The Computed Tomography Scanner:

A Description and History

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All diagrams are original drawings based on information found in the references appearing in the bibliography. No scale is used.

--INTRODUCTION--

One cool evening in 1895 at the University of Würzburg, Wilhelm Conrad Roentgen was experimenting with electrical discharge in a highly evacuated tube. Experiments of this type had been done since 1870 by other researchers, notably Sir William Crookes in England. What made this particular evening unique was that Roentgen noticed an inexplicable glow on a fluorescent screen that just happened to be across the lab from the tube. He quickly investigated this strange phenomenon by placing his hand between the screen and the tube. Much to his surprise and wonder, a shadow of the bones within the tissue of his hand appeared on the screen. The effect could be traced back to a point on the glass opposite the cathode, or negatively charged electrode: the glass glowed with a greenish light. After a more thorough investigation, Roentgen determined that the 'rays' would pass from the tube even if it was covered with a light-tight material. He soon realized the potential importance of his discovery, but told no one about it until publishing his findings--complete with a shadow photograph of the bones within a living hand. He named his discovery, of course, X-RAYS. In 1901, Roentgen received the first Nobel Prize for physics.

In the more than 80 years since Roentgen first saw the bones in his hand, x-rays have become a routinely used diagnostic and therapeutic tool of the medical profession. Until the late 1960's, the technique used to obtain a photographic image using x-rays was basically the same used by Roentgen to make the very first images: the area to be examined was simply placed between the x-ray tube and a photographic plate, a measured exposure was made, and the plate was developed by a standard photographic process. The inherent difficulty with interpreting the developed plate is that the area of interest may be occluded by overlying and underlying tissues and bone. Finally in the late '60's, advanced solid-state electronics made possible a radically new development in x-ray technology. The technique is known by several names, including CTAT (Computerized Transverse Axial Tomography), CAT (Computerized Axial Tomography), or simply CT (Computed Tomography). Using no film or chemical development process, the CT scanner produces a truly unclouded cross-section of the body through an algorithm on a high-speed digital computer. This paper is about the development and configuration of the modern CT scanner. I was inspired to write about this device for two reasons: First, it is an example of bio-medical engineering solving a major problem with a new diagnostic tool; and second, it has a great deal of "gee-whiz" appeal for me!

A historical background of early attempts in the field is given, followed by the operation and construction of the device from an engineering standpoint. Finally, some of the pros and cons of the purchase and use of these expensive machines are considered.

--HISTORICAL BACKGROUND--

All of Man's "miraculous" engineering feats were first only an idea in someone's mind. Occasionally developments are invented in theory quite a few years before the level of technology increases sufficiently for actual construction and testing. Examples such as microwave ovens, lasers, space travel, and of course computers immediatly come to mind. So it was with the CT scanner in use today.

A Frenchman named E. M. Bocage received a patent in 1921 for what is now called focal plane tomography. The word tomography comes from the Greek word tomos --meaning section, and graphy --meaning to write in a specified manner.[1] Two examples of this technique are described below.

In figure 1, the patient remains fixed while both the x-ray source and the film are moved. The motion of the source is opposite that of the film in such a way that only one particular plane of the patient's body is constantly directly between the source and film. Thus the shadows from this plane remain fixed on the film while the others become a background blur due to their orientation change with respect to the source and film.

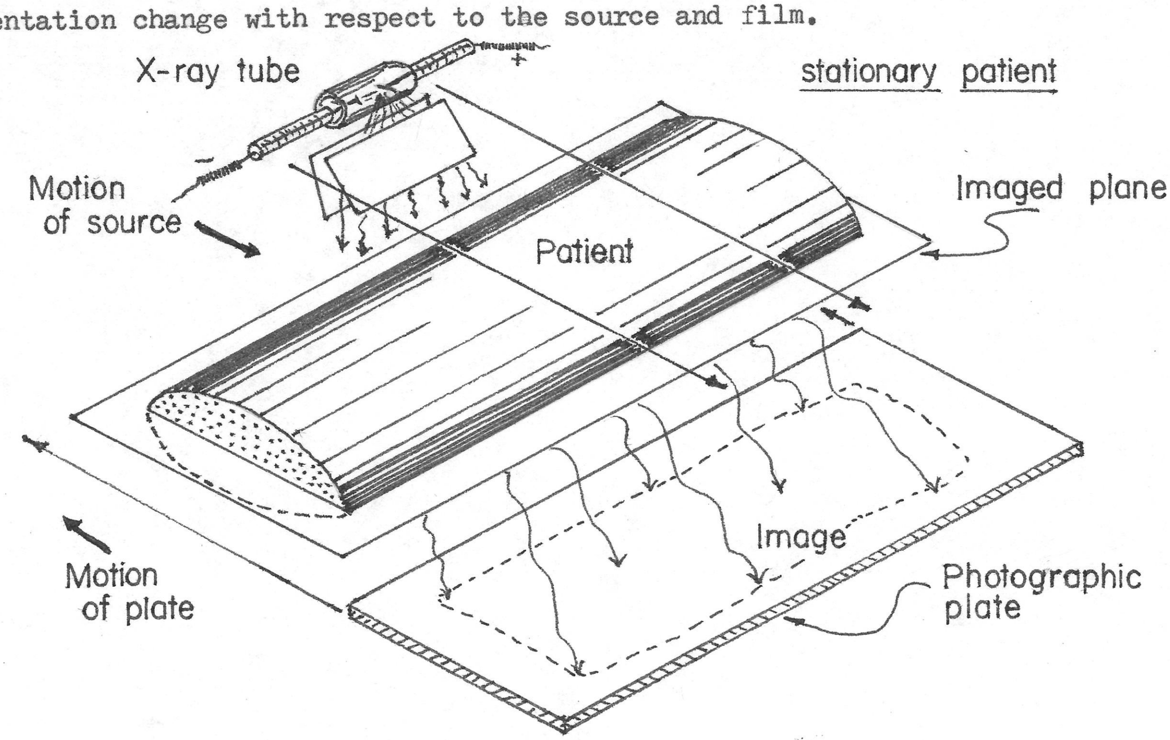

Figure 1

The resulting image is a cross-section of the patient containing a blurry artifact. This method can be used to obtain images of planes oriented parallel to the long axis of the patient.[2]

Figure 2 shows a means of obtaining a tomogram perpendicular to the long axis of the patient. Here the x-ray source remains fixed at an angle of 30^{o} above the horizontal. The patient is seated on a rotating chair with the film on a rotating platform below and opposite the source. The patient and the film are rotated in proper synchronization to hold the plane of interest fixed on the film and blur everything else.[3]

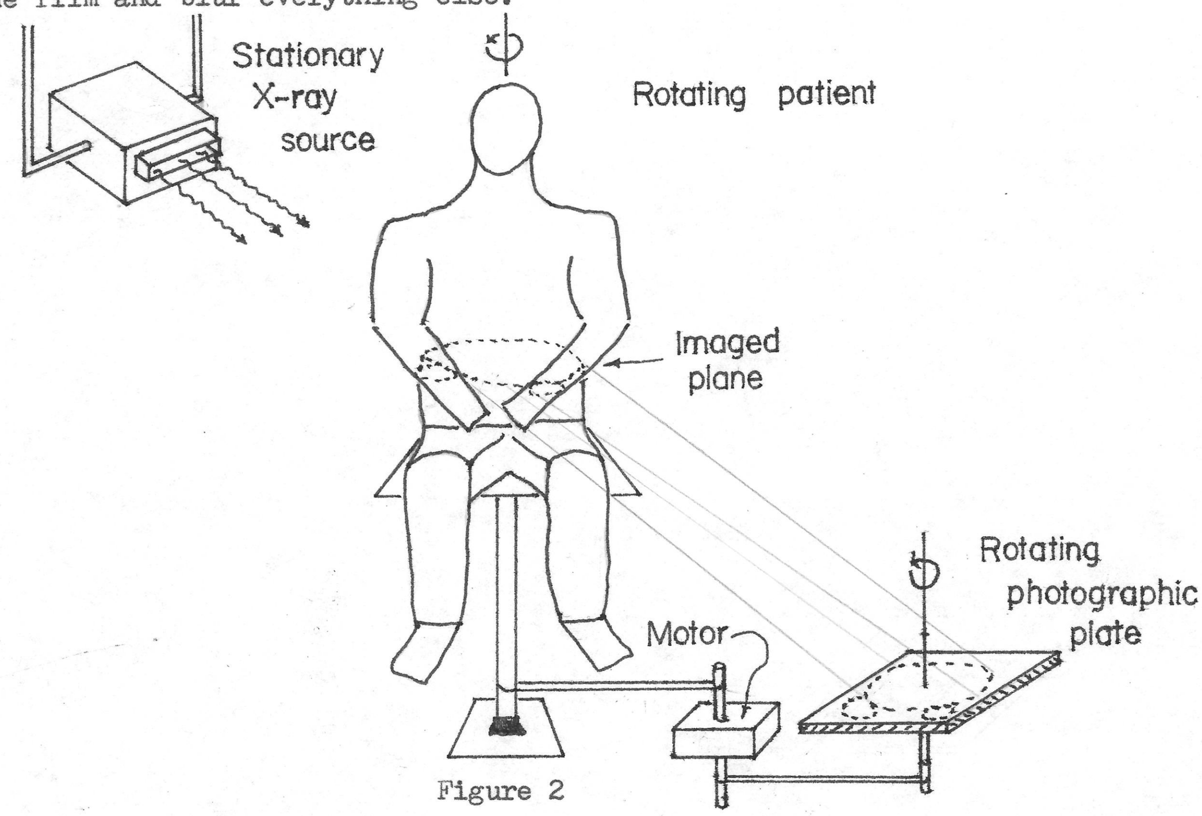

Figure 2

These methods were--and still are--used to minimize unwanted shadows by blurring them. They are useful in determining the location and size of many internal features, although the contrast range between various levels of transmission is quite small. Computed tomography goes one step further by providing blur-free images and a vast dynamic range of contrasts compared to film.

The modern CT scanner is a major accomplishment from an engineering standpoint. The first unit was developed by G. N. Hounsfield at an unlikely company named Electronic Musical Instuments, Ltd. (EMI). This first unit, introduced in 1972, was designed for use on the head only, but subsequent units were designed to scan any part of the anatomy. In 1972, no other manufacturers were interested in such a device since the CT scanner was considered too costly, too complicated, and too futuristic in concept. The initial reaction by the medical profession was so entusiastic, that more than 20 companies produce a CT device today.[4]

The basic form of all CT units will be described next.

--HOW CT WORKS--

The CT scanner operates in a deceptively simple manner. A combination of x-ray sources and detectors are set up facing each other across a cylindrical space. The patient is positioned in this space so that the proper area will be scanned. At this point, the machine rotates around the patient through 180° in 1° steps. At each degree, the rotation stops and typically 160 parallel transmission scan values are taken and stored in the computer. The parallel scans are accomplished in different ways on different machines, but the first EMI device simply moved the source and detector in 160 steps transversely at each degree. The values obtained are the fraction of the incident beam that makes it through the body to the detector. Since more x-rays can make it through skin and soft tissue than through bone, a range of transmission values appears. This range will ultimately serve as the basis for reconstruction in the final image. Once the 180° scan arc has been executed the computer has accumulated 180 x 160 = 28,800 individual values. Through various algorithms--some are described later--the computer reconstructs the cross-sectional array of points derived from the transmission data. This array is easily displayed on a black-and-white or color high resolution TV screen. The first machines introduced in 1972 required five minutes to carry out the actual scan plus nearly ten more minutes to do the calculations. Modern units frequently use multiple detectors and sources to speed up the scan and more efficient algorithms to speed up the processing. In the most recent units, the patient only has to lie still for a few seconds and the result appears in under two minutes.[5]

The following page contains diagrams of several configurations for CT scanners. While the specific details of construction may vary, the sequence outlined above takes place in all CT devices.

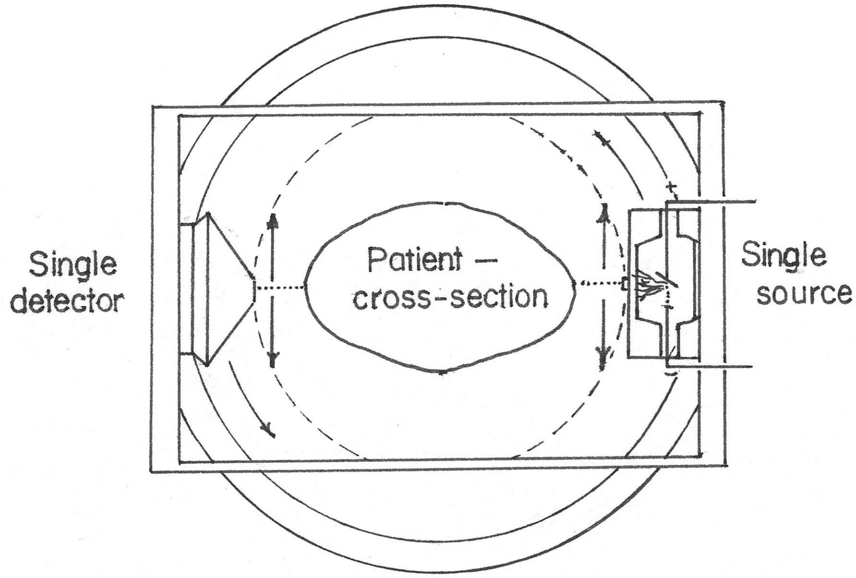

Figure 3

First Generation Unit

180° rotation and transverse translation of source and detector

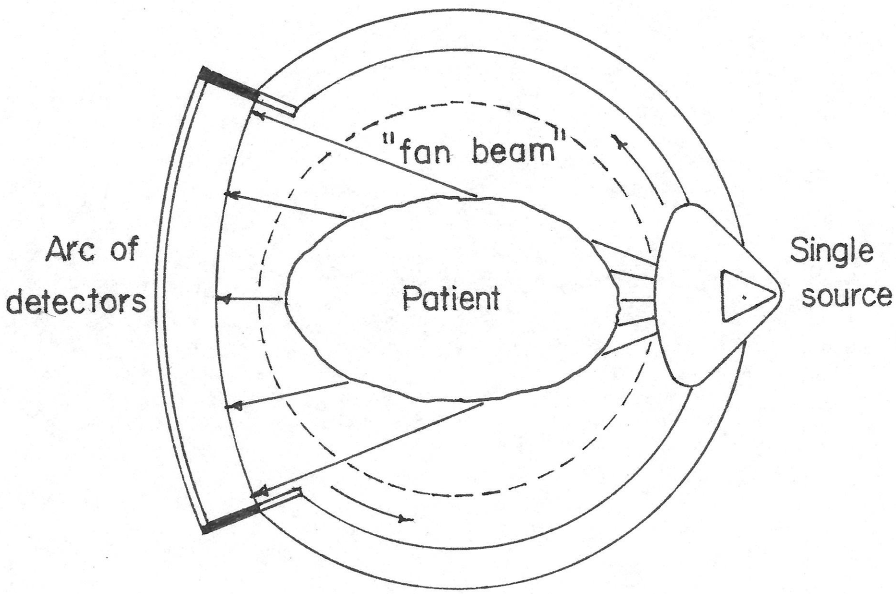

Figure 4

Second Generation Unit

180° rotation of source and detectors (no translation)

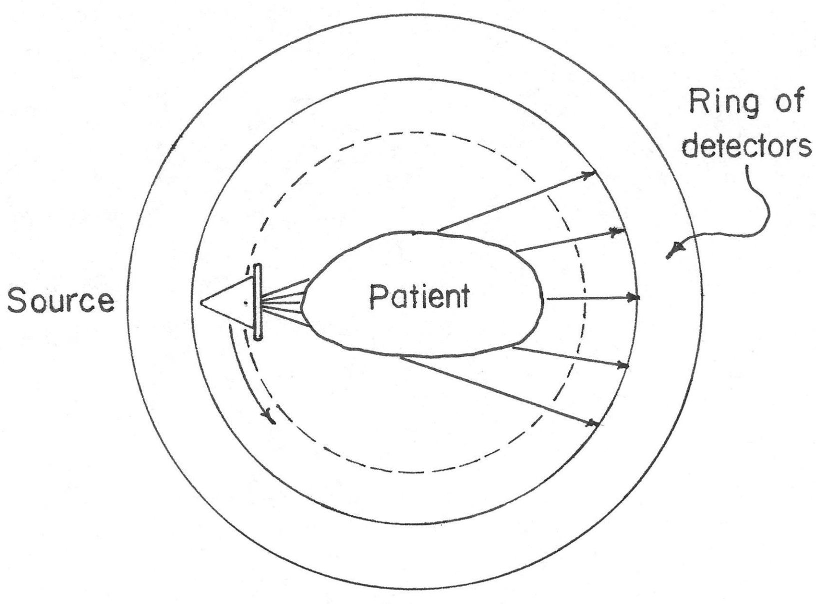

Figure 5

Third Generation Unit

180° rotation of source only

Continuous operation without returning to starting position

Computed tomography devices must operate both reliably and consistently. The electronic control system must be able to identify and compensate for any irregularities brought about by the mechanical portions of the machine. This low tolerance for mechanical variations as well as speed considerations is the reason most new machines contain few moving parts.

The source/detector relationship is probably the most important consideration, next to the computer. The source of the x-rays can be a standard x-ray tube, but special tubes have been developed with greater reliability and uniformity. Figure 6 shows a diagram of a typical x-ray tube. A potential difference of 120,000 volts across the tube causes electrons on the negative electrode, the cathode, to leave the surface and accelerate toward the positive electrode, the anode. The rapid deceleration when the electrons strike the anode causes x-rays to be emitted from the tube, but a more consistent group results when the bombarding electrons knock inner shell electrons off the atoms in the target material. X-rays are emitted when an outer shell electron falls into the vacated space.

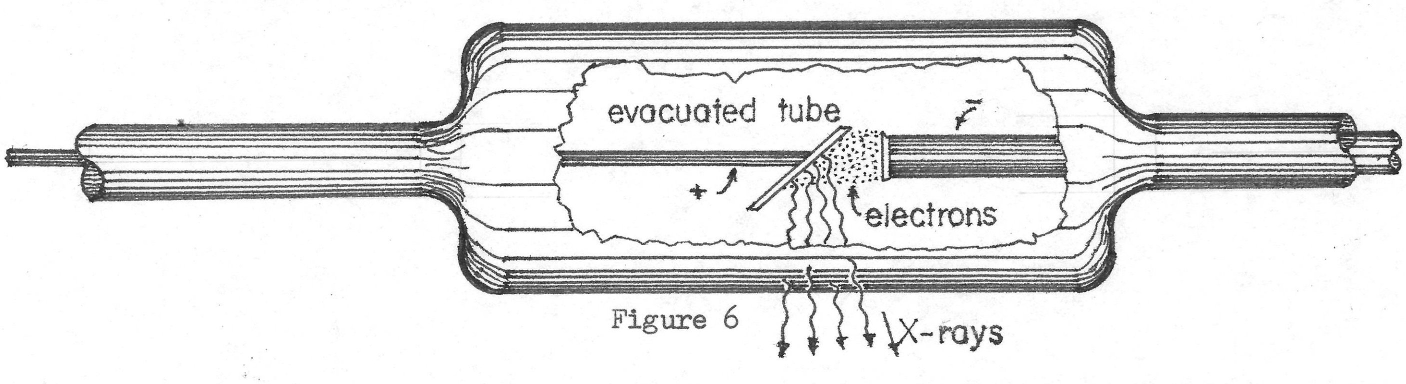

Figure 6

After passing through the patient, the x-rays have to be detected somehow. A conventional x-ray uses photographic film, but the CT process is much better suited to some form of electronic detection. This is accomplished by a scintillation detector. This type of detector makes use of the property of certain materials when they are struck by x-ray photons: they give off their own light, or scintillate. The light given off can be detected and amplified by a sensitive photomultiplier tube, which sends an electrical signal to the computer for analysis. Several types of gas-filled discharge tubes exhibit the scintillation property, as do certain crystals. NaI(Tl) crystals were used on many early units because of their high output of light for a given amount of x-ray exposure. They tend to keep glowing for a short time after the x-ray photons cease, so bismuth germanate is used in many of the modern units requiring faster scan times.

Many of the rays leaving an x-ray tube are not traveling in a useful direction, so a collimator system between the source and patient and between the patient and detector is required. A collimator is a device made of lead, or some other x-ray absorbing material, which filters out the rays not traveling directly toward the detector. Some rays within the patient's body may be scattered as they encounter obstructions, so the collimator between the patient and the detector is necessary to filter them out. The design of the collimation system affects the number of effective x-rays passing through the patient, so most modern units include elaborate collimation equipment.

The discussion of computed tomography now moves on to the mathematical methods used in reconstruction of the internal features.

--RECONSTRUCTION TECHNIQUES--

The mathematical theories enabling the computer to perform the reconstruction process pre-date the first computers in some cases. Several of the algorithms in use today utilize transformations devised by the French mathematician Fourier well over 100 years ago. No matter what numerical method is used to reconstruct the scans, the data is taken in the same manner: the intensity (I_o) of the x-ray photon beam at the source is compared to the intensity (I) transmitted through the patient to the detector. If the body was a homogeneous object with thickness (l), the relationship is[6]

$$I = I_o \, e^{(-\mu l)}$$

where μ is the linear attenuation coefficient--a proportionality constant characteristic of the homogeneous material in question. Since the body is not a homogeneous object, the attenuation coefficients vary from tissue to tissue. In this case, the exponent is not $(-\mu l)$ anymore, but the line integral of the individual attenuation coefficients of the tissues in the particular scan line. The total cross-sectional region of the scans can be divided into a cartesian coordinate system locating each individual coefficient by a function and a path length ds. The line integral can now be expressed as[7]

$$\int_{\text{source}}^{\text{detector}} \mu(x,y)\, ds \; ,$$

substituting, the intensity (I) becomes

$$I = I_o \exp\left(-\int_{\text{source}}^{\text{detector}} \mu(x,y)\, ds\right) ,$$

then taking the negative logarithm

$$\ln\left(\frac{I_o}{I}\right) = \int_{\text{source}}^{\text{detector}} \mu(x,y)\, ds \; .$$

The logarithm of the ratio of incident and transmitted intensity is easily computed, and immediately yields the line integral through the patient for that scan. Each of the 28,800 individual scan values must be analyzed this way before it can be used in reconstruction. Thus it is the properly transformed combination of line integrals that will produce a reconstruction of the attenuation coefficients in the patient. The range of coefficients can be set up on a range from zero to 100 scale factors. For such a range, water would be at the bottom and bone at the top. All the soft tissues would take up about a 6% range somewhere in between.[8] Photographic films are not able to provide different densities for such a huge range of values, but the scintillation detectors are. The output of the scintillation detector passes through an analog-to-digital converter, or ADC, and can be scaled over the entire range very easily. When the final image is to be displayed, the digitized range is converted to shades of grey or color for the TV image. The computer can scale the values in any way desired to bring out contrast in the final image. However, the set of line integrals must be converted before the image can be reproduced. This can be done in several ways on a computer. The methods fall into two types: iterative and analytic.[9]

Iterative methods are well-suited to computers and are relatively easy to program and execute. Basically, an initial estimated model of the distribution is "made up". The line integrals of this guess are compared with the values actually measured from the patient. The model is then adjusted to improve its match with the measured values. The model is simply a two-dimensional array of picture elements that will eventually become the final image. The comparison/adjustment process continues until a pre-determined level of agreement between model and measured is reached. This process is what is known as iteration. The first units produced by EMI used an iterative algorithm, but the process has two big drawbacks: first, it is very slow, and second, it cannot begin until all the scans have been made and the line integrals computed. The first units had an 80 x 80 picture element array and required ten minutes to process it. Greater resolution can be achieved by spreading the values over a 160 x 160 or larger pixel array, but this would involve a factor of four increase in processing time. It became apparent that a faster algorithm and/or one that could begin processing before all the values were available would be very nice. This is where analytic methods come in.

The math used in analytic algorithms for CT was derived mainly from the work of Fourier, a German mathematician named Radon, and an Australian astrophysicist named Bracewell.[10] Bracewell introduced his "convolution algorithm" in 1956 for use in reconstruction of radio-astronomical data. This algorithm relies heavily on the earlier discovery that a two-dimensional function, such as a cross-sectional tomogram, is determined uniquely by its one-dimensional projections in all directions (this involves a Fourier transform of the projection). A small number of these projections will form a crude model, while the actual function can be reproduced by integrating to the limit. The operation of a CT scanner produces a finite number of projections, so the reconstruction is a summing operation. The process is much faster than iteration, plus it has the added bonus of being able to commence after the very first scan. In other words, the scanning and processing take place almost simultaneously. The patient's tomogram is available immediatly for examination on the TV screen or it can be saved in digital form for later reference or transmission electronically to another location. This type of storage eliminates the necessity of storing hard copies of every scan.

The actual calculations performed using an iterative or analytic method are subject to a few conditioning steps to clean up the data. This cleanup step is necessary to compensate for fluctuations in the x-ray intensity, different path lengths through different thicknesses in the body, and x-ray scatter. All these need to be taken into account before processing.

A number of further refinements and advances have been incorporated into units since the first generation appeared ten years ago. Most have been to cut the scan time and increase the convenience of operation. The first units used a 120,000 volt power source with .033 amperes of current. The product of the voltage (joules/coulomb) and the current (coulomb/second) gives the power in watts (joules/second): 3960 W in this case. These values were necessary because the x-ray tubes available could not handle more power during the five minute scan time. New tubes have been designed to handle more power by using a rotating target anode to dissipate the heat of operation. The decrease in heating within the tube allows better uniformity of x-ray output, which improves the final reconstruction. The lower heat also allows a greater current through the tube. The greater current coupled with a large number of detectors increases the number of x-rays actually used to make the reconstruction--which means a lower total dose of radiation to the patient since fewer photons are wasted in a given reconstruction process. Other improvements include better collimation and focusing of the x-ray beam, improved detectors, and pulsed current to eliminate voltage fluctuations.[11]

The impact of CT on the medical profession will be briefly considered in the next section.

--COMPUTED TOMOGRAPHY AND THE MEDICAL PROFESSION--

The first demonstrations of CT equipment received a very favorable reaction from the medical profession. Some physicians even predicted that CT technology would soon replace all other diagnostic radiological techniques. Others were more skeptical of the ultimate impact of the device. Everyone agreed that the machine was truly amazing. As it turns out, the advent of CT has not yet had any significant effect on conventional x-ray usage, except in brain scans. The skull prevents most ordinary x-ray studies of the brain within, but the extended dynamic range of computed tomography handles this very effectively. The reason CT has not affected diagnosis in other parts of the anatomy is three-fold: First, CT is currently used as a complementary diagnostic measure to extend and confirm the results obtained by more conventional procedures. CT sometimes provides a new perspective of the internal conditions, but other times it provides nothing useful. Second, many x-ray techniques are perfectly satisfactory in their current form. X-rays of broken bones and certain parts of the intestinal system are of this type. It is easier, cheaper, and more accurate to use standard techniques in these situations. Finally--and probably most significant--CT is still a new arrival on the medical scene. Many of the doctors using CT services are understandably more comfortable and confident making a diagnosis from techniques they had been working with for years before CT was invented. Thus the ultimate impact of this device on medical diagnosis will not be known until several more years down the line.

There is no doubt that CT is here to stay. Even if no more units were sold today, a large percentage of the population would be able to receive a CT scan quite close to home.[12] Because of this, the federal government has set up guidelines to limit the number of CT units placed in a given population center. The legislation was drawn up after an "arms race" developed between competing hospitals, clinics, and even private doctors to offer CT services.

It quickly became apparent that a single scanner operating almost constantly in a city made more sense than three or four units operating infrequently. The government is interested in protecting itself and the public from unnecessary increases in medical care costs by requiring a CON (Certificate of Need) before a device costing more than $100,000 may be placed in a given area. The standard requirement is a projected usage of 2500 studies per day--or about one scanner for 120,000 people in the surrounding population.[13] The limited market has increased the competition among CT manufacturers and this has pushed the purchase price down for some units. Some now cost under the $100,000 mark, and are consequently no longer subject to the CON restrictions. This may have a considerable effect on the number of devices placed in the coming years.

New developments in CT technology are constantly popping up in the latest units. This means that many of the scanners already placed in hospitals will be somewhat obsolete in the near future. This may create a market for used or reconditioned equipment, so we may see units appearing in many smaller clinics and private doctor's offices. At that point, the medical profession will have either accepted or rejected the usefulness of CT diagnosis.

--OBSERVATIONS AND CONCLUSION--

The development of computed tomography is yet another example of the role of High Technology in our society. It is easy to get caught up in the almost romantic appeal of new inventions. It must be remembered that no matter how remarkable and futuristic computed tomography is, it is <u>not</u> a cure for any disease. In many cases, CT just provides another view of a tumor or condition that cannot yet be cured. This fact can be lost in the glitter, flash, and yes, sincere hope surrounding its recent appearance. This is not to say that computed tomography is useless, but the device does raise a legitimate question: given a fixed amount of money available, how should we decide how much to spend on purchasing a CT scanner or spend on basic research into the diseases diagnosed by that scanner? The answer is not clear-cut, and it never will be. The ideal solution probably lies in between somewhere. A similar question applies to the artificial kidney and the mechanical respirator.

I personally feel that computed tomography is a valuable new tool to extend the physician's knowledge of the internal condition of a patient without resorting to surgical methods. The device may be responsible for saving lives through early diagnosis of a dangerous condition. It is not practical to express a saved life in terms of dollars and cents, so perhaps the device is truly cheap at any price. The increased competition among manufacturers for the limited market under the CON laws will eventually drive the purchase price down to more acceptable levels. The improvements on newer models may also increase the market for replacement and used equipment.

In conclusion, I remember my parents and grandparents recalling the many summers of fear and worry about the dread disease polio. People all over the world ended up crippled or supported totally by an expensive "iron lung" after polio struck their muscular control. The need for such machines has all but disappeared, thanks to a small shot in the arm or a quick swallow of jelly. The basic understanding of the disease itself eliminated the need for such heroic methods of life support. Perhaps one day the ailments diagnosed by computed tomography will be prevented in such an inexpensive, effective, and easy way. Time will tell.

--NOTES--

1 Robert G. Waggener and William D. McDavid, "Computed Tomography", in Advances in Biomedical Engineering, Vol. 7, ed. J. H. U. Brown, Acedemic Press, Inc., 1979, p. 66.
A very useful article about the basics of computed tomography.

2 Ibid., p. 67.

3 Ibid., p. 68.

4 Ibid., p. 67.

5 Melvin P. Siedhand and James E. Holden, "Medical Imaging Systems", in Medical Instrumentation: Application and Design, ed. John G. Webster, Houghton Mifflin Company, 1978, p. 606.

6 Waggener, p. 69.

7 Ibid., p. 70.

8 Ibid., p. 69.

9 Siedhand, p. 606.

10 Waggener, p. 66.

11 Ibid., p. 81.

12 Ibid., p. 86.

13 Ibid., p. 86.

14 F. Bueche, Principles of Physics, 2nd edition, McGraw-Hill, Inc., 1972, pp. 658-660.

15 Ibid., p. 659.

16 J. M. S. Prewitt, "New Vistas in Medical Reconstruction Imagery", in Digital Processing of Biomedical Images, ed. K. Preston, Jr., and M. Onoe, Plenum Press, 1976, pp. 135-140.

--BIBLIOGRAPHY--

Budinger, Thomas F., and John Harpootlian, "Developments in Digital Computer Implementation in Nuclear Medicine Imaging", Computers and Biomedical Research, vol. 8, no. 1, February 1975, pp. 26-52.

Bueche, F., Principles of Physics, 2nd edition, McGraw-Hill, Inc.,1972, pp. 75, 658-660.

Cho, Z. H., and I. S. Ahn, "Computer Algorithm for the Tomographic Image Reconstruction with X-ray Transmission Scan", Computers and Biomedical Research, vol. 8, no. 1, February 1975, pp. 8-25.

Prewitt, J. M. S., "New Vistas in Medical Recanstruction Imagery", Digital Processing of Biomedical Images, K. Preston, Jr. and M. Onoe, editors, Plenum Press, 1976, pp. 133-160.

Siedhand, Melvin P., and James E. Holden, "Medical Imaging Systems", Medical Instrumentation: Application and Design, John G. Webster, editor, Houghton Mifflin Company, 1978, pp. 605-611.

Strohbehn, J. W.. et al., "Image Enhancement of Conventional Transverse Axial Tomograms", IEEE Transactions on Biomedical Engineering, vol. BME-26, no. 5, May 1979, pp. 253-262.

Waggener, Robert G., and William D. McDavid, "Computed Tomography", Advances in Biomedical Engineering, Vol. 7, J. H. U. Brown, editor, Acedemic Press, Inc., 1979, pp. 65-99.