Image Reconstruction (I): Computerized X-ray Scanners

Medical science tends to advance incrementally, and full-fledged breakthroughs are rare. The discovery of the x-ray by Wilhelm Conrad Roentgen in 1895 and the subsequent development of the science of radiography is one notable example. In the last 3 years, a new x-ray device known as the CAT-scanner (for computerized axial tomography) has been appearing in an increasing number of hospitals and clinics. On the basis of their experience so far, many radiologists are saying that these computerized x-ray scanners are the greatest advance in diagnostic medicine since Roentgen's discovery, while others are only somewhat less effusive in their praise. CAT-scanners have had an indisputably marked effect on the way radiologists and surgeons diagnose their patients, but it is still too soon to evaluate what the overall contribution of the scanners to the quality of health care will be.

The enthusiasm for CAT-scanners derives from their superior ability to detect abnormalities (lesions) in the brain as compared with such conventional neuroradiological techniques as standard skull x-radiography (roentgenography), angiography, pneumoencephalography, and radionuclide scanning. Radiologists also cite the relatively noninvasive character of the scanners and their potential for reducing the cost of health care for patients who otherwise would be hospitalized.

In the diagnosis of numerous abnormalities of the brain, radiologists at the Mayo Clinic have reported an overall error rate with CAT-scanning of 4 percent on 12,000 scans over a little more than 2 years, for example (*1*). Disorders visualized included brain atrophy, degeneration of the brain, hydrocephalus, cysts, tumors of the brain and the eye, infarcts (dead areas of the brain due to loss of blood supply), and hemorrhage (Fig. 1). In addition, they find that CAT-scanning is applicable to all of the above-mentioned categories of abnormalities, whereas the other methods are each limited to certain ones only.

In conventional x-radiography, the image obtained on a film after a diverging x-ray beam passes through the subject is a projection or shadow of everything standing between the x-ray source and the film. Thus, the image may contain many overlapping organs and tissues which are difficult to separate. In addition, whereas an observer can easily distinguish between air, soft tissue, and bone in an x-ray photograph, the same viewer cannot easily see the few percent difference in the attenuation of x-rays by normal and diseased tissue, even when overlapping images are not a complicating factor.

The method embodied in computerized x-ray scanners to overcome these difficulties is a specific example of a general mathematical technique called reconstruction of images from projections. In principle, if x-ray photographs are made of a person's head at an infinite number of angles, it is mathematically possible to reconstruct a full three-dimensional image of the skull and its contents from these projections. Such reconstructions can be made from a finite number of projections, but the reconstructed image is no longer exact.

A number of researchers have made reconstructions of two-dimensional cross sections normal to an axis of rotation of an object (transverse axial tomography) from x-ray photographs taken at equal angular intervals around the axis. This procedure overcomes the problem of overlapping, but the cumulative x-ray dose to a patient would be excessive. In addition, scattering of x-rays by parts of the patient's body would cause a loss of contrast, as it does in conventional x-ray radiography. The use of an electronic detector in place of the x-ray film together with a collimated, narrow x-ray beam and computer processing solves these problems.

Since the detector records only a small region at a time, in order to duplicate the area recorded in an x-ray photograph, the x-ray source and the detector must scan the region to be imaged. In the first generation scanners, the x-ray source and the detector scan together normal to the axis of rotation of the object, and thus generate a series of parallel x-ray beams in the plane of the cross section to be reconstructed. Only x-ray photons not scattered out of the beam are detected. Readings of the attenuated x-ray beam during the scan are stored in a minicomputer. At the end of a scan, the frame that holds the x-ray source and the detector rotates 1 degree, and another scan begins.

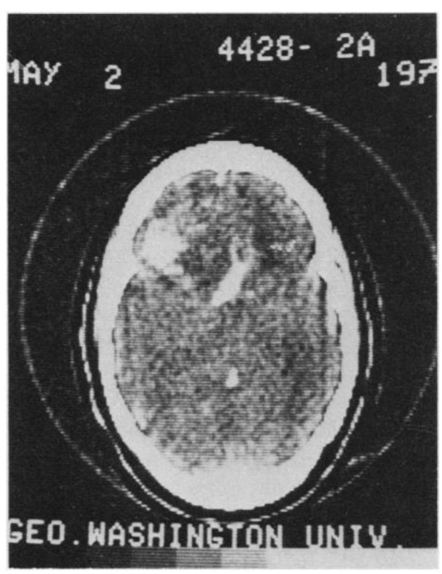

Fig. 1. Reconstruction of the head of a patient with a calcified glioma (tumor of the connective tissue that supports the brain cells) of the left frontal lobe. The view is from the top of the head down toward the body. The calcified areas are white, as is the skull. The light circle outside the skull is the water bag. The dark ring just inside the skull is an artifact. [Source: George Washington University Hospital]

The computer completes the reconstructed image of the cross section either after or as the data from 180 or more scans accumulates, depending upon which of several possible algorithms it uses (*2*). The image consists of a rectangular array of elements, each of which represents an area of the cross section about 1.5 millimeters on a side. A cathode-ray tube or television screen displays the image. The cross section is not mathematically thin; its thickness is determined by the thickness of the x-ray beam and is 8 or 13 millimeters.

In the simplest algorithm, the brightness of each element represents the sum of the total attenuations of each x-ray beam that passes through the element. The method used by scanner manufacturers involves modifying the projections, so that this line summation gives a closer approximation to the true attenuation in each element.

With computerized x-ray scanners, differences of absorption as small as 0.5 percent can be distinguished, because the entire range of attenuations need not be displayed simultaneously, as on film. By selecting a small range of attenuations to be displayed in the reconstruction, the viewer can easily pick out small changes that would be missed in a normal x-ray photograph. The spatial resolution of the image, however, is not as good as that of an x-ray photograph, being limited by the size of the picture elements. The accumulated radiation dose from a CAT-scanner is comparable to that from a series of skull x-rays. A set of three or four x-rays imparts a dose of 2 to 4 rads, as does a series of three or four sets of scans that constitutes a CAT examination. (In actual machines, two detectors are used, so two cross sections are obtained simultaneously. Thus, a typical examination results in six or eight cross sections.)

A careful evaluation of the efficacy of CAT-scanners in detecting and differentiating lesions as compared with other diagnostic techniques has yet to be reported. Many hospitals and clinics, however, have accumulated what statisticians call anecdotal data on the performance of the scanners. According to Hillier Baker at Mayo, for example, the effect of computerized x-ray scanners on the use of the other techniques has been substantial. Pneumoencephalography has decreased in use by 90 percent, angiography by 10 to 15 percent, and radionuclide scans by 60 percent.

Figures such as these cannot be taken as typical because the frequency of use of each method depends on the type of patient a clinical center treats. Thus, while pneumoencephalography has been the most drastically effected diagnostic technique in most (but not all) centers, a more typical statement of the impact on angiography and radionuclide studies is that the CAT-scanner can be used as a screening tool to select patients for whom the other methods may then be necessary.

Angiography involves the injection of a radiopaque medium into the arterial blood system, so that the cerebral vascular system is made visible to conventional x-rays. The substances used in angiography, however, are irritating to the body, and the probability of complications or even death is uncomfortably high (about 1 percent). Even so, radiologists continue to do angiography, because of its superiority in visualizing some kinds of malformations of the cerebral vascular system.

Pneumoencephalography is an especially unpleasant procedure to undergo. The cerebrospinal fluid is removed and replaced with air or another gas. Air in the spaces normally occupied by the fluid, such as the ventricles of the brain, acts as a high contrast medium in the sense that the x-ray attenuation is greatly reduced. The aftereffects are severe and include headache, nausea, and vomiting. Both angiography and pneumoencephalography may impart high radiation doses, from 25 to 50 rads, and both require hospitalization.

In radionuclide scanning, a gamma-ray emitting isotope is injected intravenously. If a lesion, such as a tumor, is associated with a breakdown of the blood-brain barrier that separates the blood from the tissue of the nervous system, the isotope can leak out and accumulate in the area of the lesion. The radiologist can obtain a map of gamma-ray intensity with position and thus locate the lesion. The dose of radiation received is quite low, the procedure is one with a relatively low risk, and hospitalization is not required, but the spatial resolution and the sensitivity for certain lesions is low.

In CAT-scanning, the patient lies on a motorized couch with the head between the x-ray source and the detectors. In the most used version of the scanner, the patient's head fits into a flexible rubber bag which projects into a water-filled box, so that all x-rays enter and exit through the water. The water ensures that even x-rays not passing through the head will be attenuated to some extent and thus acts as a reference medium. The water is also said to reduce the requirements on the performance of the x-ray detectors and to reduce the number of artifacts in the reconstruction.

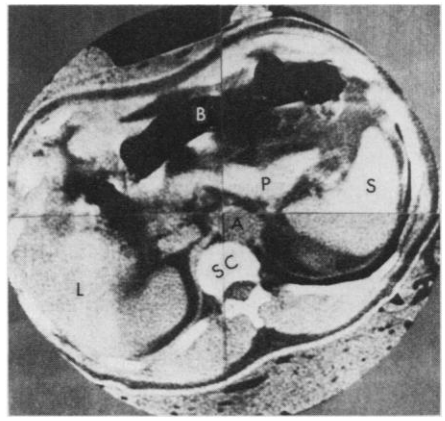

Fig. 2. Reconstruction of the abdomen of a normal patient. The view is up through the body from the feet toward the head. Some organs visualized are: *B*, bowel; *P*, pancreas; *L*, liver; *A*, aorta; *S*, spleen, and *SC*, spinal column and canal. Surrounding the abdominal cavity are the skin (white ring), fat (dark ring), and muscle (especially prominent behind the spinal column). [Source: EMI Ltd.]

The procedure is relatively comfortable for the patient, but the subject must remain motionless for the 5 minutes it takes to complete the scanning for each set of two cross sections in order to avoid so-called motion artifacts in the reconstructed image. This restriction can pose problems for very sick or uncooperative patients. Many radiologists now use a contrast medium to enhance the image of lesions, especially when tumors are suspected. The contrast medium is an iodine-containing compound which accumulates at certain types of lesions in a manner similar to radioisotopes. Severe allergic reactions can occur, but the incidence of mortality is less than one in twenty thousand, for example; thus this partially invasive procedure is considered quite safe. CAT-scans can be made on an outpatient basis, so the cost of a several days' stay in a hospital are not incurred. Outpatient savings averaged $1490 per patient according to a recent study at the University of Toronto.

Radiologists report that CAT-scanners have certain limitations. Metal clips, for example, from previous operations cause artifacts in the reconstructed image. The most serious limitation seems to be the inability to detect small lesions that are close to bone, a situation common in the region at the base of the skull. Called a partial volume artifact, the failure to image these lesions stems from the relative thickness of the cross section and from the large difference between the x-ray attenuation of bone and tissue. If a bone occupies part of the volume of a picture element, its high density obscures the small difference between the attenuation of a small lesion and normal brain tissue in the picture element.

Researchers in widely separated fields have rediscovered methods for image reconstruction many times. Radioastronomers, for example, use image reconstruction methods when they construct high resolution maps of radio sources by aperture synthesis from data obtained with arrays of antennas (*Science*, 13 June 1975, p. 1071). Electron microscopists have been responsible for much of the recent mathematical development of image reconstruction through their research on the structure of biological specimens with the use of Fourier microscopy. And in 1917 the Austrian mathematician J. Radon laid the mathematical basis for the algorithms used by the scanner manufacturers.

Although the basic ideas of CAT-scanning had been developed by the early 1960's, it was not until 1972 that a commercial scanner was available, perhaps because of a lack of small and inexpensive computers. Godfrey N. Hounsfield of the Central Research Laboratories of EMI Ltd., Hayes, Middlesex, England, headed the development of an apparatus designed for computerized x-ray scanning of the head. This device, called the EMI-Scanner, has been largely responsible for the enthusiasm for CAT-scanners and has inspired the emergence of several competitor scanners. According to the Bureau of Radiological Health, Rockville, Maryland, four companies have filed the radiation safety documents required for marketing instruments in the United States.*

The potential market for CAT-scanners is very large. Observers say that hospitals with 200 or more beds provide the most likely buyers of such devices for now. Some optimists, however, are speculating that within a decade, a CAT-scanner will appear nearly everywhere that conventional x-ray machines exist now. The total number of scanners sold is approaching 500, a little more than 200 of which are in operation. Thus, one rumor that more than 25 instrument makers are in various stages of studying, designing, or building scanners may be true.

The primary advantage of many of these

*In addition to EMI, the companies are Digital Information Systems Company, Silver Spring, Maryland (now called Pfizer Medical Systems, Inc.), Ohio-Nuclear, Inc., Solon, Ohio, and Neuroscan, Inc., Newport Beach, California. The Pfizer (ACTA) scanner and the Ohio-Nuclear (Delta) scanner can image the whole body, as well as the head.

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new machines will be speed, so that chest motion due to respiration will not degrade reconstructed images of the torso and so that an increased number of patients can be accommodated. For example, EMI now has in operation three prototypes of a body scanner that can accumulate the data for one cross-section reconstruction in 20 seconds, the length of time a healthy person can easily hold his breath.

The prospect of imaging cross sections of any part of the body is highly exciting (Fig. 2). Radiologists seem to agree, however, that the clinical efficacy of the available body scanners is still unproved. So far, these scanners have been used primarily in a research environment where their capability to detect abnormalities already located by more conventional means is being ascertained.

If the value of body scanners is yet to be shown, the demand for computerized x-ray scanners for neuroradiology is overwhelming. It is not uncommon for hospitals having CAT-scanners to operate them up to 16 hours a day, 5 or 6 days per week. For a basic study of three or four head scans, two patients per hour can be accommodated. Even so, waiting time to receive a CAT-scan can be as long as 4 weeks, and scheduling of emergencies is often a problem. The price for a CAT-scan varies from hospital to hospital and depends on such variables as whether contrast studies are done, but the average price for an examination is between $200 and $250.

The present scanners cost an average of $385,000 (plus a $25,000-per-year service contract to keep them operating), and the new fast body scanners may cost $550,000 or more. Because of this cost, observers say that as the scanners proliferate and as more and more normal patients (those in which no abnormalities are detected) are scanned, the cost of health care will rise, as reflected, for example, in the cost of health insurance. These observers question whether this cost will translate into a quantifiable improvement in health care, despite the acknowledged diagnostic capabilities of the brain scanners. To those who have to wrestle with health care planning and who do not see the patient on an individual basis, the issue may be a matter of balancing priorities. But to those who have suffered through pneumoencephalography, the value of the CAT-scanner may be more obvious.—ARTHUR L. ROBINSON

References

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were blind, or "would not be safe in the laboratory" because a limb did not function. One deaf woman chemist was required to undergo an additional examination to get her Ph.D.—*after* she had completed with honors all the requirements demanded of her "normal" colleagues.

Landing that first job is another problem mentioned frequently by our respondents (*2*). One deaf physicist with a Ph.D. from Yale was told teaching was impossible and he should stick to research, while other deaf scientists have been told by employers that they would not be safe in a laboratory, or that they should stick to teaching the deaf "where they could really make a contribution. . . ." Although the myth that handicapped workers present additional safety hazards has been disproven in practice (*3*), this concern is still widely used by employers to reject handicapped applicants.

Advancement on the job is frequently not open to the handicapped on the basis of merit. They may be deprived of professional give-and-take in the laboratory or full participation in professional associations by colleagues who will not take the time and trouble to include them. Advancement to supervisory responsibilities is often especially difficult for those whose capacity to communicate is impaired. It is somehow assumed that the handicapped will not be able to administer, travel, and communicate with foreigners, although the AAAS file is full of examples of people who do all of these things.

The appeal that many handicapped scientists make is that the able handicapped persons of our society, who are often considered to be an added cost, should be valued as a human resource to be developed. They seek recognition that the patience, incentive, and self-discipline developed by the handicapped are of positive value to the employers of scientists. They hope that changing attitudes will make it possible for all bright, able, scientifically inclined youngsters to choose science without having to be super-achievers in order to reach their goals.—JANET WELSH BROWN

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2. A. B. Crammatte, *Deaf Persons in Professional Employment* (Thomas, Springfield, Ill., 1968).
3. James H. Sears, "The able disabled," *Chemtech.* (December 1974), pp. 713–715. Reports a study of 1452 handicapped workers at DuPont.

Notes from Other Offices

Science Education: The sixth edition of the annotated bibliography, *Science for Society*, will be published in November. Like previous editions it will cover the interrelations of humankind, society, the environment, science, and technology. However, its structure will be different from previous editions. References will be indexed under 11 "science-society" issues—from aging and death through transportation. For each of these 11 issues, there will be a mini-course outline or framework. There will be some 2000 entries which include recent books and articles from a variety of periodicals during the past year.

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Opportunities in Science: Wanted: Information leading to the identification of science education projects aimed at minorities. Ongoing or now defunct programs undertaken since 1960. All educational levels. Includes projects in engineering, agriculture, biomedical, technical, and related areas directed at minority students or teachers and counselors of minority students. The AAAS has received a grant from the National Science Foundation to prepare and publish a comprehensive annotated bibliography of science education projects for minorities. Please send information about projects (including the names and addresses of individuals involved in them) to: Shirley Mahaley Malcom, Office of Opportunities in Science, AAAS, 1776 Massachusetts Avenue NW, Washington, D.C. 20036.

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Communications: Cancer, a four-cassette album of interviews with 19 recognized cancer authorities, is nearing completion and will be advertised soon in *Science*.

A revised edition of the study guide for the "Ascent of Man" series, as well as detailed guides for programs Nos. 4, 9, 10, 11, and 12, are available at 75¢ from the Communications Department, or from Professor Eleanor Webster, Department of Chemistry, Wellesley College, Wellesley, Massachusetts 02181. Films 4 and 10 stress chemistry; 9 and 12 biology; and 11 centers on philosophy. The series was written by Professor Webster, Professor Dorothea Widmayer, and Professor Maud Chaplin, all of Wellesley. The 75¢ fee purchases one set of six guides, and covers postage and handling. Supply is limited.