Image Reconstruction (II): Computerized Scanner Explosion

Computerized x-ray scanners have had a dramatic impact on the practice of neuroradiology since their introduction 3 years ago. Efforts are now under way to extend the range of applicability of image reconstruction from projections (the principle on which x-ray scanners are based) in medicine still further. In particular, researchers are working on fast x-ray scanners, on the combination of image reconstruction with nuclear medicine, and on low dose methods of imaging.

As now performed, the scanning procedure is necessarily slow. The basic scanning action consists of the motion of a narrow x-ray beam and a single detector across the head or body of a patient; this linear scan is followed by a rotation of the frame holding the x-ray source and detector about the patient and another linear scanning motion. A two-dimensional image of the cross section of the head or body in the plane that is traced out by the x-ray beam during the scanning is typically reconstructed from 180 or more one-dimensional projections, one of which is produced by each linear scan (*Science*, 7 November, p. 542).

The time to read the detector 40,000 or more times and the time to move the x-ray source and detector repeatedly through the linear and rotational motions together add up to about 4.5 minutes. Ways to reduce this time include the use of many detectors in the plane of the cross section, so that many data points are taken simultaneously, and the reduction or elimination of all mechanical motion.

One reason for needing faster scanners is that any motion of the patient during the scanning introduces artifacts into the reconstructed image, and it is often difficult for sick patients to remain sufficiently immobile for 5 minutes. Even chest motion during respiration could be overcome with 5- to 20-second scanning times because the breath could be held that long. And more patients could be accommodated, if the examination time were reduced.

Manufacturers and academic investigators who are now in the process of building computerized x-ray scanners that are equipped with multiple detector arrays are also using an x-ray source geometry called a fan beam. In conventional x-radiography, the x-ray tube emits a diverging cone of radiation that may be 40 centimeters in diameter by the time it reaches the film. In the first generation of computerized x-ray scanners, the x-rays are collimated into a thin beam which, in conjunction with a small collimated radiation detector, minimizes the effect of scattered radiation, since x-ray photons scattered out of the beam by parts of the patient's body are not detected. Scattered radiation reduces the contrast obtainable in conventional x-radiography.

The fan beam is a kind of compromise in that the x-ray beam remains confined to the plane of the cross section being imaged, but it is allowed to diverge within the plane, thus tracing out a fan-shaped area and simultaneously striking some or all of the detectors in a one-dimensional array. Because the area of the detector array is much smaller than that of an x-ray film, the scattering problem, although not absent, is reduced manyfold. Groups at Stanford University working under Douglas Boyd and Albert Macovski, for example, have shown that such scattering can be negligible if additional collimation is added to the detector array or if the projection data are modified prior to the reconstruction.

Whole Body Scans in 5 Seconds

The number of detectors in scanners is increasing rapidly. Different models now available which have 1, 3, or 30 detectors have corresponding scanning times of 4.5 minutes, 2 minutes, and 20 seconds. These instruments retain a combination of linear and rotational scanning motions, although the rotation increments have increased from 1 to 3 to 10 degrees, respectively.

Even faster x-ray scanners will retain only the rotation motion. One brain scanner just becoming available has 128 detectors and rotates continuously over 360 degrees in 9 seconds. A number of researchers are working on whole body scanners that will be able to collect all the data needed for the reconstruction of a cross section in 5 seconds with the aid of 250 or more detectors.

Many of these advanced computerized x-ray scanners collect more data than the earliest versions so that larger areas of the body can be imaged with higher resolution. As a result of the large amount of data processing, the time a computer algorithm requires for the reconstruction does not match the data acquisition time, varying from 2 to 5 minutes per reconstruction. In the future, the use of faster algorithms, multiple computer processors (one to supervise data collection and one to carry out the reconstruction algorithm), and special-purpose, hard-wired (nonprogrammable) processors should reduce this time.

Some of the fast scanners will also use a variety of detector that potentially could make the computerized scanner less expensive (an average of $385,000 for the slower scanners and upward of $500,000 for the first fast whole body scanner). The early scanners have had detectors consisting of a scintillating crystal, such as sodium iodide, and a photomultiplier tube. The cost and complexity of an array of these detectors can rapidly increase when very many are used. One alternative is a multiwire gas-filled chamber. Operation of the multiwire chamber is the same as that of a conventional single-wire gas chamber, but an array of wires makes it possible to determine the location of the x-ray photon being detected. Boyd's group at Stanford has built a multiwire proportional chamber filled with xenon gas at high pressure, for example, and David Chesler and his colleagues at Massachusetts General Hospital in Boston, who are building a 5-second whole body scanner, are experimenting with a similar detector. Some commercial scanners also will have gas detectors.

Ultimately, machines having arrays of many x-ray sources and many detectors will avoid all mechanical motion whatsoever. A start in this direction has been made by researchers in the Biophysical Sciences Laboratory, headed by Earl Wood, at the Mayo Foundation in their efforts to make cross-sectional images of the beating heart. According to Richard Robb at Mayo, motion pictures of multiple cross sections of a beating heart of a dog have been made by electronically synchronizing the heart beat with x-ray pulses. The investigators use a fluorescent screen, an image intensifier, and a television camera to record two-dimensional projections at the rate of 60 per second. From the projections obtained at 36 viewing angles, cross-sectional reconstructions at many anatomic levels of the heart can be made for each instant of time and displayed to show the dynamic changes in the size and shape of the heart.

The investigators' next step will be to use perhaps 30 x-ray sources along with image intensifier–television detectors positioned in a semicircle. By making 30 x-ray images simultaneously at intervals of 1/60 second, electronic synchronization would not be required, and the technique could be applied to visualizing the human heart without the effects of heart motion obscuring the image.

Sometimes it would be useful to obtain

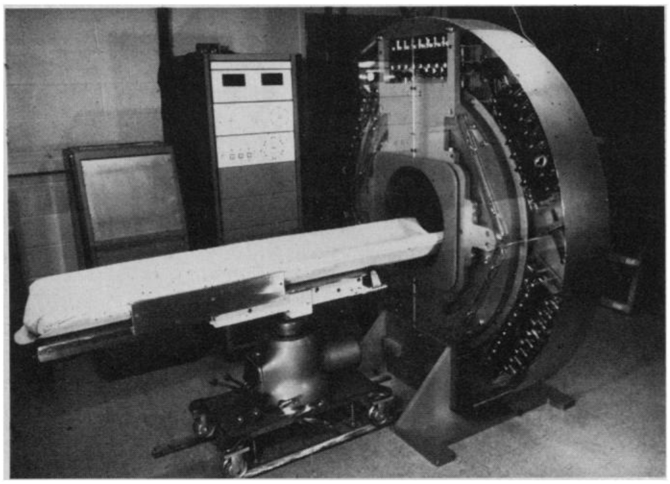

Fig. 1. The whole body positron emission transaxial tomograph designed at Washington University, St. Louis. The patient lies on the couch, which slides into the detector array with eight detectors in each side of the hexagon. The scanning motion consists of a 5-centimeter linear scan followed by a 3-degree rotation. This sequence is repeated until 60 degrees are covered. [Source: Michael Phelps, Washington University]

images of body or head sections other than the transverse axial cross sections obtained from x-ray scanners. In principle, other orientations could be derived from a set of cross sections, but the thickness of the cross sections (up to 13 millimeters) would limit the usefulness of such images. William Glenn at Massachusetts General Hospital and Samuel Dwyer, III, at the University of Missouri, Columbia, have collaborated on a way to overcome this problem by making several overlapping cross sections with a conventional x-ray scanner. From 16 reconstructed cross sections each 8 millimeters thick and covering a total thickness of about 3.5 centimeters, a computer can create a full three-dimensional image with a resolution of about 2 millimeters and display two-dimensional sections at several orientations. Time varying displays can also be made so that a rotating image of the ventricular system of the brain can be shown, for example.

The image obtained in radionuclide scanning is analogous to an x-ray in that it is a two-dimensional projection. It is unlike an x-ray in that the source of radiation is a gamma-ray emitting isotope localized within the patient's body—that is, it is an emission rather than a transmission technique. By applying methods similar to those used with computerized x-ray scanners, however, image reconstruction from projections can be combined with nuclear medicine. In fact, David Kuhl and his coworkers at the University of Pennsylvania were using image reconstruction methods before the x-ray scanners were developed, and their instrument has evolved through several stages.

The present scanner has 32 coplanar scintillation detectors in a boxlike arrangement that surrounds the patient's head. The detector array rotates continuously, and one reconstructed cross section can be obtained in 50 seconds up to a few minutes. The resolution of the reconstructed image is about 1.6 centimeters and, as in most nuclear medicine techniques, is much coarser than the 1.5-millimeter resolution of x-ray reconstructions. According to Kuhl, the reconstructed image correctly assays the radioactivity to within 5 percent, which is more than adequate, since the objects being imaged have a high contrast. (The computerized x-ray brain scanners advertise an ability to see differences in x-ray attenuation of 0.5 percent, but the difference in attenuation between normal and diseased tissue may be only a few percent.)

Kuhl and his associates have used their scanner for diagnosing various cerebral lesions. In another study, they made three-dimensional maps of local cerebral blood volume by reconstructing cross-sectional maps of the intensity of gamma-ray emission from red blood cells labeled with technetium-99, which had been injected intravenously.

Other researchers have made cross-sectional reconstructions from gamma-ray emission with the use of a gamma (or Anger) camera. A gamma camera is a large (up to 38 centimeters in diameter) position-sensitive scintillation detector and is often used for conventional radionuclide scanning. Thomas Budinger, Grant Gullberg, and their associates at the University of California, Berkeley, and at the Lawrence Berkeley Laboratory, for example, have imaged the brain, the heart, the kidneys, and the liver by rotating patients in front of the gamma camera and recording data at 36 or 72 different angles. Since the detector is two-dimensional, the data necessary for as many as ten cross sections are obtained simultaneously. Such a system is not suitable for clinical use, however, because sick patients cannot always be moved, and because it is slow.

If attenuation of the gamma rays as they pass through the patient's body is severe, the image of the radioactive region may be distorted in position or in intensity. An imaging technique with the two gamma rays emitted in opposite directions with equal energies when an electron and a positron annihilate can overcome this difficulty. Sources of positrons are radioactive isotopes that are introduced into the patient just as in standard nuclear medicine procedures. In addition, the contrast of the reconstructed image is enhanced because scattered radiation is not detected. A technique called coincidence counting is used to ensure that a detection event is registered only when two gamma rays traveling in opposite directions are detected within a very short time by two opposing detectors. This limits the detected events to a well-defined region between two detectors placed on either side of the patient.

Michael Phelps, Michel Ter-Pogossian, and their associates at Washington University, St. Louis, have developed an instrument they call a positron emission transaxial tomograph (PETT). Forty-eight sodium iodide detectors are arrayed around the patient in a hexagonal arrangement with eight detectors on each side of the hexagon (Fig. 1). Each detector is connected to the eight on the opposite side of the array for coincidence detection, a situation roughly analogous to the fan beam geometry of the fast x-ray scanners. Both linear and rotational scanning motions are required, and one reconstructed cross section with a resolution of from 1 to 1.5 centimeters can be completed in 2 to 5 minutes.

With the latest version of their system, the Washington University researchers have imaged such organs as the heart, the brain, the liver, the pancreas, the spleen, and the kidneys of healthy subjects. They have also detected tumors, arterial-venous malformations, and strokes in brain studies, and have seen myocardial infarctions in the heart.

Phelps is especially enthusiastic about the use of carbon-11, nitrogen-13, and oxygen-15 as positron sources. These isotopes of atoms common in organic materials can be used to label such compounds without disrupting their chemical or physiological behavior, and the metabolism of the compounds observed by image reconstruction. Phelps says that conventional labeling isotopes are, in effect, foreign to the body and may affect the way the compound is metabolized. The "organic" isotopes are short-lived, and a cyclotron is needed in the hospital to generate them. At present, cyclotrons of the type required may cost $500,000, in part because only a few are sold in a year. Positron sources that do not require cyclotrons and thus can be used in any clinic include gallium-68 and rubidium-82.

(Continued on page 710)

RESEARCH NEWS

(Continued from page 648)

An imaging system developed by G. L. Brownell and his associates at Massachusetts General Hospital can be used both for image reconstruction and conventional radionuclide imaging. Two-dimensional arrays each containing 127 detectors (scintillating crystals and photomultiplier tubes) sit on opposite sides of the patient. When the two arrays are used as a coincidence detector, the picture corresponds to a normal isotope scan. When the arrays rotate through 180 degrees, however, and readings are taken at intervals of 5 to 7 degrees, the information required for several cross sections is accumulated. So far, the Massachusetts General group has made cross sections of artificial test objects (phantoms) and of the brain in human subjects.

Researchers working under Victor Perez-Mendez at Lawrence Berkeley Laboratory, and under Leon Kaufman and Chang Lim at the University of California, San Francisco, have constructed and tested a positron annihilation image reconstruction system that involves no scanning motion at all. The reconstructed image, however, is not a true transaxial cross section, but is more akin to an earlier form of tomography known as focal plane imaging. According to Kaufman, the entire system could cost much less than the least expensive x-ray scanner.

The multiwire proportional chambers used in the coincidence detector are a major factor in the cost estimate. The detector is similar to the xenon detector that is expected to be used in some fast x-ray scanners, but the array is two-dimensional, covering an area 48 by 48 centimeters. Coincidence events are detected by elements in the two arrays opposite one another on either side of the patient.

Still other improvements to computerized scanners are being explored. Observers consider imaging techniques that do not impart the 2- to 4-rad dose of x-rays but retain the ability of x-ray scanners to make images with a high fidelity to be especially important because 2 to 4 rads is still too high for routine screening of nominally healthy persons. One way to reduce dosage is to find improved algorithms so that accurate images can be reconstructed from fewer data points. Research on combining image reconstruction from projections with ultrasound (which is considered safe because it produces no ionizing radiation) and with nuclear magnetic resonance are all under study for this reason.

Budinger, Kenneth Crowe, and their associates at the Lawrence Berkeley Laboratory have been studying the utility of radiography using helium ions and other so-called heavy charged particles as another approach to low dosage imaging. The interactions suffered by such particles do not result in their being absorbed as x-rays are, but are more like collisions between hard spheres in which a small amount of energy is lost in each collision. Thus, in heavy charged particle imaging, it is the energy of the transmitted particles rather than their number that is measured.

In other respects, imaging with heavy charged particles proceeds in the same way as with x-rays. Budinger, Crowe, and their colleagues have reported on cross-sectional reconstructions of the brain. Instead of a linear scanning motion, the investigators used a parallel beam of helium ions that is equivalent to the many parallel beams produced by the x-ray scanners. The method is not yet ready for clinical use, however, because the patient must be rotated in front of the beam which is obtained from the Berkeley 184-inch cyclotron.

—ARTHUR L. ROBINSON

Economics

(Continued from page 649)

is composed of a finite number of linear segments. In this respect, however, the example is quite misleading. In most applications of activity analysis to the firm the matrix A will have many rows and columns—perhaps running into the thousands—with many possibilities of substitution, with an explicit account of intermediary goods, and with a great number of different outputs. As distinct from the description of production by means of one function, there will rarely be a single commodity whose output is being studied in isolation.

This point may be seen by examining a highly aggregated model of an economy along the lines of input-output analysis, a precursor of the activity analysis model introduced by Leontief in the 1930's. Let us imagine that the economy produces only two outputs, each of which can be consumed directly or used as an input into production, and let labor be the only scarce factor. An input-output table for this economy might be given by

$$\begin{array}{cc} \begin{bmatrix} 6 & -7 \\ -3 & 10 \\ -1 & -1 \end{bmatrix} & \begin{array}{c} O_1 \\ O_2 \\ L \end{array} \end{array}$$

where I have specifically deleted the columns referring to costless disposal. In this example, and in its extensions to a more disaggregated model of the economy, there is no single output on which our attention is focused; the totality of all outputs is studied simultaneously.

An activity analysis model of an economy-wide production set would be considerably more general. Each output would be capable of being produced by more than one activity; there would be many scarce factors, such as machinery of various types and inputs of raw materials. We would be explicit in the representation of import and export possibilities open to the economy and might even consider having the model extend over time so as to explore its dynamic properties. The activity analysis model makes available a study of production which is of astonishing flexibility and generality.

Tjalling C. Koopmans, one of the two recipients of the Nobel award, was led to his introduction of the activity analysis model in the early 1940's by a study of the efficient use of transportation facilities. Koopmans, who was employed by the British Merchant Shipping Mission in Washington, D.C., during World War II, became concerned with the problem of selecting shipping routes to deliver a preassigned list of commodities to specified destinations in such a way as to minimize the total cost of shipping. Koopmans realized that the problem could be cast in the form of an activity analysis model in which each basic activity represented the selection of a particular shipping route. To take a simple example, consider a homogeneous commodity available at each of two locations, I and II, and which is required in definite amounts at each of three destinations, A, B, and C. The possibilities of shipping may then be described by the following activity analysis model

$$\begin{array}{cc} \begin{bmatrix} -1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & -1 & -1 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ -5 & -3 & -7 & -10 & -20 & -8 \end{bmatrix} & \begin{array}{l} \text{I} \\ \text{II} \\ \text{A} \\ \text{B} \\ \text{C} \\ \text{Cost} \end{array} \end{array}$$

in which the last row represents the cost of shipping a single unit from a given origin to a given destination.

In his memorandum on the transportation problem, Koopmans suggested a method of solution based on an economic idea which was to become of central importance in subsequent developments. He realized that a vector of prices—one at each location—would be associated with an optimal shipping plan. The prices would meet the condition that each route in use