the winner was a small firm in Cambridge Massachusetts, American Science and Engineering (AS&E). This firm was known principally for its major product, an x-ray inspection system for airports. The company responded with a novel scanner design that employed a stationary ring of scintillation detectors, with the x-ray tube rotating around the patient, but inside the detector ring. The AS&E design yielded scan times equal to those of the GE scanner, but with one major advantage: detector responses could be normalized during scans, rather than only between scans with a phantom in place, which was the case for the GE scanner. The stationary ring design became known as the fourth generation of CT scanners. This design is depicted in Figure 19.

The 1970’s were years of rapid development in the CT scanner design. Four generations of CT scanners evolved over a period of
only 4 years, and scanning times decreased from 5 minutes to 5 seconds. In 2 additional years, the minimum scan time decreased to only 2 seconds (Figure 20). Additional designs were proposed for CT scanners, including the nutating geometry of the EMI 7000 series (later adopted by a few other manufacturers) and the shifting gantry of the Artronix scanner.

By the end of the decade, marketplace competition among CT manufacturers had become severe, and only 9 of the more than 20 original competitors remained. As the market matured in the 1980's, the number dimin-

Figure 19
A fourth-generation computed tomographic scanner with a stationary ring of scintillation detectors and an x-ray tube that rotates around the patient.

Figure 20
Single-image collection time for the ten-year period after the introduction of CT scanning.
lished further. Today the CT market is dominated by the large international companies that traditionally have supplied equipment for medical imaging. Other companies, including EMI, Searle, Pfizer, Syntex, Artronix and Varian, sold their interests to these conglomerates, simply withdrew from the market, or went bankrupt.

Still, a few investigators remained intrigued by the challenge of further reducing the data acquisition time for CT imaging. The ability of CT to reveal subtle differences in tissue densities promised impressive gains in imaging moving structures such as the heart, if only the imaging time could be reduced from seconds to milliseconds. At the Mayo Clinic, Wood and his colleagues addressed this challenge by developing the Dynamic Spatial Reconstructor (DSR) diagrammed in Figure 21. These investigators recognized that a single conventional x-ray tube could not be rotated and still provide the x-ray intensity necessary for millisecond imaging. In the DSR, 28 separate x-ray tubes were aligned with 28 light amplifier-television detectors mounted behind a fluorescent screen on the opposite side of the patient. The entire apparatus rotated around the body at 15 revolutions per minute to yield a new set of 28 two-dimensional x-ray projections every 1/60 second. A complete set of scan data for up to 240 contiguous sections of anatomy could be acquired in 10 msec. However, 50 msec yielded better images with substantially less noise.

The DSR was an exciting concept; but the instrumentation was bulky, complex and expensive, and equipment problems were more the rule than the exception. One major problem was the production of x rays; firing multiple...
x-ray tubes and maintaining synchrony between them and 28 detectors was a technological challenge of the first order. The only way to circumvent this challenge was to create an entirely new approach to x-ray tube design.

At the University of California in San Francisco, Boyd and coworkers were exploring alternative ways to generate x-rays. Their approach employed an electron beam that is deflected magnetically to sweep quickly across a semicircular anode (Figure 22). A bank of detectors, on the opposite side of the patient, receives the x-rays emitted by the anode and transmitted through the patient. By combining four separate anodes with two independent detector banks, 8 tomographic sections can be produced in 100 msec or less. Although the spatial resolution and rendition of tissue density are inferior to those of a conventional CT unit, they are still diagnostic for many applications. And the temporal resolution is far superior. Boyd's unit, known as the cardiovascular CT scanner, is commercially available from the Imatron Corp. A number of units have been installed in the United States and a few other countries, and the technology is becoming recognized as especially useful in cardiac and musculoskeletal imaging.

Today computed tomography is a mature industry that contributes substantially to medical diagnosis. It is hard to imagine that less than 2 decades ago clinical CT did not exist, and that specialties such as neurology, neurological and orthopedic surgery, gastroenterology and rheumatology were practiced without its benefits. Applications of CT continue to evolve; 3-dimensional surface images for reconstructive surgery (Figure 23) and quantitative CT information for bone densitometry and treatment planning in radiation oncology, are among the more recent, promising developments.

Figure 22
Computed tomography has contributed several advances in addition to new clinical information. This technology focused attention on the resolution of subtle differences in tissue density (attenuation) as an important contribution to medical diagnosis. It revealed the usefulness of cross-sectional (as well as sagittal and coronal) anatomical information to the diagnostic process. Computed tomography was the first technology to employ the digital computer as integral to acquiring and analyzing diagnostic information. In this manner, CT positioned radiology at the leading edge of the advance of medicine into the computer era. And CT was the first diagnostic technology to separate the acquisition of imaging data from its display and interpretation. This separation has subsequently been emulated in several other imaging disciplines. Because of this separation, images are no longer automatically an accurate depiction of an object, and quality control is now required as an essential part of the imaging process. Quality control should always be supervised by a physicist knowledgeable about diagnostic imaging. Hence, CT firmly established the medical physicist as an essential member of the clinical team.

**Magnetic Resonance Imaging**

In the 1920's and 30's, physicists were intrigued with the magnetic properties of nuclei and with the way in which those properties are expressed under different experimental conditions. Of special interest, were the properties of hydrogen, because this element has a very simple nucleus (a single proton) and strong magnetic properties. In 1933, Stern and colleagues discovered that a beam of hydrogen molecules splits into components that follow slightly different trajectories when traversing an inhomogeneous magnetic field. From these trajectories they accurately computed the magnetic moment of the proton. They then repeated the experiment with deuterium, a hydrogen isotope containing a neutron as well as a proton. Their results led to calculation of a magnetic moment for the neutron, a surprising result since the neutron has no net electrical charge and was thought to be unaffected by magnetic fields. Rabi, a former student of Stern's, became interested in the magnetic properties of nuclei. Experimenting in the late 1930's, he showed that the electrical charge in nuclear particles is asymmetric, implying that the proton and neutron may not be fundamental particles. Rabi added substantially to the physics underlying the technology of nuclear magnetic resonance (NMR), and received the Nobel prize in physics in 1944.

Although Rabi's experiments were ingenious, they suffered from some limitations. These were addressed by several other scientists interested in the problem of nuclear mag-

![Figure 23](image_url)

> Figure 23
3-dimensional surface reconstruction of the heart obtained from a contiguous set of magnetic resonance images obtained with a spin-echo pulse sequence. An atrial septal defect is apparent. (Courtesy of Michael Vannier, M.D., Mallinckrodt Institute of Radiology, St. Louis, MO).
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netism. Among these experimenters were Bloch and Purcell, who in 1945 independently measured the magnetic moment of the proton to an accuracy of 1 part per million. They capitalized on the recognition that certain nuclei resonate and emit a radiofrequency signal when placed in a magnetic field and pulsed with radio waves of the correct frequency. Bloch and Purcell both demonstrated these very weak signals and showed that their amplitude and frequency distribution yield information about the sample’s chemical composition. These results are the basis of NMR (nuclear magnetic resonance) spectroscopy. Bloch and Purcell were awarded the Nobel prize in 1952.

As the work of Bloch and Purcell matured into laboratory methods to probe the chemical composition of samples, several refinements occurred. For example, the radiofrequency emitted by a certain type of nucleus was found to shift slightly in response to the presence of electrons from nearby atoms. This frequency shift obviously could be used to determine the chemical configuration of complex molecules, provided that inhomogeneities in the applied magnetic field did not introduce frequency perturbations. To prevent such perturbations, magnetic fields were required with inhomogeneities no greater than 1 part in $10^8$. By the late 1940’s, several groups had produced magnetic fields of adequate uniformity, and demonstrated frequency shifts for phosphorus, fluorine and nitrogen, as well as hydrogen. The implications of NMR for chemistry, especially organic chemistry, were overwhelming. In the words of Packard, “Chemists got the point very quickly, thanked the physicists and took over.”

For the past four decades, NMR has been an increasingly important tool in chemistry and biochemistry. Its success is attributable principally to three important characteristics. First, it is not particularly difficult to interpret NMR spectra in terms of fundamental properties of chemical compounds. Second, new discoveries from NMR have continued to fuel the vitality of fields such as protein chemistry and the chemistry of metabolism. Third, remarkable progress has been made in the sophistication of NMR instrumentation and the analytic techniques associated with it. Especially important was the development of pulsed NMR, whereby the sample is exposed to a pulse of radiofrequency energy containing a selected range of frequencies. By using Fourier transform methods to analyze the emitted radiofrequency signal, NMR data could be gathered and analyzed much more rapidly. Other major advances that enhanced the usefulness of NMR spectroscopy included powerful computers connected on-line to the spectrometer, and high strength superconducting magnets that yielded greater resolution of subtle frequency shifts than earlier magnets of lesser field strength. Today NMR spectroscopy is an essential feature of any laboratory involved in chemical analysis. An example of an NMR spectrum of phosphorus obtained from muscle is shown in Figure 24.

In 1971, Damadian, a physician at the Downstate Medical Center in Brooklyn, was pursuing his interests in cellular dynamics. Using NMR, he investigated the behavior of water in bacterial cells as the intracellular concentrations of sodium and potassium were changed. Changes in these electrolytes had been suggested as one possible correlate to cancer, so he extended his studies to NMR measurements of the relaxation properties of water in implanted tumors in rats. He found that the relaxation constants of water (i.e., hydrogen) were longer in the tumors than in normal tissues, and suggested that NMR should be present in the operating room as an aid to identifying malignant disease in excised tissues. Damadian even patented a device to provide such a diagnosis. These proposals attracted international attention, but soon were found to be somewhat simplistic.

While Damadian was speculating about the role of NMR in cancer diagnosis, Lauterbur, a chemist at the nearby State University of New York in Stony Brook, was exploring ways to produce NMR images. His first success was an image reconstructed from NMR signals extracted from four projections through two water-filled capillary tubes (Figure 25). This rather crude picture was the beginning of the magnetic resonance imaging (MRI) technology in clinical use today. Lauterbur termed his imaging method “zeugmatography” from the
Figure 24
P31 NMR spectrum obtained with a 6 cm internal diameter surface coil placed directly over the gastrocnemius muscle of a 30 year old normal male. The data represent the sum of 64 transients and were obtained with a 1 meter bore 1.8 T magnet and a Spectroscopy Imaging System Co. console. (Courtesy of Ray Nunnally, Ph.D., the University of Texas Southwestern Medical Center).
Greekzeugma, which means "that which joins together." The temporal simultaneity and geographic proximity of Damadian's and Lauterbur's efforts in nuclear magnetic resonance yielded an unfortunate result: neither person is comfortable with the other's claim as a pioneer in the field.

The initial work of Damadian and Lauterbur stimulated some interest, but more skepticism among seasoned researchers in diagnostic imaging. NMR signals are extremely weak and susceptible to noise interference from a variety of sources. In the chemistry laboratory, this problem is solved by acquiring NMR data over several hours and adding thousands of measurements to obtain a result. In the clinical setting, such long periods of data acquisition are impractical. In addition, chemical samples analyzed by NMR are small and homogeneous, whereas the body is much larger and certainly is not homogeneous. To develop NMR into a clinically useful imaging technology, major investments in new instrumentation, including extremely uniform and intense magnetic fields, would be required. And whether the technology would ever work was uncertain. Sources of funding for such a risky venture were problematic, to say the least.

Progress in science usually occurs one step at a time. The next step in the NMR imaging story occurred in 1974 at the University of Aberdeen, where the first image of a biological specimen (a mouse) was obtained. Not only were the mouse's organs visible, but the darkest area in the image corresponded to edema around a neck fracture. These results were encouraging enough for the Aberdeen group; they immediately ordered a magnet specifically for human imaging. Unfortunately, three years elapsed before the magnet was delivered.
In the meantime, Damadian was not idle. Using a method called “field focusing NMR (FONAR)”, he acquired images of a live rat with an implanted tumor, followed by an image of a human chest. These images were published in 1976 and 1977. Damadian’s results were interesting, but his technique was very time consuming, because the tissue region was sampled one point at a time.

If magnetic resonance imaging were to be clinically important, a way had to be found to speed up the data acquisition process. It was found by Mansfield and associates at the University of Nottingham in England. They developed a procedure to sample a region by a line (rather than a point) at a time. With this procedure, a planar region of tissue could be sampled by moving the data-acquisition line incrementally through the region. Mansfield’s approach greatly shortened the imaging time, but it also provided a complex NMR signal that yielded barely recognizable images (Figure 26). This problem was never completely resolved by the Nottingham group.

At Aberdeen, the new magnet finally was installed and Mansfield’s line-scan technique was adopted and improved. With these advances, human images were obtained that were substantially better than those from Nottingham. Still, motion artifacts were a problem because in the Aberdeen approach two signals obtained at slightly different times were subtracted to produce the image. Eventually, this problem was resolved, in part, by stimulating the sample with radiofrequency pulses of constant duration but different amplitudes, rather than of constant amplitude but different durations. This approach was named the “spin-warp” method, and it produced promising, but still not very good images. Many researchers remained skeptical of the ultimate clinical value of magnetic resonance imaging.

A second group of Nottingham researchers became interested in the challenge of

**Figure 26**

One of the first magnetic resonance images of human anatomy. (Mansfield and Maudsley, 1976).
NMR imaging, and produced images of the wrist and forearm. These images were obtained by a new technique that employed alternating magnetic gradients to select and move a data-acquisition line in the specimen. This approach offered distinct advantages and yielded significantly improved images. Bones, muscles, tendons and arteries were clearly visible in the early images, and in 1980 this group produced the first recognizable pictures of the human brain. Shortly thereafter, the research group disbanded and several members accepted positions in the United States. This emigration was repeated by several other British investigators over the succeeding couple of years, and caused considerable consternation about the NMR-induced “brain drain” from Great Britain to the United States. In the United States today, many of the best known researchers in the field (now called magnetic resonance imaging or MRI) have origins in the early experimental groups in England and Scotland.

Remembering the history and clinical success of computed tomography, many companies followed the development of MRI with great interest. The first company to invest in the technology was EMI Ltd., still riding the crest of its success in computed tomography. With the help of Nottingham consultants, EMI built a resistive-magnet unit and produced an image of the head in 1977. Two years later, EMI joined with Hammersmith Hospital to build a superconducting MRI unit. This group was interested in the possibility of distinguishing tissues by emphasizing differences in the relaxation constants T1 and T2. They used different pulse sequences to accentuate these differences and obtained excellent results.

The EMI group’s first published results, in 1981, revealed brain images with excellent rendition of subtle differences in tissue. These images left little doubt about the potential clinical utility of MRI. Skepticism turned to excitement as imaging researchers examined the EMI experiments and contemplated the possibilities of MRI for anatomical imaging. Of particular significance was the potential of MRI to reveal soft tissue structures in regions such as the posterior fossa and the pelvis that are difficult to access with x-rays. EMI soon replaced their original projection reconstruction method of data analysis with a two-dimensional Fourier transform technique. They also added a method for simultaneous acquisition of multiple images. With these improvements they acquired exquisite images with significantly reduced imaging times and resolution loss caused by patient motion. In 1981, EMI launched the first clinical trials of magnetic resonance imaging.

In the United States, interest in MRI surfaced in the late 1970’s at the University of California at San Francisco (UCSF). There Kaufman and Crooks studied animals in a 30cm bore magnet, and then constructed a superconducting unit designed for patient studies. They developed a “multi-slice” approach to imaging with which data are collected from nearby slices of tissue while the tissue in a previously-sampled slice is given time to recover. The work at UCSF was supported initially by Pfizer Inc., and later by Disonics after Pfizer withdrew from diagnostic imaging. The work by Kaufman and Crooks led ultimately to the superconducting MRI unit currently marketed by Disonics.

By the mid-1980’s, several international companies had developed MRI units and were seeking approval from the United States Food and Drug Administration to market them in the U.S. These units encompassed a variety of designs. Some employed resistive magnets and operated at relatively low field strengths. These units were the least expensive, but they yielded images inferior to those produced by other designs. A permanent magnet unit produced by the Fonar Corporation founded by Damadian was initially greeted by ridicule. Early Fonar images suffered from substantial distortion, and many institutions could not handle the 200 ton weight of the unit. The problems of image quality and unit design were quickly resolved, however, and today the Fonar unit is highly competitive with other models. Its lower operational cost is one significant advantage of this unit.

The most popular design for an MRI unit employed a superconducting magnet operated at relatively high field strength (0.35–2 tesla). This design is employed by several manufacturers. Uncertainty existed initially about
the optimum field strength for magnetic resonance imaging, and heated debates oc-
curred at meetings between representatives of different companies. These debates even-
tually subsided as the advantages and limitations of different field strengths became ap-
parent.

Over the past four years or so, substantial advances have occurred in magnetic reso-
rance imaging. Fast-scan techniques have evolved for producing images in a few sec-
onds or less, and methods for display of flowing fluids are now available. The rendition of soft
tissue detail is exquisite, and MRI is the technol-
ogy of choice for several clinical problems, es-
pecially in the central nervous system. Explora-
tion of the clinical importance of imaging ad-
tional elements besides hydrogen continues,
and the eventual utility of spectroscopy as a
clinical tool remains promising. Some investi-
gators believe that the clinical potential of nu-
clear magnetic resonance has only been sam-
ped, and that this technology eventually will
become the most significant advance in clini-
cal imaging and image-based research since
the discovery of x rays.

Because of its complexity, diversity and
potential, magnetic resonance represents a
significant challenge to researchers in diag-
nostic imaging. There is no immediate physical
limit to its ability to reveal information of inter-
est to the diagnostician. The major obstacles
to realization of its potential are the ingenuity
of clinicians to use the technology appropri-
ately, and the ability of scientists to under-
stand what is happening physiologically when
magnetic resonance signals are elicited from
tissue. These obstacles reflect the challenge of
magnetic resonance. Our ability to meet this
challenge is limited only by our understanding
of the properties of the technology and of the
tissues to which it is applied. Magnetic reso-
ance promises to be a highly productive are-
na of research and clinical application for sev-
eral years to come.

Conclusions

After reviewing the development of meth-
ods to produce cross sectional images, and af-
ter contemplating their contributions to the
detection, diagnosis and classification of dis-
eas and injury, it is clear that clinical medi-
cine has benefited greatly from these meth-
ods. But the evolution of cross sectional imag-
ing is far from over. Today additional
approaches are being explored. Some utilize
electric and magnetic fields generated intrinsi-
cally by the neuroelectrical behavior of ner-
vous tissue. Others employ external sources of
radiation of wavelengths that heretofore have
not been used for imaging. So the story of de-
velopments in cross sectional imaging is far
from over, and its history is alive and constantly
evolving. Any doubts about the truth of this
statement will be dispelled in another 25 years
by the authors of monographs celebrating the
centennial anniversary of the Radiological So-
ciety of North America.

Suggested Readings

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