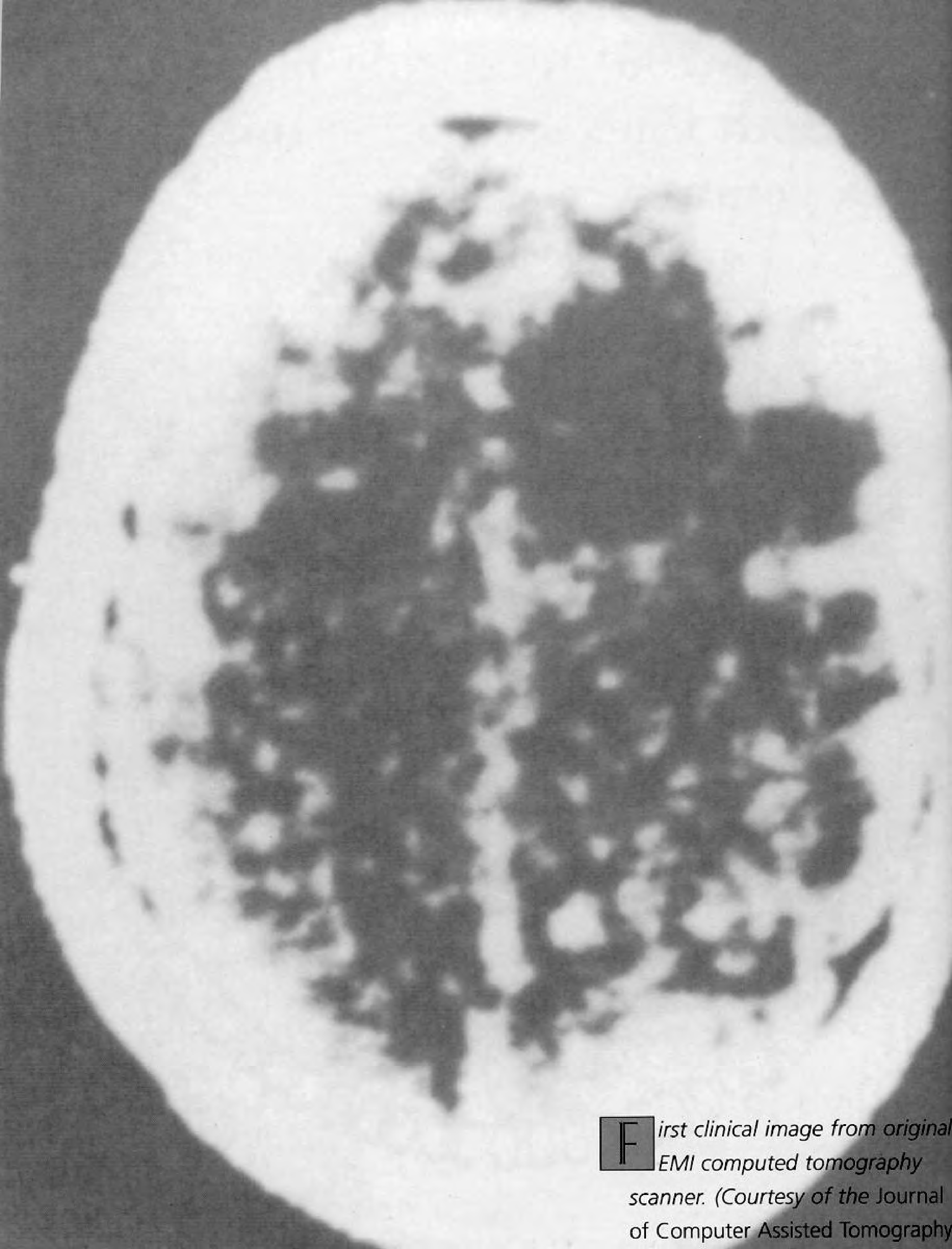


First clinical image from original EMI computed tomography scanner. (Courtesy of the Journal of Computer Assisted Tomography

CHAPTER SIXTEEN

Computed Tomography

Ronald G. Evens, M.D.

Early Investigations in Computed Tomography

The ability to reconstruct a picture or image from a variety of electromagnetic energy sources has been a goal and challenge to scientists since the time of Röntgen's discovery. Exercises in reconstruction of images from individual data points have been of interest to mathematicians, physicists, and physicians for many years. These investigators included Radon, Oldendorf, Kuhl, and Cormack.[1,2]

Mathematicians were especially challenged, and many authors identify professor Radon of Austria as an important contributor to the ultimate development of computed tomography (CT). In 1917 Radon, a leading mathematician, was evaluating complicated equations. He found that formulas could be utilized to reconstruct a three-dimensional object from a very large number of two-dimensional projections of that object. His mathematical theories became the basis of important scientific developments in many disciplines, not only radiology but also astronomy and pathology.

Several decades passed before the next major step in the development of CT. Allen M. Cormack (Fig. 16.1), a trained physicist with essentially no experience in radiology, was asked to consider certain difficulties in radiation therapy treatment planning at the Groote Schuur Hospital Department of Radiation Therapy at the University of Cape Town, South Africa.[3] Many radiation therapists and physicists were aware of problems in calculating radiation dose in patients because of the inconsistent structural makeup of normal body tissue (various amounts of fat versus muscle versus bone). Cormack did something about it by approaching the inhomogeneity tissues problem from a mathematical standpoint. Over several years he evaluated various mathematical formulas and published his work in 1963 and 1964 with "virtually no response" from anybody. Dr. Cormack was a corecipient of the Nobel Prize with Godfrey Hounsfield in 1979, who stated that he was unaware of Cormack's work from the 1960s. Certainly Dr. Cormack's important contributions did not stimulate other research or commercial activity, and it remained for Hounsfield in London to invent a practical system for imaging patients with X rays that would allow the reconstruction of a three-dimensional image from multiple two-dimensional image data points.

The Hounsfield CT story begins in 1968 when he successfully completed a large project for the EMI Corporation and the government of the United Kingdom. He had worked for the EMI Corporation for many years and was an important senior scientist in their Central Research Laboratory (CRL). This laboratory was the basic research division for a corporation that was well known for music and entertainment (recording artists included Frank Sinatra and the Beatles), Thames Television in Great Britain, and commercial electronics. They were also involved in sophisticated electronic equipment (including defense electronics) but had never been in the X-ray business. Godfrey Hounsfield (Fig. 16.2), a highly respected computer scientist with no real knowledge of X-ray equipment, asked for a sabbatical and some time to work on a completely new field: the imaging of patients. It is hard to imagine a more successful sabbatical project for EMI, Hounsfield, or many thousands of grateful radiologists and their patients. A company known for the Beatles and television soon became a major commercial force in medical imaging.

Hounsfield and a small group of research colleagues started a laboratory in Hayes, England, a short distance from London's Heathrow Airport, a fortunate location for many of us who began visits in the 1970s. For several months, the laboratory worked on developing a prototype unit to use X rays (from a radioisotope source of gamma rays) that could obtain data from various phantoms, with the goal of obtaining two-dimensional data that could be reconstructed by computer techniques. Several months of work finally resulted in an image of an anatomical specimen that showed something, but not much. Hounsfield reports that this first image required nine days of scanning time and two-and-a-half hours of computer time in order to process a single image (Fig. 16.3).[4]

Fig. 16.1 Allen M. Cormack. (Courtesy of the Center for the American History of Radiology, Reston, Va.)

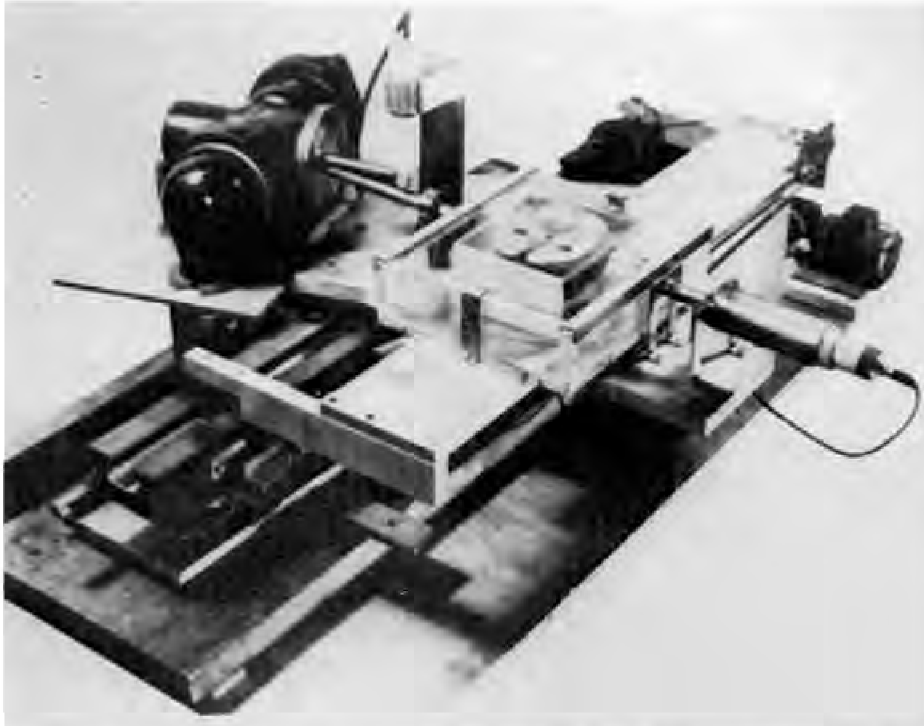
But when these scientists observed the reconstructed image, they saw a spectacular success that encouraged the EMI corporation to fund a major research effort. Hounsfield and colleagues sought advice from British radiologists as to what would be clinically accepted. Their goal was to develop equipment that could obtain clinical images in a few minutes and spatial reso-

Fig. 16.2 Godfrey Hounsfield (b.1919). (Courtesy of the Center for the American History of Radiology, Reston, Va.)

Note: Portions of this chapter appeared as Chapter 25 in Joseph K.T. Lee, Stuart S. Sagel, and Robert J. Stanley, *Computed Body Tomography with MRI Correlation*, 2nd edition (New York: Raven Press, 1989).

Fig. 16.3 Hounsfield's laboratory prototype for X-ray transmission CT. (Courtesy of the Center for the American History of Radiology, Reston, Va.)

▶



lution that could show reasonable anatomical data. Months stretched into years, and finally a clinical prototype unit was ready for clinical studies of the brain. Scanning times still required several minutes and any motion or unexpected tissue inhomogeneity were serious problems, so the head and brain were selected for study by the first EMI equipment. The first prototype unit was placed in the Atkinson Morley Hospital, a research hospital supported by the U.K. government, near Wimbledon in 1972.

Clinical Development of CT

The Atkinson Morley Hospital results were exciting to the radiologists assigned to this most important project. Professor J. Ambrose headed a team of neuroradiologists who provided clinical support to Hounsfield and his EMI colleagues. Their clinical results were first described at the British Institute of Radiology's annual congress in April 1972, and Hounsfield/EMI's tomography unit was immediately recognized as a major improvement for neuroradiology.[5] Word of this success traveled even faster around the globe than Röntgen's announcement in early 1896. EMI called their first production unit the Mark I, and, by today's standards, it was quite primitive. It could only be used for the head and had a very slow scanning time of about four-and-a-half minutes for each image "slice." Most importantly, concerns about tissue inhomogeneity required that the head be included into a water bag (water in a rubber sack) that allowed a relatively easy approach to the mathematical reconstructions of the image. In spite of all these complexities, many academic institutes desired equipment for further clinical studies. Most of the early research was performed on EMI units, as the traditional commercial radiology companies were "caught napping," and it took them several years to get their versions of CT on the market. EMI had little significant commercial competition for several years, and essentially everybody used EMI equipment. Most early installations were in the United States, and the first three head units were installed in the Mayo Clinic, Massachusetts General Hospital, and Presbyterian St. Luke's Hospital. The Mallinckrodt Institute of Radiology was the first institution to install two head units (the ninth and sixteenth commercially built) in 1973.

The impact on neuroradiology was spectacular! Quickly, it was obvious that CT was a major advance. It was amazing to see the ventricles of the brain without having to instill air or contrast material. In a very few months, by spring of 1974, CT was recognized as a major improvement by radiologists throughout the world, and the name CT was soon known to politicians, government regulators, and the general public. H. L. (Bud) Baker of the Mayo Clinic has reported on the early years of neuroradiology and the spectacular impact on neuroradiology.[6] The choice of the head for the first CT studies was the best possible decision for the rapid expansion of CT technology. The head has always been difficult to study, because the skull and its surrounding bony density made analysis of the brain and its contents most difficult. CT allowed radiologists and their colleagues to image the ventricles of the brain for the first time without using invasive techniques (air or iodinated contrast material injected into the spinal canal or directly into the brain through a "burr" hole provided by a neurosurgeon). In a very few months, CT was known to nearly all physicians, lots of patients, and most news reporters and politicians throughout the civilized world. In fact, it had gone from being called computed tomography, to CT, to CAT scanning (after the formal term of computerized axial tomography), and the easy-to-remember acronym of "CAT" became a most popular phrase among the lay public.[7]

Nineteen seventy-four and 1975 were years of rapid growth in both use and media popularity of CT in neuroradiology practice. CT was not yet technically able to image other parts of the body with enough speed to be clinically useful. The neuroradiology growth was so rapid that CT became a symbol of the growing concern over uncontrolled, expensive medical technology expansion, and CT became a national controversy. It was also a time of growth of commercial interest in CT, and by 1976 at least twenty separate corporations were advertising products or announcing their intention to enter the market.

So many corporations entering the market not only increased the development of technology, but also increased the marketing/media hype. Most of the companies tried to announce their equipment and call it a new "generation" to emphasize their own special and particular improvements. The first several approaches to the use of CT in the body were neither commercially nor clinically successful, and the use of CT in locations other than the head had to wait for several technical improvements, particularly faster scanning in order to reduce physiologic motion.

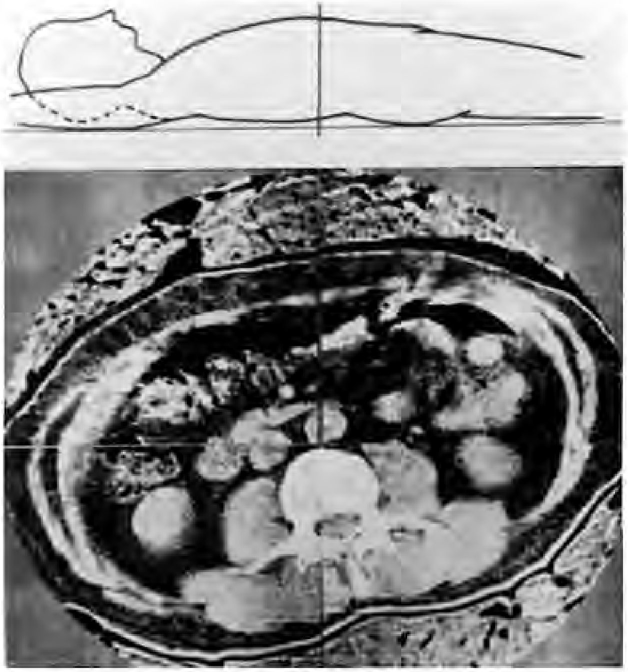
Late in 1975 EMI, the original commercial concern, announced a new CT unit that they called the "5000 series." This was also called the "3rd generation" or the "4th generation scanner," depending upon the view of the reporter. Most importantly, it successfully initiated a scanning technology with an eighteen-second scanning time that allowed practical imaging of the chest, abdomen, and pelvis. Body CT had arrived. EMI initially created three prototype scanners that were located in well-known research institutions. The first was installed in the Mallinckrodt Institute of Radiology in St. Louis, the second at the Mayo Clinic in Rochester, Minnesota, and the third in Northwick Park Research Institute near London. These three institutions rapidly reported a series of clinical trials indicating that the success of CT in the head to improve medical diagnosis was also true in the rest of the body (Fig. 16.4).[7,8,9] Within three years after the introduction of CT in 1973, this invention was known throughout the world and had become a major topic of discussion in Congress, at cocktail parties, and especially in the lay press—by physicians, politicians, and the public.

CT Is the Example of "High Tech/High Cost"

The 1970s were a time in which the cost of medical care was receiving increasing attention. Patients were becoming more demanding of the best care. Insurance programs became wide-

Fig. 16.4 One of the earliest CT images of the abdomen, ca. 1975, from the first successful body scanner, the EMI-7000. The value of CT in the abdomen was clearly demonstrated, showing many major organs and vascular structures. Note that the image is in four parts, because computer capabilities did not allow printing of a single detailed image. The pieces had to be cut and glued together. (Author's collection)

▶



ly available through employers and government. The federal deficit was growing, and one of the reasons was the federal government's payment for medical care (especially for the Medicare and Medicaid programs established in 1964), and medical care had become a political issue. CT was invented at the right time for patients, but at the wrong time because of the federal deficit. The acronym CAT became a buzz word to identify a perceived example of "high tech" with an associated high cost attributed to unnecessary and inappropriate X-ray procedures. It was a great example for politicians and others upon which to focus when wanting to talk about the high and rising cost of medical care. Not only were the public and physicians talking about CAT, the secretary of HEW, the President of the United States, and certain senior physicians began to talk about the problems of "CAT fever."[10,11]

At a time when most radiologists and other physicians were convinced of the importance of CT, not only for the head but now for the body, only sparse efficacy and economic data were initially available to counter the concerns of others. Fortunately, multiple studies were begun by many academic institutions in the United States in order to answer these concerns. Investigators began reporting on the cost of CT, and clinical studies soon demonstrated how the appropriate use of CT could actually reduce the cost of other examinations and the total cost of care.[12,13] Examples included reports from Canada evaluating a variety of neurologic diseases, the reduction in radionuclide brain scanning in community hospitals, and the decrease of the use of many other procedures after the installation of CT in a large teaching hospital.[14,15,16]

The challenge to CT by political forces was met by clinical and economic data. No previous imaging technology had undergone such scrutiny. They were the first economic studies of a radiological procedure of installation from national data that documented economic and utilization adjustments with time, experience, and improved technology. This approach demonstrated a model for analyzing costs based on standard utilization and expense data and suggested a method for establishing charges that would allow coverage of these costs.

Cost and economic data were important, but the convincing data was from several efficacy studies from 1976 to 1978.[17] Studies in the first two or three years of head and body CT experience were limited to clinical descriptions on a relatively few patients, and while the results were spectacular, they were not scientifically convincing to critics. Soon, however, larger efficacy studies reported high accuracy, sensitivity, and specificity plus reduction of previously utilized diagnostic procedures in a series of patients following head trauma.[18] Safe and relatively simple CT had indeed replaced more expensive, more complicated, and more risky procedures such as arteriography, pneumoencephalography, and exploratory cranial surgery. Other important papers evaluated CT in a variety of clinical conditions and reported important changes in both diagnostic and therapeutic planning.[19,20,21] By 1980 data had been reported from multiple institutions, and even the most critical opponents had to become supporters of this new technology.[22,23,24]

CT Becomes Nationally Accepted

What a change between 1976 and 1980. Nineteen seventy-six, an election year, was highly politically charged against CT and any new technology for medical care. The local and national elections often included reports on the CAT scanner, and local politics often became battlegrounds with radiologists and hospitals standing against health planners and politicians for the development of CT technology. Soon, however, the efficacy data and economic reports from around the United States and national organizations such as the American College of Radiology were changing opinions. A most important report was a statement from radiologists at five highly respected institutions (the Cleveland Clinic Foundation, the Mallinckrodt Institute of Radiology at Washington University, the Mayo Clinic, New York Hospital–Cornell Medical Center, and the University of California at San Francisco), which stated in the strongest terms that body CT was clinically important and necessary for modern patient care.[27] A national society of computed body tomography and its members reported the results of a consensus panel and listed the appropriate use of CT (Fig. 16.5).[28] A national study used economic data from several sources and independently evaluated the uses of CT in a variety of medical conditions and reported that CT would not increase the overall cost of diagnostic procedures, but in fact "more than paid for itself" because of the reduction in other medical testing.[29] Finally, an important report from Maloney and Rogers suggested that expensive new technology such as CT was not the major problem in health care cost, but that "little ticket" items which were individually not costly but were used in very high volume (such as laboratory testing) were a major factor in the rise in national health care cost.[30]

Data won the battle for respectability, and CT was accepted by everyone as a major advance in health care at reasonable cost by the year 1980. Although politicians and planners made CT a scapegoat because of its relatively high cost, this approach clearly was a serious mistake, as CT has led to a major revolution in diagnostic imaging. CT had quickly become so beneficial that it could not be stopped by legislation and guidelines develop-

Fig. 16.5 Charter members of the Society of Computed Tomography at its first scientific meeting in 1978. From left to right: Elias Kazam, Stuart Sagel, John Haaga, David Stephens, Jack Wittenberg, George Harell, Patrick Sheedy, Melvin Korobkin, Dieter Schellinger, Ralph Alfidi, Robert Stanley, Robert Hattery. Not pictured: Ron Evens and Fred Sample. (Author's collection)

ment. The positive publicity for CT was capped by the awarding of the 1979 Nobel Prize in medicine in October of that year to Hounsfield and Cormack for their pioneering efforts. By 1981 the National Institutes of Health had organized a consensus conference stating that CT was a major advance of the highest level and actually encouraged its increasing use and availability for neurological studies.[31]

Conclusions

CT is one of the youngest technologies in radiology, less than twenty-five years old in our hundred-year history. CT is more than a technology; it was the introduction of the computer to our specialty in a meaningful fashion. Hounsfield's invention followed the mathematics of Radon and Cormack but was only possible with the data storage and analysis capabilities of modern computer technology. The success of CT has been followed by magnetic resonance imaging and color Doppler sonography, and hopefully it will soon be followed by electronic radiology imaging.

CT, coming at a time of increasing sensitivities about health care costs, also became a social experiment. Attempts by health care planners to inhibit its development were unsuccessful. CT is no longer controversial; in fact, it is essential to modern medical practice. Its invention added another Nobel Prize to the history of our specialty. Its development is not completed—faster scanning times, spiral CT, and three-dimensional reconstruction are just a few of the possible adaptations for clinical care that are currently under development and clinical trial (Fig. 16.6).

Fig. 16.6 Three-dimensional CT (1987), a logical extension of the spatial calculations the computer makes in producing a traditional CT image, has proven most useful in reconstructive surgery and in conformational treatment planning in radiation oncology. (Courtesy of Emory University)

Personal Reflections

Hounsfield (left) and the author (center) in press interviews (1975). (Author's collection)

It is a privilege to be a part of history—I was able to meet both Nobel laureates (Hounsfield and Cormack) as I became a part of CT history.

Godfrey Hounsfield was certainly the inventor of record who brought about the commercial and clinical development of CT. Because of our early contact with the EMI Corporation, he made several trips to the Mallinckrodt Institute in the 1970s and 1980s. I quickly predicted that he would win the Nobel Prize and wanted to give my family (Hanna and three young children) the privilege and pleasure of meeting him. When he came to give the Scott Lecture in 1975, I invited him to our home for dinner and found that he stayed on England's time when he came to America and wanted to have "dinner" by the London clock. Accordingly, we had dinner at 1:00 in the afternoon so that he could go to bed at 4:00 p.m. and arise the next morning at 2:00 a.m. He was very pleasant, and my children still remember this great opportunity.

I did not even know Cormack until many years later. In fact, when I heard the Nobel laureate announcement on the radio while driving to work one morning in 1979, my first thought was, "Who is Cormack?" In 1980 while participating in a symposium in Berlin, my host asked if I would like to tour East Berlin. Saying yes, I was assigned a companion who turned out to be Allen Cormack. We had a very pleasant tour in a private car for about three hours, and Cormack told me of his last visit to Berlin. In 1938, while he was living in South Africa, his father died in England. He and his mother traveled to England in order to settle his father's estate and came by ship to Hamburg, where he spent two days (it was a package tour) in Berlin—at a time of growing Nazi strength and just before World War II. He remembered an important parade that occurred down the Unte de Linden Avenue with Hitler and his associates in special cars at the front. Quickly the world became chaos. We were driving in East Berlin, a remnant of that war, fortunately now reunited with the West.

How fortunate are many patients because of the scholarship of these two great scientists and inventors.

▶ ▶ ▶ ▶ ▶ ▶

REFERENCES

1 Kuhl, D.E., and Edwards, A.Q., "Image Separation Radioisotope Scanning," *Radiology* 80 (1963):653-662.

2 Cormack, A.M., "Representation of a Function by its Line Integrals, with Some Radiological Application," *J. Appl. Physiol.* 34 (1963):2722-2727.

3 Cormack, A.M., "Early Two-dimensional Reconstruction (CT scanning) and Recent Topics Stemming from it," *J. Comput. Assist. Tomogr.* 4 (1980):658-664.

4 Hounsfield, G.N., "Computed Medical Imaging," *Science* 210 (l980):22-28.

5 Ambrose, J., and Housfield G., "Computerized Transverse Axial Tomography," *Brit. J. Rad.* 46 (1973):148.

6 Baker, H.L. Jr., "Computed Tomography and Neuroradiology: A Fortunate Primary Union," *A.J.R.* 127 (1976):101-110.

7 Evens, R.G., "New Frontier for Radiology: Computed Tomography," *A.J.R.* 126 (1976):1117-1129.

8 Sagel, S.S.; Stanley, R.J.; and Evens, R.G., "Early Clinical Experience with Motionless Wholebody Computed Tomography," *Radiology* 119 (1976):321-330.

9 Sheedy, P.F.; Stephens, D.H.; Hattery, R.; et al., "Computed Tomography of the Body: Initial Clinical Trial with the EMI Prototype," *A.J.R.* 127 (1976):23.

10 Bogue, T., and Wolfe, S.M. *CAT Scanners: Is Fancier Technology Worth a Billion Dollars of Health Consumer Money?* Washington, D.C.: Health Resource Group,1976.

11 Shapiro, S.H., and Wyman, S.M., "Cat Fever," *New Eng. J. Med.* 294 (1976):954-956.

12 Evens, R.G., and Jost, R.G., "Economic Analysis of Computed Tomography Units," *A.J.R.* 127 (1976):191-198.

13 Evens, R.G., and Jost, R.G., "Utilization of Body Computed Tomography Units in Installations with Greater than One-and-a-Half Years' Experience," *Radiology* 131 (1979):695-698.

14 Wortzman, G.; Holgate, R.C.; and Morgan, P.P., "Cranial Computed Tomography: An Evaluation of Cost Effectiveness," *Radiology* 117 (1975):75-77.

15 Turcke, D.A., and Gilmore, G.T., "Computed Tomography's Impact on Nuclear Medicine Service in Two Community Hospitals," *Appl. Radiol.* 6 (1977):149-151.

16 Whalen, J.P., "Radiology of the Abdomen: Impact of New Imaging Methods," *A.J.R.* 133 (1979):587-618.

17 Abrams, H.L., and McNeil, B.J., "Computed Tomography: Cost and Efficacy Implications," *A.J.R.* 131 (1978):81-87.

18 Ambrose, J.; Gooding, M.R.; Uttley, D.; et al., "EMI Scan in the Management of Head Injuries," *Lancet* 133 (1979):115-119.

19 Clifford, J.R.; Connolly, E.G.; and Vorhees, R.M., "Comparison of Radionuclide Scans with Computer Assisted Tomography in Diagnosis of Intracranial Disease," *Neurology* (Minneap.) 26 (1976):1119-1123.

20 Evens, R.G., and Jost, R.G., "The Clinical Efficacy and Cost Analysis of Cranial Computed Tomography and the Radionuclide Brain Scan," *Semin. Nucl. Med.* 7 (1977):191-198.

21 Fineberg, H.V.; Bauman, R.; and Sosman, M.,"Computerized Cranial Tomography: Effect on Clinical Diagnosis and Management, a Prospective Study," *J.A.M.A.* 238 (1977):224-227.

22 Larson, E.G.; Omenn, G.S.; Margolis, M.T.; and Loop, J.W., "Impact of Computed Tomography on Utilization of Cerebral Angiograms," *A.J.R.* 129 (1977):1-3.

23 Robbins, A.H.; Pugatch, R.D.; Gerzof, S.G.; et al., "Observations on the Medical Efficacy of Computed Tomography of the Chest and Abdomen," *A.J.R.* 131 (1978):15-19.

24 Weyman, P.J.; McClennan, B.L.; Stanley, R.J.; et al., "Comparison of Computed Tomography and Angiography in the Evaluation of Renal Cell Carcinoma," *Radiology* 137 (1980):417-424.

25 Evens, R.G., "National Guidelines and Standards for Health Planning: Their Relation to Radiology," *A.J.R.* 131 (1978):1101-1104.

26 Meany, T.F., "CT and the Planners," *A.J.R.* 126 (1976):1095-1097.

27 Evens, R.G; Alfidi, R.J.; Haaga, J.R.; et al., "Body Computed Tomography: a Clinically Important and Efficacious Radiologic Procedure," *Radiology* 123 (1977):239-240.

28 Alfidi, R.J.; Evens, R.G.; Glenn, W.; et al., "(Society for Computed Body Tomography). Special Report: New Indications for Computed Body Tomography," *A.J.R.* 133 (1979):115-119.

29 Gempel, P.A.; Harris, G.H.; and Evens, R.G. *Comparative Cost Analysis: Computed Tomography Versus Alternative Diagnostic Procedures* 1977-1980. Cambridge, Massachusetts: Arthur D. Little, Inc., 1977.

30 Maloney, T.W., and Rogers, D.E., "Medical Technology: A Different View of the Contentious Debate Over Costs," *New Eng. J. Med.* 301 (1979):1413-1419.

31 Evens, R.G., "Computed Tomography—A Controversy Revisited," *New Eng. J. Med.* 310 (1984):1183-1185.