THE MANY STEPS AND EVOLUTION IN THE DEVELOPMENT OF COMPUTED TOMOGRAPHY TECHNOLOGY AND IMAGING METHODS, THE QUEST FOR ENHANCED VISIBILITY

The First Fifty Years

Perry Sprawls
Emory University and Sprawls Educational Foundation, www.sprawls.org. USA

- *Abstract*— **Computed Tomography (CT) is considered the second most significant contribution of physics and technology to medicine following Roentgen's discovery and introduction of x-ray imaging, radiography. . CT is an x-ray imaging process but greatly extends the scope of structures, functions, and conditions within a human body that can be visualized for medical diagnosis. Compared to radiography CT provides two major advantages, It is a tomographic method that provides close viewing (within millimeters) of objects and locations within a human body without interference from overlying body sections. The second value is its high contrast sensitivity, the ability to produce visible contrast among different soft tissues, even when enclosed within a dense bony skull. The production of CT images is a sequence of two distinct phases. The first is scanning an x-ray beam around a patient body and measuring the total attenuation along different pathways through the slice of tissue that is to be imaged. This produces a data set consisting of large number (1000s) of measurements. The second phase is a mathematical process of calculating, generally referred to as "reconstructing" a digital image from the acquired data set. Allan Cormack, a physicist, first developed a mathematical process for calculating the distribution of x-ray attenuation values throughout a simulated body section. Godfrey Hounsfield, an engineer on the staff of EMI, developed the technology for scanning and measuring x-ray attenuation along many pathways through a human body. He also developed a mathematical process for reconstructing tomographic images. One of the first, an image of the brain showing a tumor while enclosed in the skull introduced CT to the world as a new and revolutionary diagnostic method. In 1979 Cormack and Hounsfield jointly received the Nobel Prize. EMI manufactured the first CT systems that were limited to imaging the head. Robert Ledley was to soon develop the who body scanner. Two major limitations with the scanners were less than desired image quality and the long time (minutes) required to scan and produce an image, what was to follow were many technical improvements producing different "generations" of CT scanners each generally providing faster data acquisition. Much of this progress was associated with the advances in design of the detectors. The first was a single small detector, followed by multiple detectors and fan-shaped x-ray beams that could make more measurements simultaneously and faster acquisitions. A major advancement was the multi-row detectors that introduced multi-slice imaging. A major and essentially concluding step in the development of general purpose clinical scanners was the invention and development of spiral scanning by Willi Kalender. This rapidly produced volume, rather than slice, data sets and opened up many possibilities for image reconstruction. Along with the many developments to provide improved image quality and faster imaging there were significant advances in radiation dose management and scanners for special clinical applications including dentistry and breast imaging.**
- *Keywords*— **tomography, reconstruction, digital, scanning, detectors.**

I. INTRODUCTION AND OVERVIEW

As a clinical medical physicist and educator it has been my opportunity to work with computed tomography from its beginning and on throughout my career. My introduction was a course in the EMI factory where Hounsfield developed the first system in preparation for installing one of the early scanners in my institution, Emory University Hospital in Atlanta. That was to become one of my major projects. Continuing from the first scanner on to the present the capabilities and complexity of CT have expanded and so have the role and responsibilities of medical physicists. As we continue to apply our physics knowledge and experience supporting CT as a highly valuable clinical modality and provide education for future generations there is value in knowing the history leading up to the technology we use today. It was a step-by-step process by many physicists and engineers that is a major part of our heritage. That is the journey that I share with you here.

The introduction of computed tomography (CT) for medical imaging in 1976 is sometimes considered as one of the greatest contributions to diagnostic medicine, second to x-ray imaging (radiography and fluoroscopy) by Roentgen in 1894. Both are physical methods developed by physicists and engineers, with the significance of each being recognized with Nobel Prizes. Both are forms of x-ray imaging; but the difference is how the images are formed. One method simply passes an x-ray beam through a section of a human body and projects shadows. The other (CT) is a much more complex process of two distinct phases. The first phase passes x-radiation through in the plane of slices within a body and measures accumulative attenuations from many different directions. This produces the sets of "scan data." The next and evolutionary phase is the mathematical "reconstruction" of an image of the slice of body section from the scan data.
The fundamentals of mathematical image reconstruction applied to tomographic body sections were developed over the years with several innovative contributions by mathematicians and physicists. However it was the development and availability of digital technology and computers that made it possible for an engineer, Geoffrey Hounsfield, to develop the first computed tomography (CT) to be used for medical diagnosis.

The development and clinical application of x-ray CT was to be a major evolution in the field of medicine. Physicians were being presented with a completely new view of the human body, tomograms. There was now the need to learn and teach cross-sectional anatomy. It was now possible to "get in close," within a few millimeters, and view anatomical features without interference from other body sections. In several ways, scientifically, technically, and medically, x-ray CT was to be an introduction to the many other "computed tomography" imaging modalities that were based on image reconstruction, including MRI, SPECT, and PE--each using computed tomographic imaging but providing visualization of very different tissue and functional characteristics.

Our specific interest here is x-ray computed tomography. From its initial development and introduction for medical imaging in 1976 it has continuously evolved with many innovations with the goal of enhanced visualization of structures and conditions within the human body and with considerations for radiation exposure and associated risks--two often opposing goals because several aspects of image quality are directly or indirectly dependent on the quantity of radiation used in the imaging process.

The characteristic of CT that has been a driving force for continuing physics research and technological development is that it is a sequential imaging process requiring a series of x-ray attenuation measurements which is time consuming. A measurement of progress and advancement over the years has been scanning speed and the time required to produce an image. This is significant for several reasons including patient throughput and ability to image with reduced patient motion interference. An associated factor is that image quality, especially detail (spatial resolution) and noise are dependent on the number of measurements (samples) in a scan and data acquisition. It is the combination of increased image quality (clinical visibility), limiting radiation dose, and reduced acquisition time that has resulted from the efforts of many physicists and engineers for now a half century. Those contributions are extensively recorded in the scientific literature. Books and review articles focusing on the history, as identified in the References and Bibliography, provide the details of this major era of medical physics and the associated professions.

Our purpose here is not to repeat the many excellent publications, both scientific reports and historical reviews, but to provide a guide and overview through the continuing evolution of computed tomography physics and technology. The Bibliography at the end of this article identifies publications on the history of CT. Two of the most comprehensive are the books, *From the Watching of the Shadows* by S Webb and *Computed Tomography* by W Kalender. Here we will consider the vision and motivation of the contributors, the relationship and dependence on other scientific and technological developments, and the efforts to increase the value of CT as a major medical method for diagnosis and guiding therapeutic procedures.

The history of computed tomography is not just a series of events along a timeline. It is a comprehensive and dynamic process of expanding and enhancing the clinical value and capabilities of x-ray imaging. It is a continuing *step-by-step* process of developments and innovations increasing the quality and capabilities of CT as a medical procedure. The steps range from small to large with each providing something of value. As we read and view images and illustrations of those developments let's give attention to the advances in imaging capabilities each provides. That is the theme we will follow.

The goal of medical physics and engineering research and development with respect to imaging is increasing the range of visibility of structures, functions, and conditions within the human body, managing risks, and availability as needed to enhance the practice of medicine and clinical care of patients around the world…Step by Step.

II. X-RAY IMAGING

The first and giant step to this goal was the discovery and development of x-ray imaging. It is the foundation of our exploration of medical imaging physics and provides context for computed tomography as an evolutionary application of physics in the field of medicine.

X-radiation provided the first method for imaging the internal structures of the human body for medical purposes. It began with Roentgen's discovery, intense research, and demonstration of its medical capabilities in 1897 and illustrated in Fig.1.

Fig.1. Roentgen's lecture and demonstration of the "new kind of radiation" by producing an image of the hand of the University's anatomy professor.

With Roentgen's early work and as news of the x-ray process spread around the world the human hand was the common anatomical region to be imaged. It was thin and relatively easy for the x-radiation to penetrate and the bones provided high contrast in relation to the soft tissue. This is demonstrated in an image of the author's hand shown in Fig.2.

Fig.2. An x-ray image of the Author's hand simulating what is believed to have been a significant event in Roentgen's discovery.

Roentgen reports that he had observed and was investigating the penetrating characteristics of the new radiation (Ref.1). When he was holding a coin to see if it would be penetrated he saw the shadow image of the bones in his hand. Perhaps we can consider this the “birth” of medical x-ray imaging.

Projection X-ray Imaging

Producing images by projecting an x-ray beam through a region of the human body was to become one of the most significant medical procedures for well over a century. This was the modalities of radiography and fluoroscopy. The history of the developments and evolution of these methods with an emphasis on the physics and technology is described in previous publications (Ref. 2, 3, 4, and 5).

Even though projection imaging was a revolutionary and extremely valuable contribution to medicine, it had two characteristics that limited clinical applications and motivated research and development for methods that could provide greater visibility of anatomical structures and clinical conditions within the body. With the projection method the images of the internal objects are “stacked” or overlaid with some covering or blocking the view of others. While this type of image is appropriate and extremely valuable for some clinical applications--the chest is an example--it has major limitations for imaging the human head. The soft tissue brain enclosed in the bony skull is essentially invisible in a conventional radiograph.

The other characteristic of the projection method is relatively low *contrast sensitivity*, especially when compared to some of the future methods including CT and MRI. The contrast sensitivity of an imaging procedure is the relationship between visible contrast in an image and the physical contrast among the soft tissues and the fluids within the body. A major challenge is that soft tissues and body fluids, especially blood, have close physical density and atomic number (Z) values that are the source of physical contrast that forms images. Over the years there has been continuing research and development to address this limitation. One has been to design x-ray spectra that are optimized to produce a high contrast-to-patient dose relationship. This has been especially significant in mammography by using combinations of x-ray tube anode materials, filter materials, and KV values. Another has been the development of contrast media that can be administered to a patient to provide temporary contrast specially to visualize the blood circulatory system, urinary track, and digestive system. A historical review of those developments has been previously published. (Ref. 5).

Classical Tomography

Almost from the beginning of x-ray imaging the limitation to visibility of some anatomical structures by overlying regions within the body was recognized as a problem to be solved. This introduced the need to image selected layers or slices through the body that was to become the process of *tomography.* The limitation was the x-ray projection process produced images of a 3D volume anatomical region…not selected slices. Research and development resulted in a series of technical devices and methods for producing images of slices, tomograms, with projection imaging. Webb provides an excellent historical review. (See Bibliography).

The many tomographic methods developed were based on the same physical principle. That was to use motion during the x-ray exposure to selectively blur the anatomical regions other than in the slice of interest. These regions would be in the image but blurred and hopefully less visible than the details in the slice of interest. Of the many methods developed and tried the one illustrated in Fig.3 was to become the most widely used and common tomographic procedure up until the development of computed tomography.

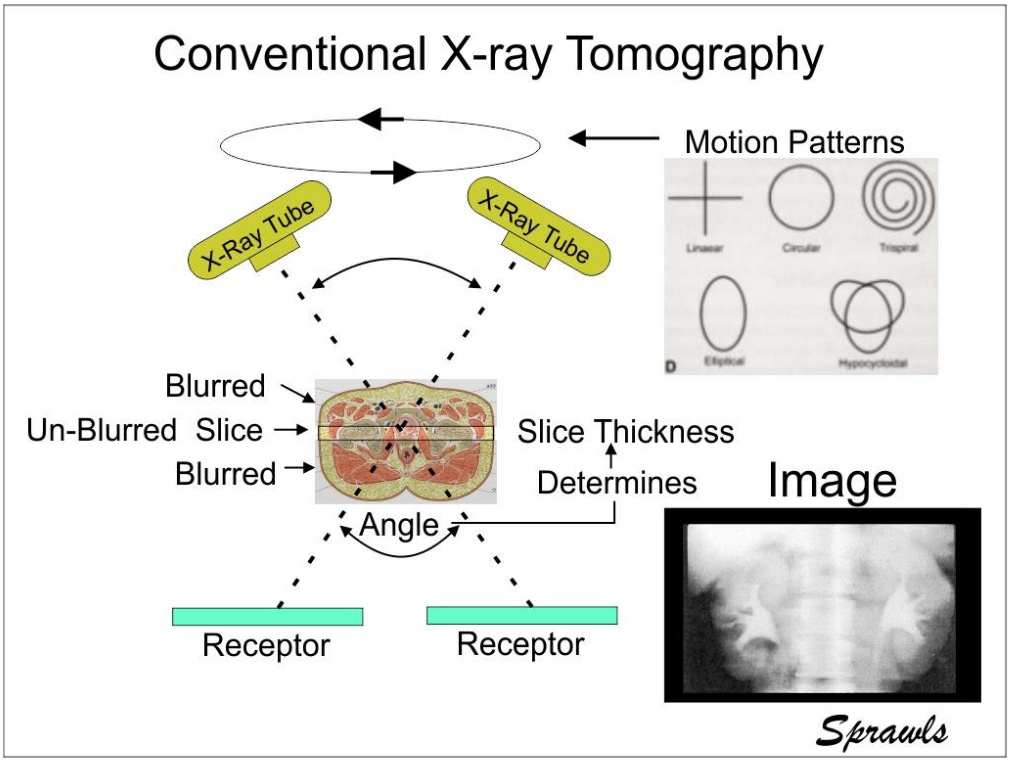

Fig.3. An overview of the conventional x-ray tomography process.

The x-ray source and the image receptor, usually film and intensifying screens, were mounted on a mechanism that rotated them around a “pivot point” located in the slice that was to be imaged without blurring and with good detail. The motion of the x-ray beam blurred the image of the anatomical regions on each side of the slice. This process does not eliminate the adjacent regions from the image; it just blurs them in relation to the slice that is being imaged. The expectation is that the anatomical structures within the slice will become more visible. The image in Fig.3 is an example in which the visualization of the kidneys is enhanced. In addition to the most widely used method illustrated in Fig. 3 other approaches included having the patient on a rotating stool during the x-ray exposure synchronized with a rotating image receptor.

Depending on the design of the system there are adjustments that are made by the operator for specific clinical procedures. The slice thickness is controlled by adjusting the angle of movement. This tomographic method does not produce a well-defined slice with a specific thickness. The blurring increases with distance out from the location of the pivot point. Slice thickness is a somewhat arbitrary designation of the area in which there is not significant blurring, at least compared to the anatomical areas that are being blurred to reduce their visibility. To enhance the blurring of some anatomical features a variety of motion patterns could be selected.

The production of tomographic images using an x-ray beam projected through a full anatomical region and blurring the interfering layers with motion was a valuable clinical procedure for many years and benefited from a series of innovations and developments as described in the references cited above. It was a significant step to increasing visibility of some specific anatomical structures, such as in the abdomen or pelvic regions. However, not just the slice of interest was included in the image. There were the overlying body sections, somewhat blurred, but interfering with the visibility of details within the slice being imaged.

That was the challenge to be overcome and the solution was to be provided by computed tomography (CT).

It would require a method in which an image could be formed with an x-ray beam limited just to the tissue slice of interest without passing through and producing images of the overlaying body sections as illustrated in Fig. 4.

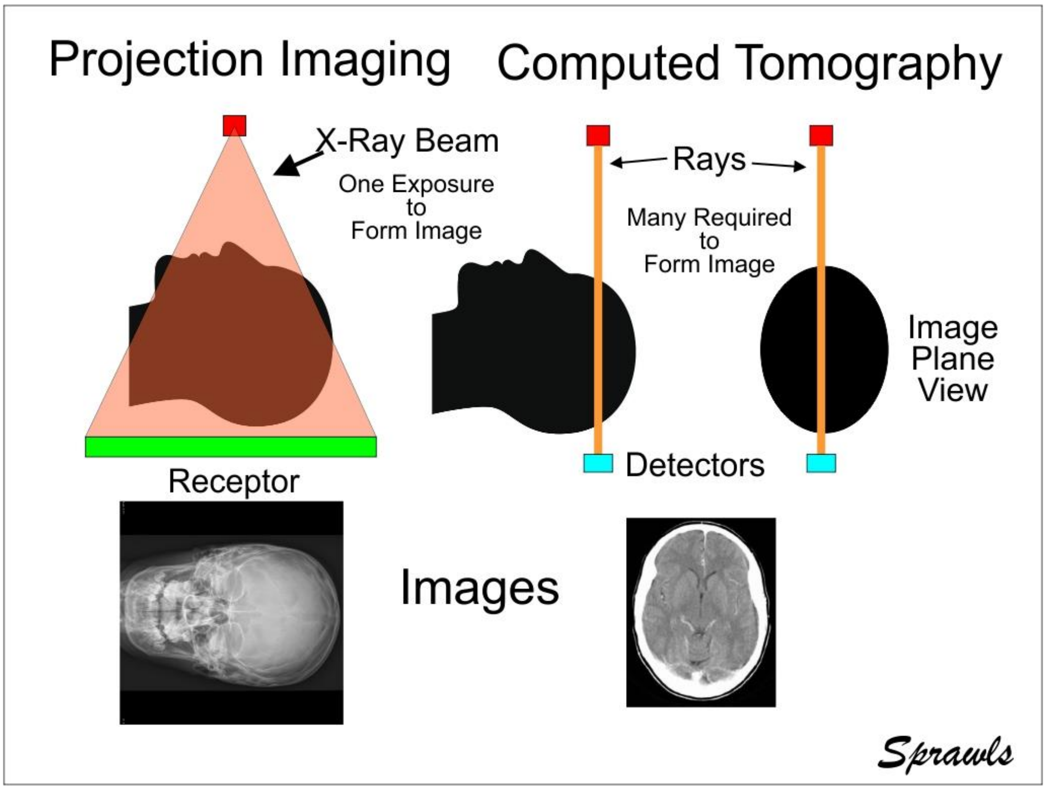

Fig.4. Comparing projection x-ray imaging, radiography, to computed tomography with respect to the passage of the x-ray beam through a region of the human body.

This illustration shows the major difference between the two imaging methods. With the projection method the x-ray beam is normal (90 degrees) to the plane of the image and forms the image directly by casting shadows. When the x-ray beam passes through the tissue slice in the plane of the image it cannot form an image directly. It requires that an image be "reconstructed" from x-ray attenuation measurements made by passing an x-ray beam through the body in the plane of the slice to be imaged. That is the principle and process of computed tomography.

The major factor associated with CT that has motivated many years of continuing research and development is the acquisition of the x-ray image by making many individual measurements or samples with small "rays" passing through the body. This is a time consuming process. A major effort has been to speed up the acquisition process generally by developing systems that make more and more simultaneous measurements. This has reduced acquisition times for one image from several minutes down to a fraction of a second. It has been the technology developed to reduce acquisition time that defines the different "generations" that will be described later.

III. FROM CASTING SHADOWS TO RECONSTRUCTING IMAGES

With the x-ray projection methods images are shadows of internal body structures formed by projecting an x-ray beam through anatomical regions of the human body. In radionuclide imaging (nuclear medicine) they are formed by acquiring photons from a body section that is within the field of view of a gamma camera. The difference is that the tomographic methods produce images of thin sections or slices through a body section. Each method has its features with respect to physical image characteristics and clinical applications. There are both values and limitations of each.

From a historical perspective the projection methods were the first, and they predominated for at least 80 years. It was the introduction of digital technology and computers beginning in the 1960s that enabled the development of the computed tomographic methods that were to revolutionize clinical imaging. The development of x-ray computed tomography (CT) was a major step in this process.

Computed tomography (CT) and the methods to follow including MRI, SPECT, and PET consist of two phases: the *acquisition* of data often referred to as scanning, and the mathematical calculation of an image from the acquired data, generally referred to as *image reconstruction.* A reconstructed image is a mathematical representation of some physical characteristic of the tissue at each point within the imaged area. With CT, X-ray attenuation is the physical characteristic. The calculated value for each point within an image (pixel) is a discrete sample and is subject to statistical error. This error appears in an image as visual noise. Developments over the years have addressed this issue resulting in more precise representations of tissue characteristics. Here our interest is specifically on x-ray computed tomography and its evolution through many steps or "generations" of development. To provide perspective we will review the technical and mathematical requirements for producing "reconstructed" tomographic images. The two distinct functions and phases, technical and mathematical, in the production of a CT image are compared in Fig. 5.

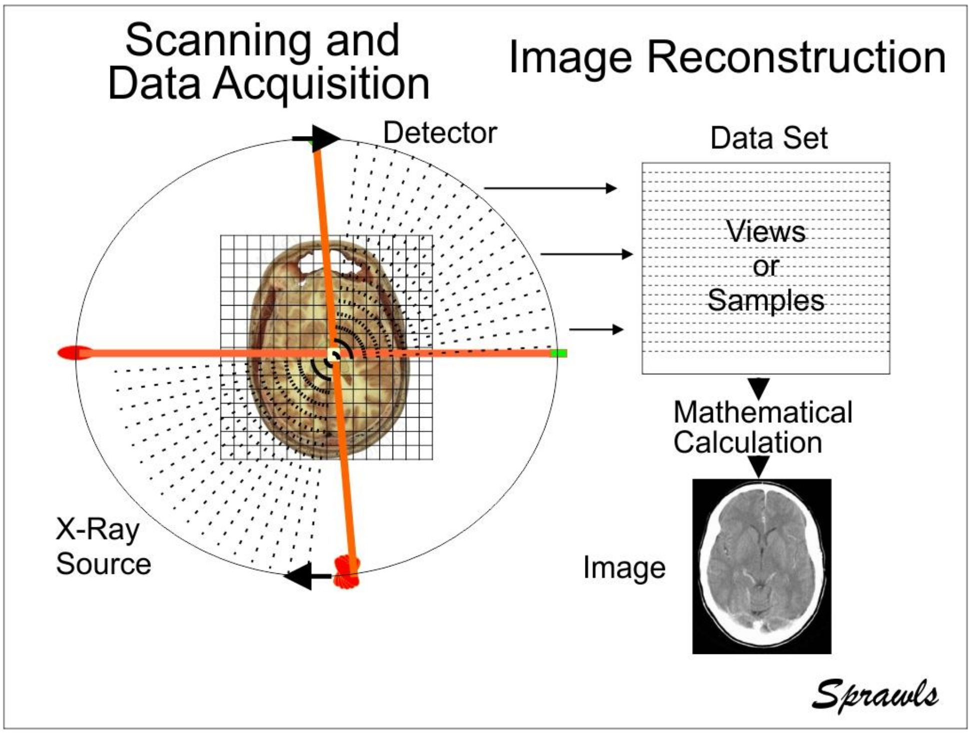

Fig.5. The two phases of CT, scanning and acquiring data that is then used to mathematically calculate, or reconstruct, an image.

The continuing developments and evolution of computed tomography over many years generally progressed along two pathways, the physics and technology for *data acquisition* and the mathematical methods for *image reconstruction*. The common goal of each is to produce high-quality images (visibility) with consideration for radiation dose to patients and as fast as possible.

It was the specific requirements for the data to be used for image reconstruction that placed demands on the technology for scanning and data acquisition. Image reconstruction requires a large set of measurements, or samples, to form each image and as described before, that is a time consuming process.

The computed tomography process requires passing an x-ray beam and collecting attenuation data through the body in the plane of the slice being imaged and then using that data to create an image of the slice. It is a two-step, or phase process.

The physical quantity being measured and displayed in the images is x-ray attenuation values. The image displays attenuation values for each voxel in the tissue slice but these cannot be measured directly. The measurements during the scanning and acquisition phase are of the total or integral attenuation along pathways through the body section as illustrated in Fig. 6.

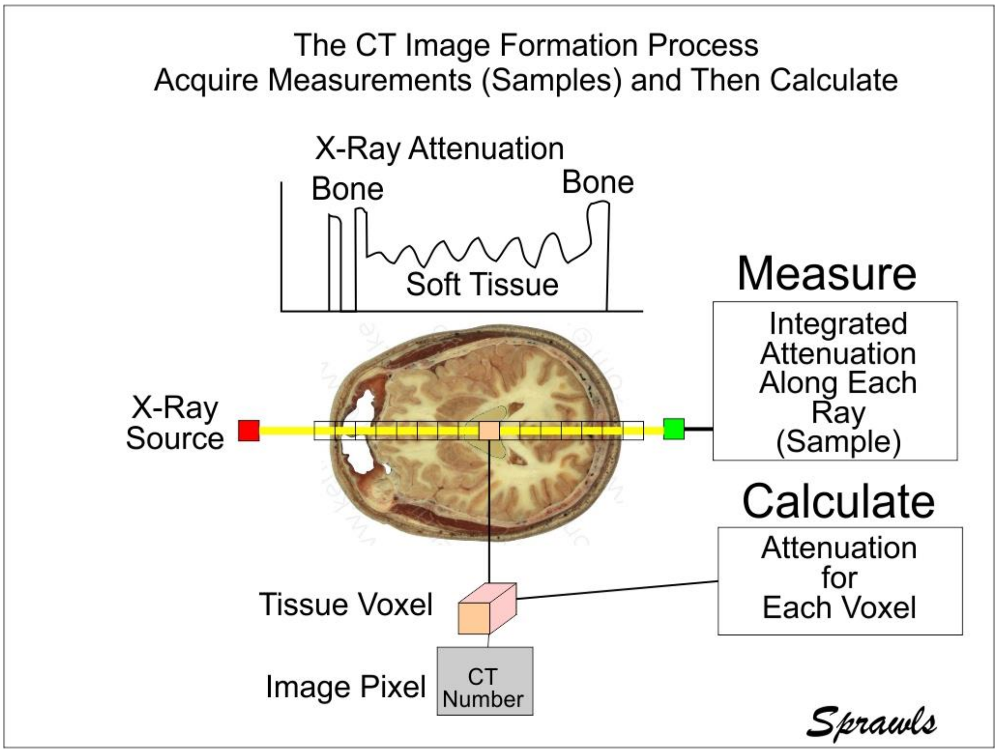

Fig. 6. The two phases in the formation of CT images, measuring and acquiring data followed by calculating attenuation values for each voxel. The illustration is for one ray through the body but many (100s) are required to produce an image.

The first challenge that had to be overcome to make computed tomography possible was developing a mathematical method for calculating attenuation values for individual voxels/pixels from measurements of total or integral attenuation along a pathway through a body section as shown. This was to become known as *image reconstruction*.

IV. MATHEMATICAL IMAGE RECONSTRUCTION

The need for imaging methods that could move beyond projection imaging and its limitations was the motivation for a variety of investigations both for medicine and other potential applications. Although some of this research was innovative and significant, apparently it did not contribute to the actual development of the CT methods and systems for medicine. Webb in *From The Watching of Shadows* provides an extensive review of these investigations. One of these was Tetelbaum S. I., About a method of obtaining volumetric images using X-ray radiation, 1957, Izvestia Kiev Polytechnic Institute, Works of the Electrotechnical Faculty, although this innovative work did not get recognized and contribute to the development of CT.

The Radon Transform

In 1917 the Austrian mathematician Johann Karl August Radon (Ref. 6) introduced the "Radon transform" which represents projected data or line integrals of functions (for example density values) in a form that could be processed with the inverse transform to reconstruct the original functions, as could be displayed in images. This is generally recognized as a significant event in the field of image reconstruction but apparently did not directly contribute to the development of the first CT methods and systems for medicine.

Cormack and Hounsfield

It was Alan Cormack and Geoffrey Hounsfield as discussed later who developed reconstruction methods independently and without knowledge of Radon's work. In addition to developing mathematical reconstruction methods they also combined that with the technology and process for scanning and acquiring data to form tomographic representations and images. That is the origin of computed tomography for medical applications.

V. ALLAN M. CORMACK DOING THE MATH

Allan Cormack, a physicist who recognized the need for more accurate radiation attenuation characteristics within a body section for radiation therapy treatment planning, developed the method that is the foundation of computed tomography. In 1979 he and Godfrey Hounsfield jointly received the Nobel Prize in Physiology and Medicine for "for the development of computer assisted tomography."

Fig.7. Allan Cormack along with postage stamps honoring him and cover of his biography, Imaging The Elephant.

Cormack's early career can be reviewed in the BIOGRAPHY section at the end of this chapter. In 1950 he returned to South Africa from Cambridge and during this period he was asked to serve for six months as the resident medical physicist in the radiology department in Cape Town, where he supervised the use of radioisotopes as well as the calibration of film badges used to measure hospital workers' exposure to radiation. This was his introduction to medical physics. At Groote Schuur Cormack witnessed firsthand how radiation was being used in the diagnosis and treatment of cancer patients. Baffled by deficiencies in the technology used for such procedures, Cormack began a series of experiments and developments.

One of his special concerns was that treatment planning was based on a body cross-section assumed to be of homogeneous attenuation rates. This was because it was not possible to determine the actual distribution of attenuation characteristics throughout a section of a body. This was the problem his research addressed and results reported in his paper, *"Representation of a Function by its Line Integrals, with Some Radiological Applications"* published in 1963 with a follow-up in 1964. (Ref.7, 8.)

In his Nobel Lecture on December 8, 1979, *Early two-dimensional reconstruction and recent topics stemming from it,* and published in *1980* (Ref. 9) Cormack provides a comprehensive review of his activities.

He emphasized that it was a mathematical problem that was to be solved. Even after extensive search of the literature he did not learn of Radon's publication until the 1970s.

It was necessary for him to develop the mathematical reconstruction process from the beginning. Much of his lecture discussed various mathematical issues relating to the general problem, which included the effects of noise that is associated with measurement of radiation. It is interesting that his analysis gave emphasis to the potential advantages of using protons rather than x-radiation for CT imaging.

By 1963 he had constructed the apparatus shown in Fig.8 and began experiments.

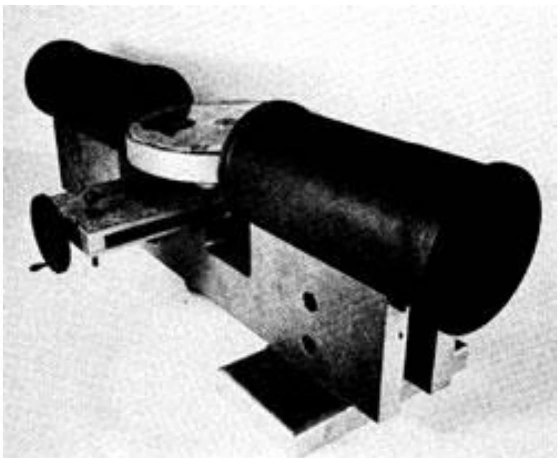

Fig. 3 (Nobel address)

Fig. 8. Cormack's experimental apparatus.

The apparatus consisted of a radioactive source in one of the black cylinders and a radiation detector in the other. A circular phantom with some embedded objects is in the center and can be rotated in increments. A diagram of the phantom is shown in Figure 8. The experiment was to make measurements of the radiation through the phantom along different directions or angles of rotation, and then mathematically calculate the attenuation characteristics along a line through the phantom. A result is shown in Fig. 9.

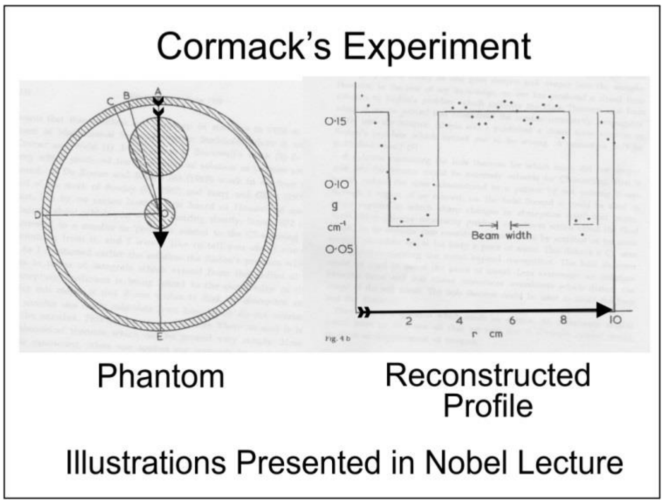

Fig. 9. Diagram of phantom scanned and reconstructed profile of attenuation along a pathway through the phantom as illustrated. The dots representing the calculated values are compared to the actual values represented by the solid line.

He reconstructed profiles along other pathways through the phantom. Although he did not combine these profiles and display as images of the phantom it was a fundamental method for producing *computed tomographic images.* He had combined the processes of scanning and measuring total radiation attenuation along pathways through the phantom and then mathematically calculating attenuation values at points within the plane of the phantom.

As discussed in his Nobel Lecture these results were published in 1963-64 (Ref.3,4) but attracted very little interest—and none from the medical imaging profession. His normal teaching and research kept him busy and he thought very little about this project until the early 1970s. That is when he first learned of Radon's publication and Hounsfield's development of the technology and process for computed tomography imaging at EMI in London.

With renewed interest his research was focused on exploring the mathematical work of others that applied to image reconstruction and investigating some of the features that would be of value in medical imaging. One of these was the capability of determining very small differences in attenuation (tissue density) within an image plane. This was to become perhaps the most significant characteristic of computed tomography imaging.

Between 1956 and 1964, most of his research in connection with the development of computerized axial tomography was conducted on his own time. Neither of his two Journal of Applied Physics papers met with significant response, despite the fact that they proved the feasibility of his method for producing images of heretofore non visible or barely visible cross sections of the human body.

VI. SIR GODFREY NEWBOLD HOUNSFIELD DEVELOPING THE TECHNOLOGY AND METHOD

The development of the first CT system for medical applications is considered as the *second giant step* toward the goal of expanded medical imaging capabilities. It is significant to recognize that this along with Roentgen's *first giant step* were both recipients of Nobel Prizes. It was Godfrey Hounsfield who developed the first computed tomography system and method producing one of the first clinical images shown in Fig. 10.

Fig. 10. Godfrey Hounsfield and a first clinical image showing the tissues and a tumor within the skull.

Hounsfield's early career can be reviewed in the BIOGRAPHY section at the end of this chapter. This includes biographical information presented and published associated with awarding of the Nobel Prize and provides insight into his early life and the factors contributing to his distinguished career as an engineer and innovator. (Ref.10.)

From His Autobiography
I joined the staff of EMI in Middlesex in 1951, where I worked for a while on radar and guided weapons and later ran a small design laboratory. During this time I became particularly interested in computers, which were then in their infancy.

[After one of his projects was abandoned] … rather than being immediately assigned to another task I was given the opportunity to go away quietly and think of other areas of research which I thought might be fruitful. One of the suggestions I put forward was connected with automatic pattern recognition and it was while exploring various aspects of pattern recognition and their potential, in 1967, that the idea occurred to me which was eventually to become the EMI-Scanner and the technique of computed tomography.

The steps in my work between this initial idea and its realization in the first clinical brain-scanner have already been well documented. As might be expected, the programme involved many frustrations, occasional awareness of achievement when particular technical hurdles were overcome, and some amusing incidents, not least the experiences of travelling across London by public transport carrying bullock's brains for use in evaluation of an experimental scanner rig in the Laboratories. The experimental system Hounsfield used for developing the process is shown in Fig. 11.

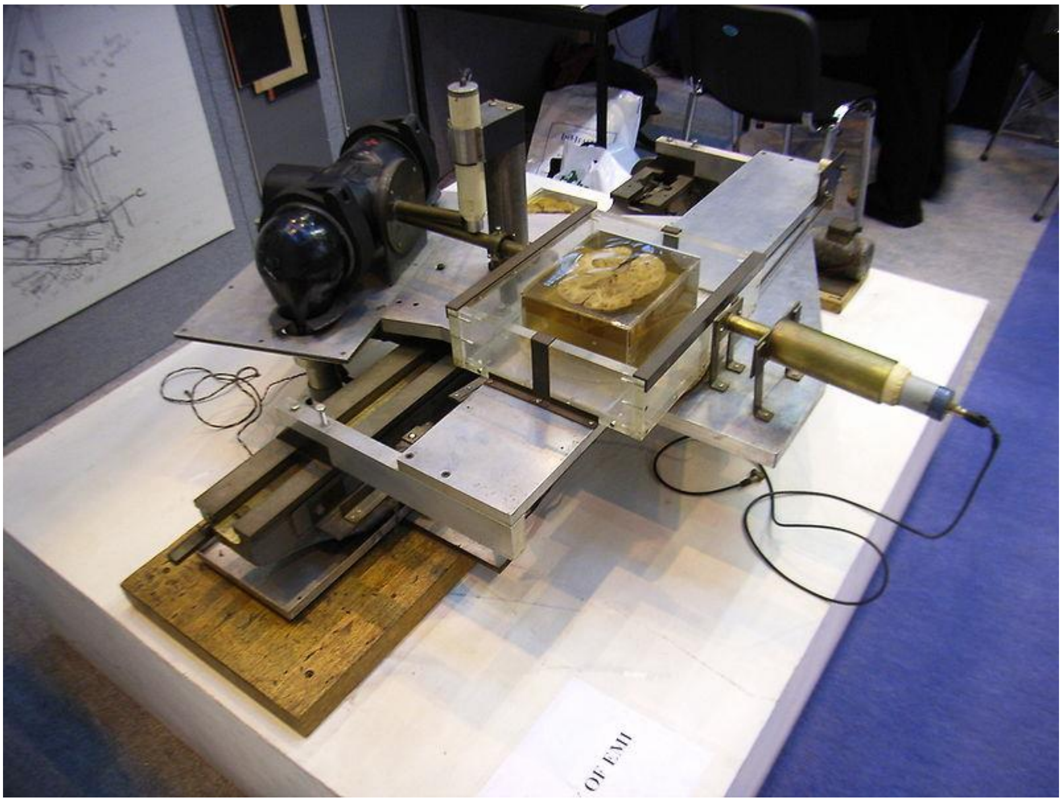

Fig. 11. Hounsfield's laboratory device used in the development of the computed tomography method.

After the initial experimental work, the designing and building of four original clinical prototypes and the development of five progressively more sophisticated prototypes of brain and whole body scanner (three of which went into production) kept me fully occupied until 1976. Since then I have been able to broaden my interest in a number of projects which are currently in hand in the Laboratories, including further possible advances in CT technology and in related fields of diagnostic imaging, such as nuclear magnetic resonance.

VII. THE FIRST CLINICAL COMPUTED TOMOGRAPHY AND BEGINNING OF A REVOLUTION

Hounsfield's work leading to the development of the first CT system for clinical applications and the immediate demonstration of its capabilities for imaging the soft tissues of the brain within the skull along with its high sensitivity for showing contrast among the tissues, especially between normal and pathologic, is clearly the foundation of modern medical imaging. A description of his system and imaging method, along with some clinical results, was published in 1973 (Ref.7, 8).

It is significant that he developed both the *technology* for scanning to collect data on x-ray attenuation through a body section and a *mathematical* method for image reconstruction--the two major phases of computed tomography. His diagram of the scanning process is illustrated in Fig. 12.

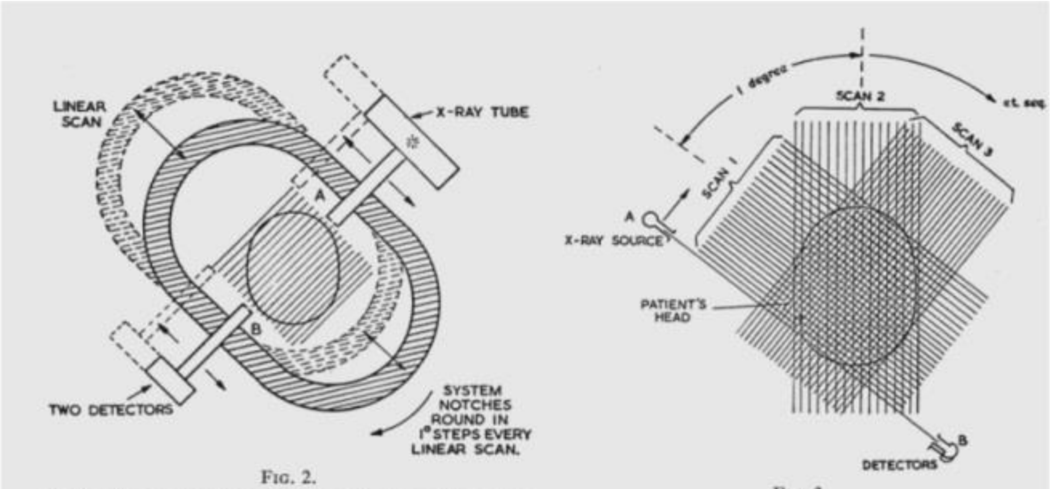

Fig. 2.
Motion of scanning frame and detectors for producing two continuous slices.

Fig. 3.
Simplified illustration of the scanning sequence.

Figure 12. Hounsfield's diagram of the scanning process for his first CT system used for clinical imaging.

This is of major historical significance from two perspectives. First, it illustrates the high level of creativity and design by Hounsfield to solve a complex problem of measuring x-ray attenuation through multiple pathways through a body section that could then be used for image reconstruction. Second, it provides the foundation and reference point for the many developments in CT technology that was to continue over at least the next half-century.

Characteristics of Hounsfield's Scanner

The scanning process for Hounsfield's first-generation scanner as illustrated in Fig. 12 was the "scan-rotate" method. A relatively small "pencil" x-ray beam was projected through the patient's body and recorded by a single detector. The x-ray tube and detector were mounted and moved together during the scanning process. The x-ray tube and detector assembly would be rotated around the patient in one degree increments for 180 positions or "views." In each angular position the x-ray beam would then be scanned across making 160 measurements. This would provide a total of 28,800 data points that would later be used to reconstruct one image. A typical scan time for one image was approximately 4.5 minutes.

As described by Hounsfield, each beam path forms one of a series of 28,800 simultaneous equations in which there are 6,400 variables. If there are more equations than variables they can be solved to provide values for each cube in the slice (voxel). The picture is built up in the form of a 60 by 60 matrix with the value in each point representing the absorption coefficient of the material in the corresponding volume of material in the slice. After appropriate scaling the absolute value of the absorption coefficient for the various tissues is calculated to an accuracy of ½ %.

For the early scanners the images were displayed on a CRT and photographed with a Polaroid camera for clinical viewing or the digital values could be printed out as shown in Fig. 13. It is the Author's recollection that the digital printouts were interesting but of little practical value.

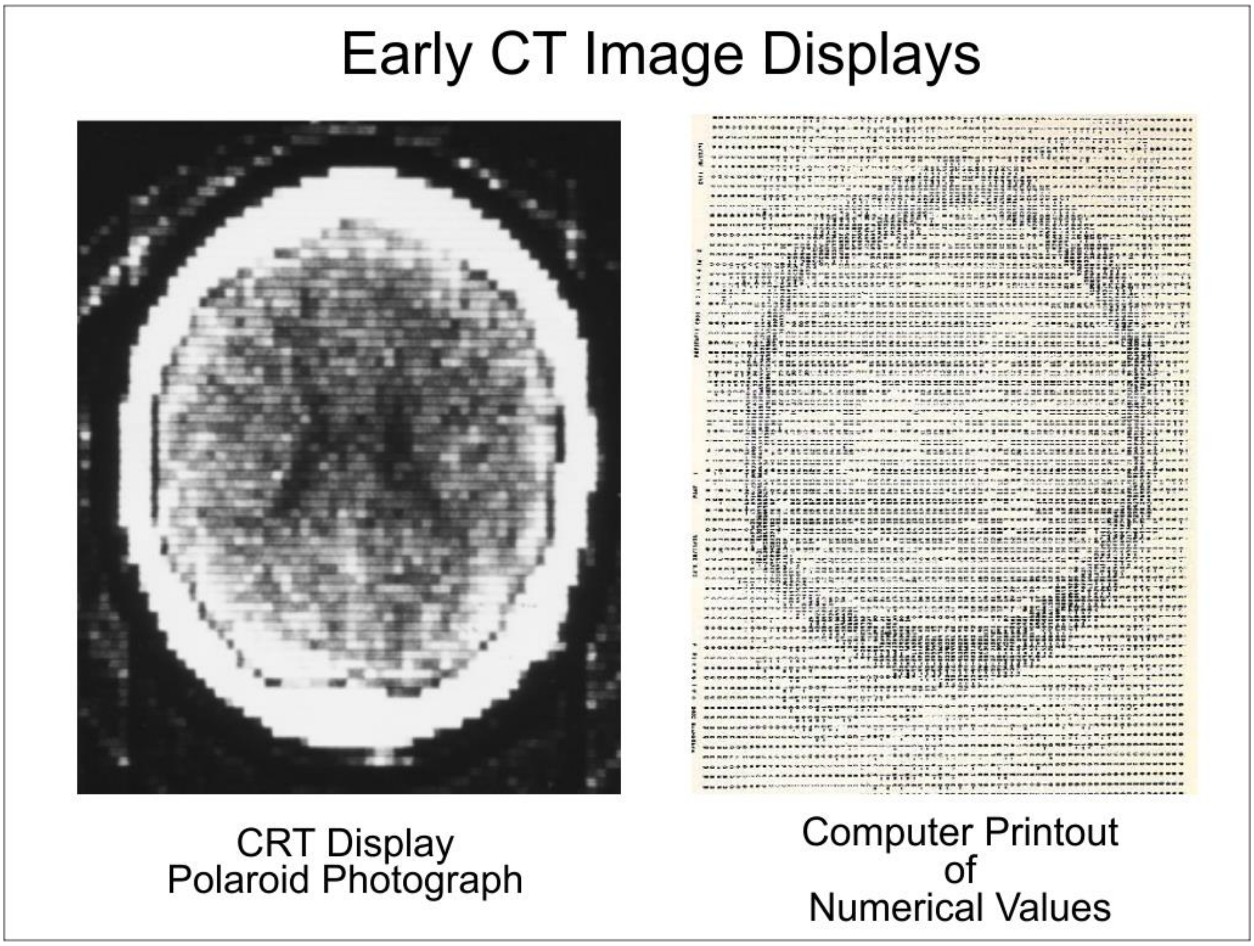

Fig.13. The two types of image displays for the first CT scanners.

Numerical Values for Tissues

There were two major features of computed tomography as developed by Hounsfield that were to revolutionize medical imaging and clinical medicine. One, as discussed above, was the formation of truly tomographic images. This was the ability to produce images up close and within a very short distance (a few millimeters) of an anatomical location and without interference from the overlying and surrounding anatomy, especially the dense skull. This was a significant "two-dimensional" *geometric characteristic*.

The other factor that can be considered as the "third dimension" or "numerical depth" of the image is the characteristic that was a major revolution in medical imaging. That was calculating a numerical value for each tissue that was determined from the x-ray attenuation measurements. For this Hounsfield used two scales, both expressing tissue attenuation values in relationship to that of water. These are compared in his diagram shown in Fig. 14.

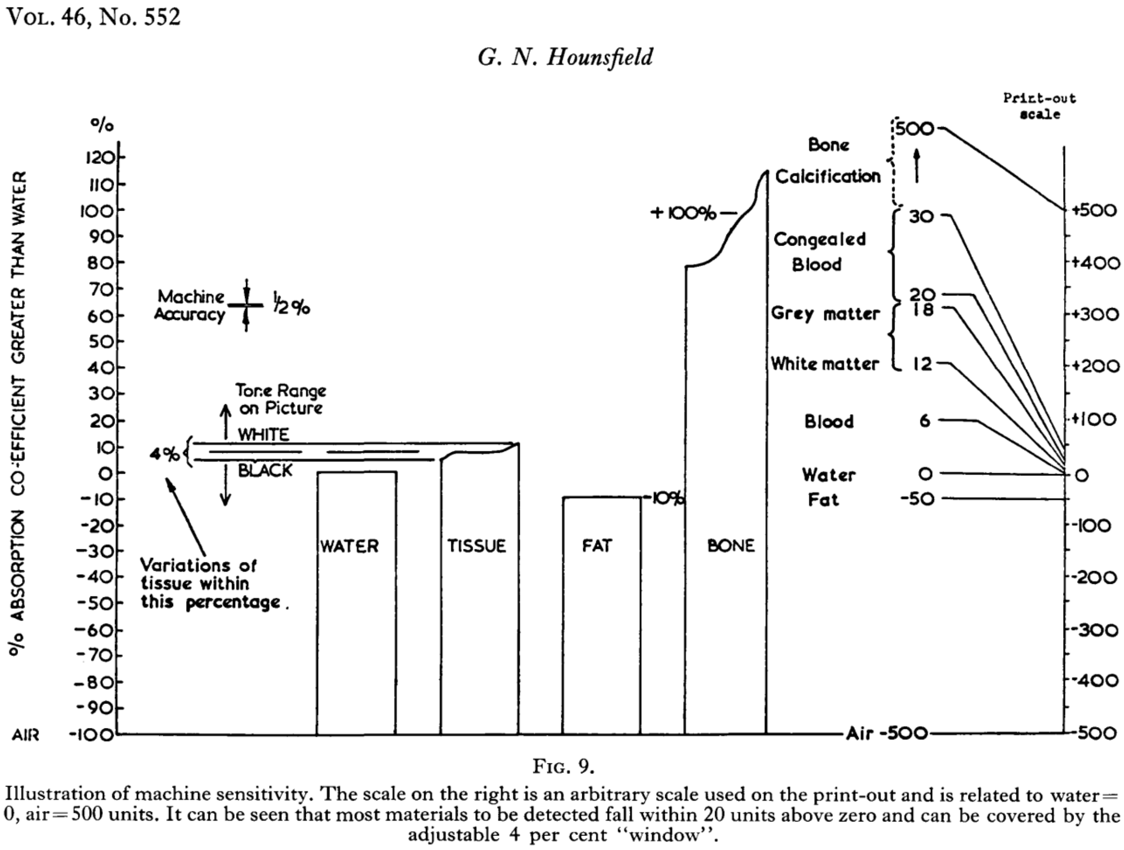

Fig. 14. Hounsfield's diagram published in Ref. 11 that illustrates many of the features of the CT method.

The scale on the left shows the tissue attenuation as percentage values compared to water. The scale on the right displays numbers calculated from attenuation coefficient values with water assigned a value of zero and air a value of -500. These were known as CT numbers and expressed in *Hounsfield units* on the scale that he developed as shown in Fig. 14.

These numbers could be printed out as shown in Fig. 13. The scale was later changed with air assigned a value of -1000. This provided an expanded scale with a wider range that was especially useful at the upper end for the larger range of densities and attenuation values of bone.

In this diagram Hounsfield illustrates several major and valuable characteristics of the CT process. This is made possible by having images in a digital form that can be computer processed to selectively enhance visibility of specific tissue characteristics, especially abnormal or pathologic conditions.

Contrast Sensitivity

In comparison to radiography, CT has a very high *contrast sensitivity* or ability to produce visible images among tissues that have very little physical contrast based on differences in physical density. As illustrated the various soft tissues produce numerical values that are sufficiently different and a source of contrast that can be displayed in an image.

Windowing

Windowing is the specific feature of CT that makes possible the high contrast sensitivity and ability to see the contrast among the soft tissues. One of the advantages of capturing or reconstructing images in a digital form (rather than on analog film) is the ability to record a wide range of x-ray attenuation measurements ranging from bone to air. The soft tissues are confined to a very small range in between. Hounsfield shows this as 4% of the total range. If this “raw” image is displayed there would be visible contrast between bone and air but little or none among the soft tissues. Windowing is the process of selecting the small range of numbers representing the low physical contrast among the soft tissues and displaying with high visual contrast using the full image brightness “tone range” from black to white as illustrated in Fig.14. Windowing was to become one of the highly valuable features of the various digital imaging methods. Most digital imaging methods have a wide dynamic range and can record a wide range of data, signals, or radiation exposures acquired from a patient’s body during an imaging procedure. This is very different from film used in radiography that has a very narrow dynamic range or latitude. Windowing is used to select a small range of data from the wide acquired range and display it with high visual contrast. The success of CT to produce visual contrast among soft tissues, as in the brain, depended on the ability to window.

VIII.THE EARLY EMI SCANNERS AND CLINICAL APPLICATIONS

In 1971 the prototype scanner was installed at Atkinson Morley Hospital in London and used by James Ambrose, MD who presented a report on the examination and findings for 70 patients in 1972 and publishes in 1973 (Ref.13). In the summer of 1972, EMI launched Hounsfield and Ambrose on a lecture tour of the United Kingdom and United States. Five scanners were preordered, with expected delivery in 1973. By June 1974, EMI had sold 35 scanners in the United States alone.

The one installed in the Author’s institution, Emory University in Atlanta, is shown in Fig. 15.

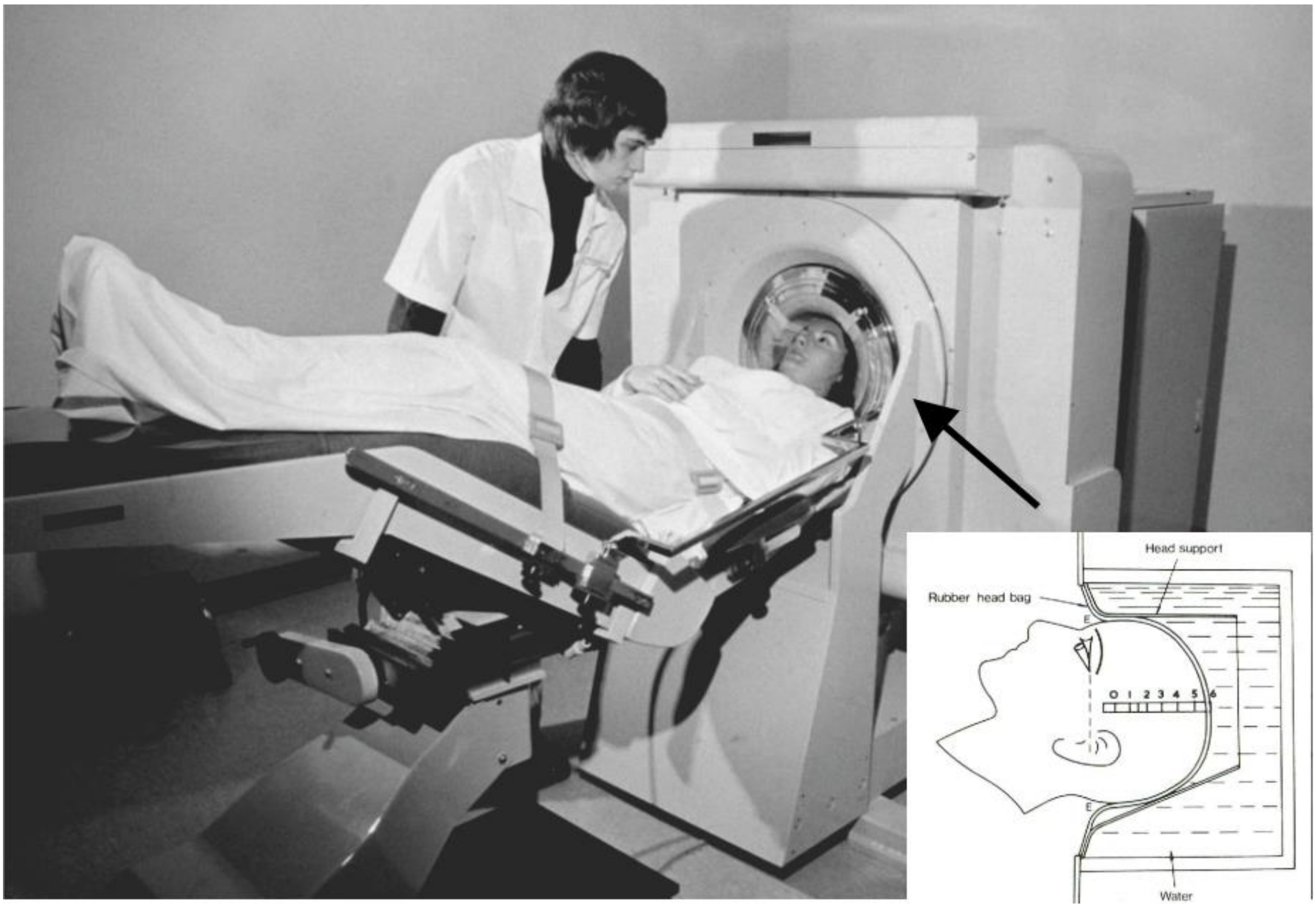

Fig. 15. Technologist preparing a patient for scanning with an early EMI system.

Here we will use it as an example of the early scanners to explore some of the design features and operational details.

It was a head-only scanner and the patient's head was tightly surrounded by a water-filled bag. The major purpose of the water bag was to reduce the wide range of x-ray beam attenuation and exposure to the detectors from air outside of the head to the thickest part of the skull.

Because of the long scan times (approximately four minutes per slice) patient motion was a problem and strong restraining belts were required. On a later scanner the Author installed additional automobile seatbelts because of the motion problem.

As the medical physicist working with this first scanner the concerns were generally mechanical issues, image artifacts, and calibrating the relation of CT numbers to material densities. For this we designed and constructed our own phantoms and test objects.

The Scientific, Technical, and Medical Impact of the Hounsfield CT System

Hounsfield's development of computed tomography (CT) revolutionized and made a rapid impact on clinical medicine because of the synergistic combination of several significant factors.

A major scientific contribution was establishing numerical values relating to physical characteristics of tissues in the body with a high level of sensitivity for distinguishing among the different tissues. This made possible the production of images with high contrast sensitivity. It was the combination of this with the scientific and mathematical method of image reconstruction that was the foundation of computed tomography.

Hounsfield's engineering and development of the technology was a major contribution. The innovative mechanical design to produce and collect the attenuation data that was required for image formation by a reconstruction process provided a solution to a complex problem with many factors that had to be considered. In addition to its immediate impact it provided future scientists and engineers with considerable insight into design characteristics that would be used in the development of CT systems by many manufacturers.

A major factor contributing to its rapid impact was Hounsfield's early and continuing collaboration with physicians, especially Dr. Ambrose. In the early stages of his research on producing images of objects that were enclosed and hidden in some structure the thought of the human body came up. Discussions with some medical professionals confirmed a need and focused attention to the human head with the brain hidden within the skull and not visible with any other imaging methods available at that time. As the system was developed and the first prototype installed in a hospital the medical staff identified applications, demonstrated its value, and publicized and promoted this as a major medical breakthrough.

The foundation was established, and it was on to the future.

IX. ROBERT LEDLEY AND THE WHOLE BODY CT

A next major step in expanding the clinical value and range of anatomical regions that could be imaged was the development of the whole body scanner.

The head-only CT as developed by Hounsfield was a major contribution to the field of medicine in several respects. The ability to produce tomographic images displaying visible contrast among soft tissues was the breakthrough. It was imaging the previously invisible brain within the dense skull that made the immediate impact. Even though other parts of the body were being imaged with conventional radiography and fluoroscopy and especially enhanced with the use of barium and iodine-based contrast media, potential applications of CT were becoming apparent. The transition from a head-only to a full-body imaging system would require a major redesign for scanning and acquiring the data. This was to be the contribution of Dr. Robert S. Ledley shown along with the first whole body scanner in Fig. 16.

Fig. 16. Dr. Ledley with the ACTA scanner in 1974.

The early career of Dr. Ledley can be reviewed in the BIOGRAPHY section at the end of this chapter. He began his work on CT scanning in 1973. He assembled a group at Georgetown to build the Automatic Computerized Transverse Axial, or ACTA, scanner, which could scan the entire body. In 1974 he established the Digital Information Science Corporation (DISC), selling the machines for $300,000 each. After obtaining the patent for the ACTA scanner, he sold his company to Pfizer Medical Systems Company. The CT division was later purchased by some of the larger and established medical imaging equipment manufacturers.

What was becoming apparent in the industry was that the companies where the two major CT systems were invented and developed (EMI and DISC) did not have the medical imaging capability; manufacturing, marketing, and service support to survive in the CT business.

Dr. Ledley was inducted into the National Inventors Hall of Fame in 1990 and awarded the National Medal of Technology and Innovation by President Bill Clinton in 1997. The original prototype of the ACTA scanner is at the Smithsonian Institution in Washington.

X. THE CONTINUING DEVELOPMENT AND EVOLUTION OF COMPUTED TOMOGRAPHY

The early systems developed by pioneers especially Hounsfield and Ledley introduced and established CT as a revolutionary clinical diagnostic method. This was to be the foundation for many years of research and development to expand the capabilities and desirable characteristics of computed tomography. Much of this involved development in technology, especially electronics and digital imaging and computer technology.

What was to follow is a continuing series of developments, *each a step* toward the goal of increasing the capabilities and values of computed tomography as a major medical procedure.

Every year at major medical conferences including the Radiological Society of North America (RSNA) new advances in technology were introduced by the industry and updates on clinical imaging were presented by the medical professionals. Often the clinical presentations were demonstrating the innovations and capabilities of the technology.

It has become the practice to organize the evolution of computed tomography into "generations" each distinguished by specific design or functional characteristics. Each generation provided another step to the goal of increased visibility and especially faster scanning and data acquisition. Throughout the evolution of CT through the several generations it was the time required to produce an image that was the major challenge. Developments resulted in the reduction of time to produce one image from approximately four (4) minutes to seconds. For many years and encompassing the first five generations the scanning and data acquisition was limited to one image at a time. A major evolution was developments in detector technology along with innovations in data acquisition scanning and reconstruction methods that made possible the simultaneous data for multiple image slices and three-dimensional (3D) volumes.

We will first consider the developments within the first five "single-slice" generations followed by the evolution of detectors and the additional generations.

The Single-Slice Scanner Generations

Hounsfield's design and systems manufactured and distributed by EMI introduced CT to the world and established it as a major method for medical diagnosis. What were to follow were many additional innovations and designs to enhance performance. This was driven by three major objectives:

- To reduce the time required to produce images.
- To increase visibility of anatomical structures and signs of pathology
- To reduce and manage radiation dose to patients

The continuing series of designs especially related to the scanning process are classified into generations. A specific generation was generally characterized by the combination of x-ray beam shapes and scanning motions. Those are the geometric characteristics. Before looking at the special features of each generation let's review the general process and technical requirements for data acquisition that apply to all generations and illustrated in Figure 17.

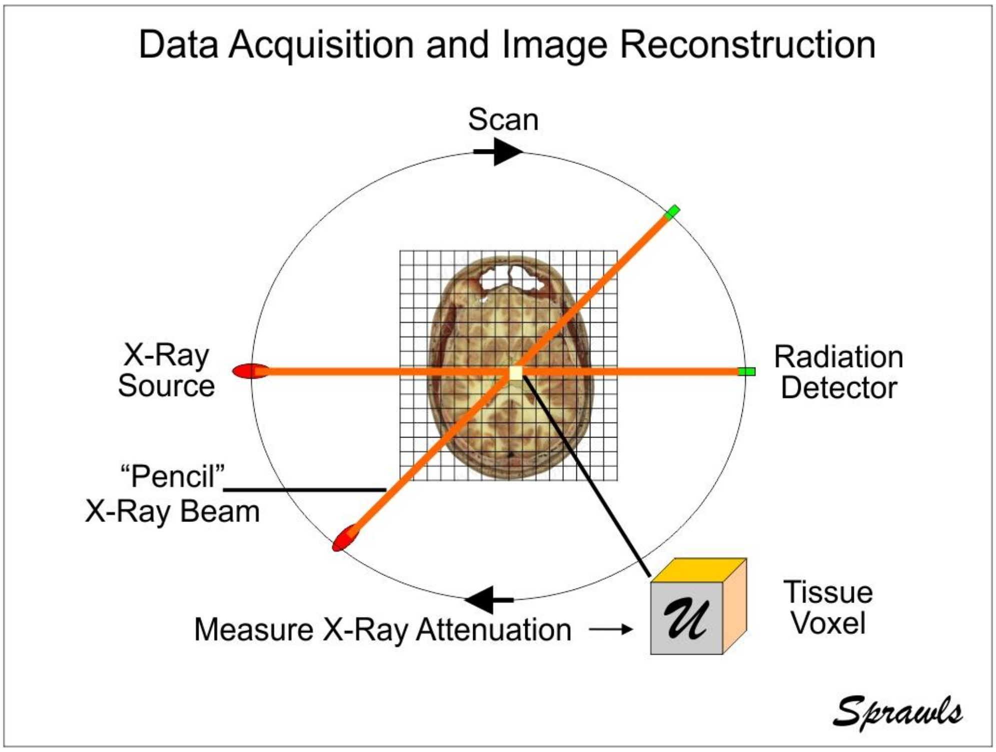

Figure 17. The objective of data acquisition by scanning and mathematical reconstruction is to determine the x-ray attenuation values for each individual tissue voxel within the imaged slice.

The first of two major phases in the formation of a CT image is the *physical or technical* scanning and acquisition of data that can then be used in the *mathematical* image reconstruction process. The number of measurements or samples required in the acquisition to form one image depends on the physical quality characteristics of the image.

The image is formed as a matrix of tissue voxels with an x-ray attenuation value determined for each. The size of each voxel is a major factor in several image quality characteristics, especially detail and noise, and should be taken into consideration in the production of a CT image. The size of each voxel within the tissue slice and corresponding pixel size within the image is determined by the matrix dimension (number of voxels/pixels) for a specific anatomical field of view. For the reconstruction process the matrix size (number of voxels) is a factor that determines the number of measurements that are required in the acquisition process. The number of required measurements is a factor determining the time to produce an image. The early experiments by both Cormack and Hounsfield used a single beam of radiation that was manually rotated around the object step-by-step. This was a very slow process that demonstrated the principle of computed tomography (CT) but not practical for clinical imaging.

The development that made clinical imaging possible was the mechanical *scanning* of the x-ray source and detectors around the patient's body. This established "CT scans" as the common name for the imaging procedure. It was the scanning function that was to be the focus of continuing research and development and evolution of the CT imaging for years to come with the different designs defining the series of generations. The design of a specific generation generally depended on the development of related technologies, especially radiation detectors.

First Generation

The system designed by Hounsfield and produced by EMI was the first generation. Some of the features have been described previously but more details of the scanning process are illustrated in Figure 18.

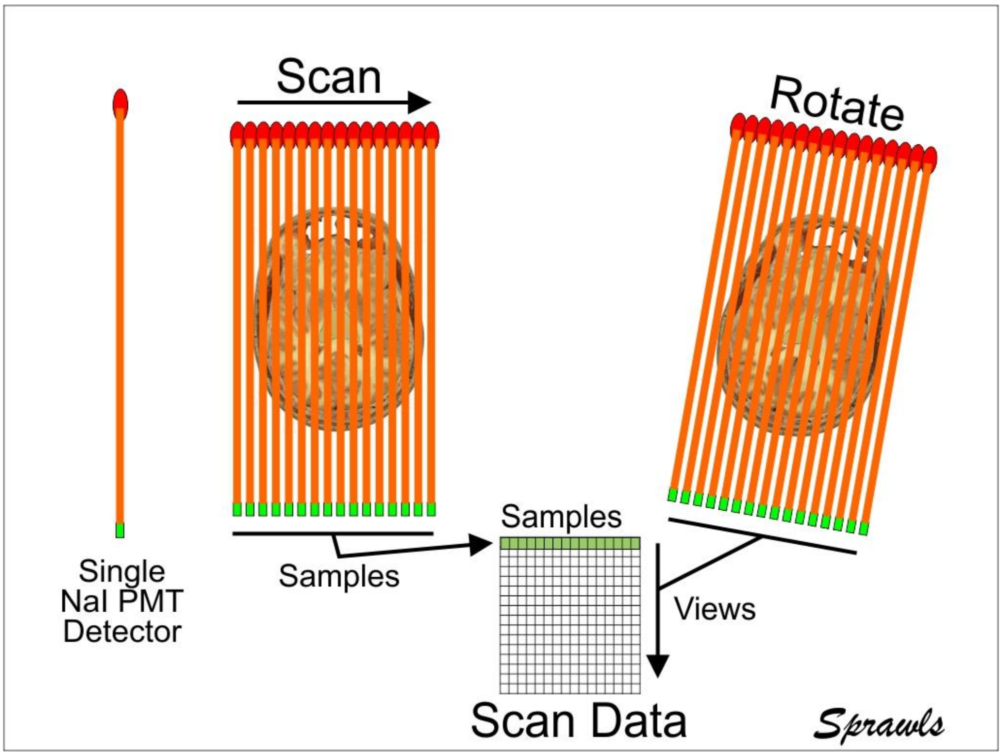

Figure 18. The scanning geometry for the first-generation CT scanner.

The limiting factor with the first-generation technology was only one detector in the image plane recording one measurement (sample) at a time. The scan data to reconstruct an image was acquired with a combination of two motions. First, the single beam was scanned across the patient making individual measurements along the way to make up one *view*. The tube and detector was then rotated about one degree for the next scan to develop the next view. A typical scan time per image was approximately four (4) minutes. This was to produce images with a 60 x 60 matrix compared to the 512 x 512 that became typical for future generations. A major goal of future generations was to produce higher quality images (smaller voxels) combined with faster acquisitions.

Second Generation

The second generation introduced the design feature that was to drive and apply to all future generations by using an array of multiple detectors in the image plane as illustrated in Figure 19.

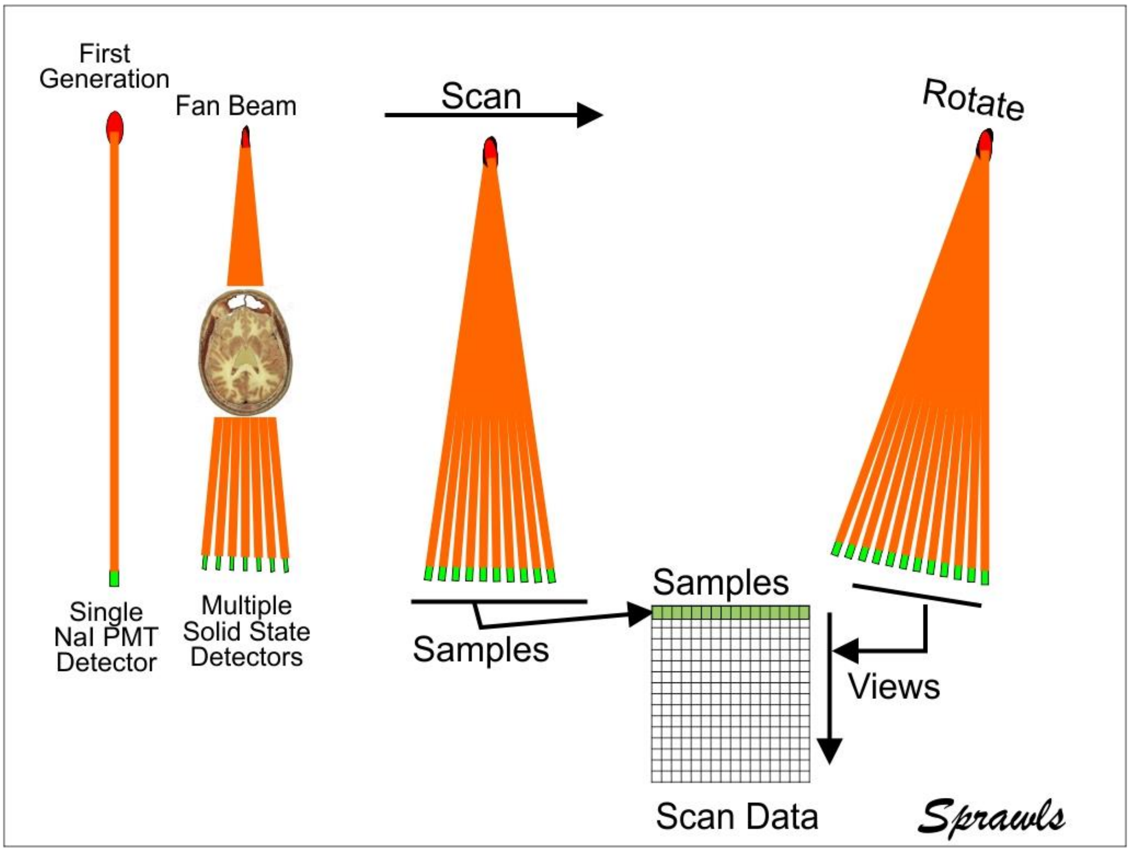

Figure 19. The geometry of the second-generation technology using an array of multiple detectors.

With an array of several side-by-side detectors and a wider fan- shaped x-ray beam more measurements or samples can be made simultaneously increasing the acquisition speed for an image. The fan beam did not have the width to cover the body section so it was necessary to scan as in the first generation. However, the scanning was in larger steps and produced a view faster.

Third Generation

The development of larger detector arrays with a fan beam that could cover a full body section made it possible to acquire a complete view from each x-ray tube location as illustrated in Figure 20.

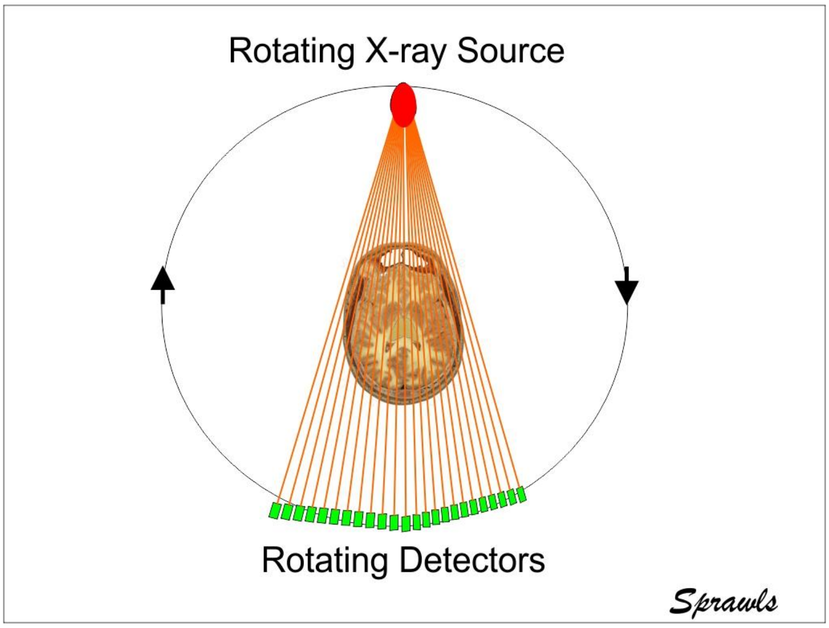

Figure 20. The rotate-rotate design that acquired a complete view from each x-ray tube location.

The technology that made this possible was the development of detector arrays consisting of many small detectors.

Fourth Generation

A next step in detector development was a stationary array that completely encircled the patient's body as illustrated in Figure 21.

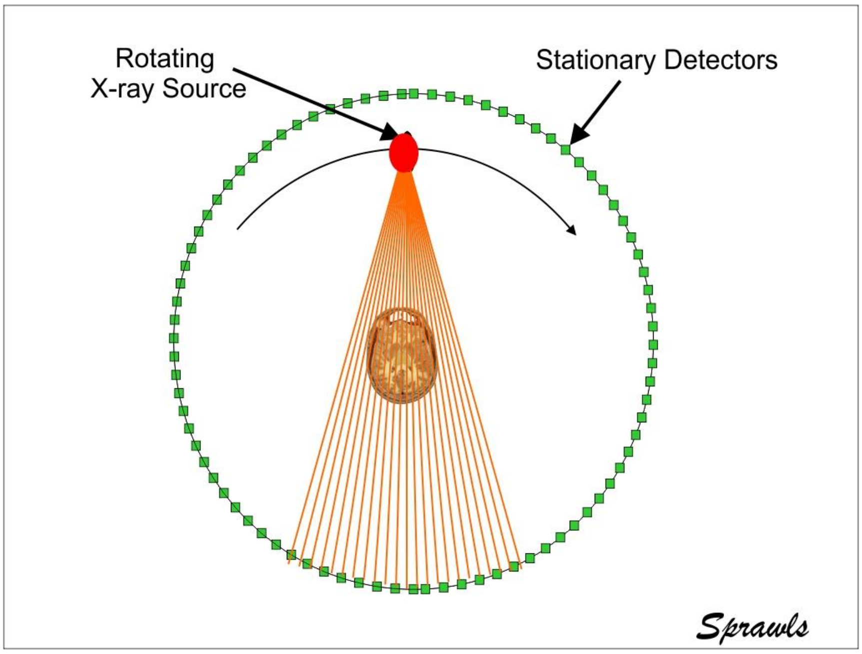

Figure 21. A large circular array of detectors that does not need to be moved.

Fifth Generation

The generally recognized fifth generation introduced a major evolution in CT design by scanning with no physical movement and much faster image acquisition. It used a scanning electron beam as illustrated in Figure 22.

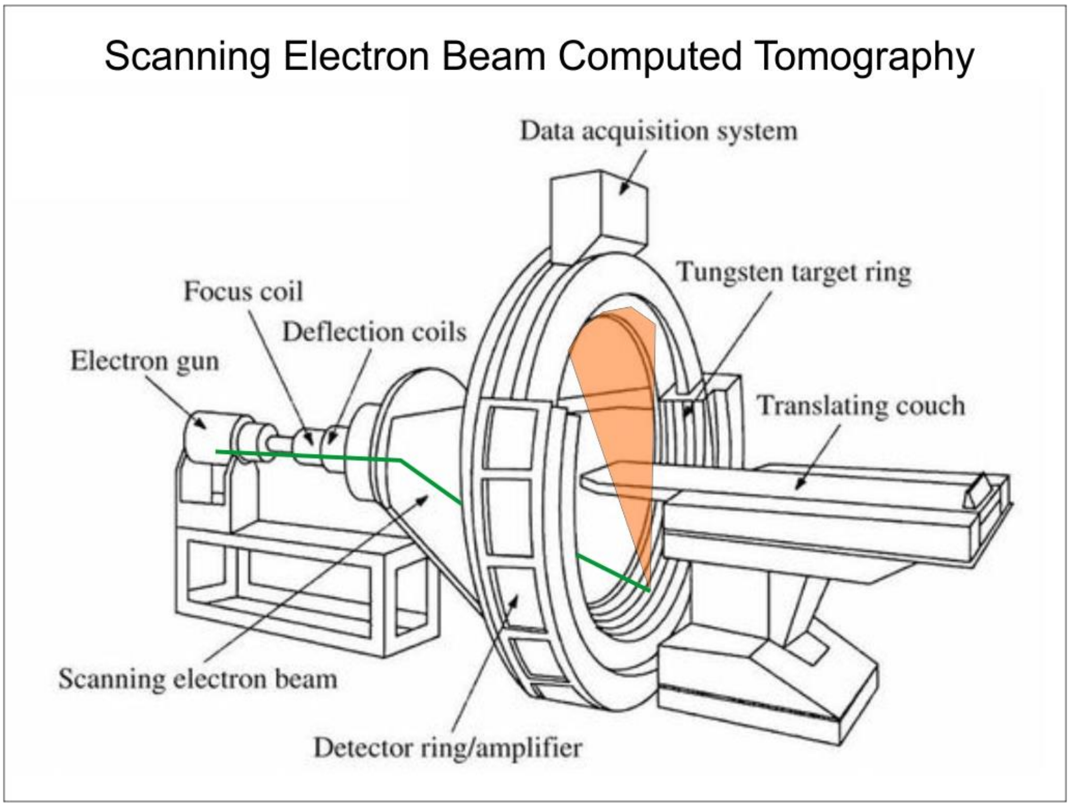

Figure 22. The scanning electron beam design that provides rapid scanning.

This method was developed by Dr. Douglas P. Boyd and other researchers from the UCSF Department of Radiology. Along with the Emerson Radio Corporation they established Imatron Associates and the scanner was known by that name. Its major clinical application was cardiac imaging to detect calcifications within the coronary arteries to evaluate the risk of heart disease.

The unique feature was a very large "x-ray tube" with an electron gun on one end and a very large semi-circular tungsten target serving as the anode on the other end. This was all enclosed in a large vacuum structure. The highly focused electron beam was scanned along the surface of the tungsten anode at a very high rate, up to 17 images per second.

This scanner enhanced the development of cardiac imaging and was generally located in research institutions. Because of its limitations in imaging most other sections of the body and organ systems it was generally not practical for most medical imaging facilities. As the more conventional CT systems were developed with the capability for cardiac imaging the unique value and role of the IMATRON system diminished. The other systems could perform a complete range of clinical procedures, including cardiac.

XI. THE DEVELOPMENT AND EVOLUTION OF DETECTORS

The detectors were the components of CT systems that established design characteristics and imaging capabilities with respect to functionality, image quality and acquisition speeds. This has evolved from essentially a single detector used by Hounsfield to multiple detectors in many different configurations. As previously illustrated it was the number and configuration of the detectors that defined the different generations.

The evolution of detectors has involved a combination of two major characteristics: materials and geometric characteristics of the individual detector elements, both in size and arrangements within arrays. For faster high-quality image acquisition the need was for large arrays of small individual detector elements. The requirements for the individual detector elements included high x-ray attenuation and conversion efficiency, low noise, and uniformity sensitivity among elements. This was to be a continuing challenge as the different detector technologies were developed and evolved. This was to include two major types of detectors with respect to materials, gaseous and solid, as illustrated in Figure 23.

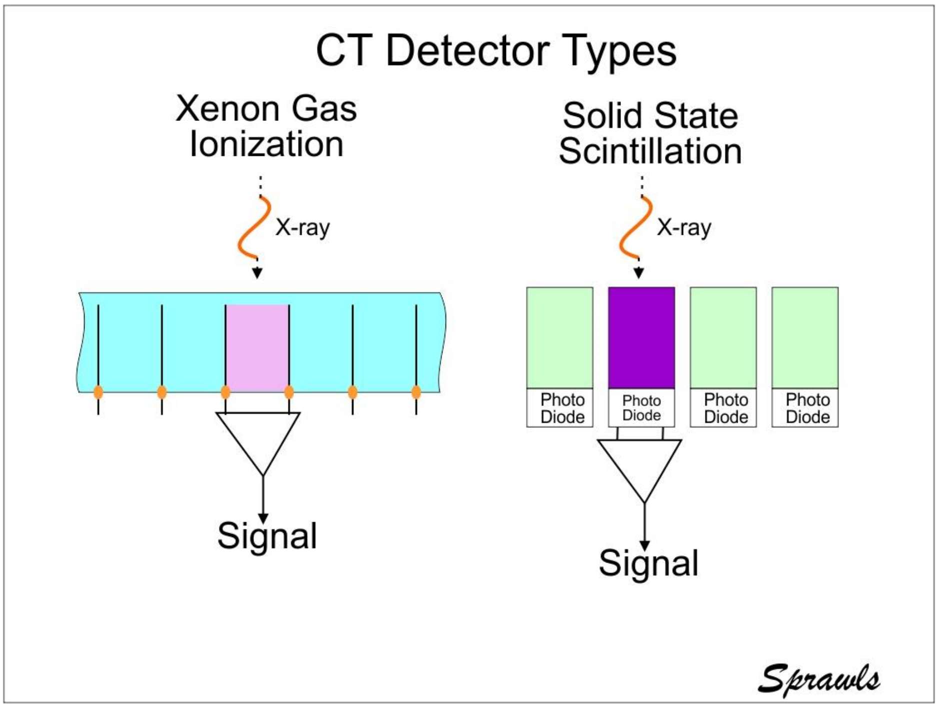

Figure 23. A comparison of the two detector types.

Each type of detector had desirable features that contributed to its value in advancing scanning performance.

Xenon Gas Detectors

A design that fulfilled these requirements with available technology was an array of small ionization chambers filled with xenon gas. This was constructed with the individual elements separated within a common enclosure capable of withstanding very high pressure. Xenon pressures up to around 25 atm were used to enhance x-ray attenuation. A value of this design was uniformity in sensitivity among elements because they shared the same gas pressure. Xenon detectors contributed to the advancement of third-generation CT systems, but their somewhat limited x-ray attenuation resulted in the transition to solid state detectors for all future applications as the solid state technology and electronics developed. Also, solid state units were more suitable than gas for construction of multiple row detector arrays that were to become the future of CT.

Solid State Detectors

A major advantage of solid-state over gaseous detectors is higher x-ray attenuation resulting in greater sensitivity. This improves the image quality to patient radiation dose relationship. A major challenge in the development of solid state detector systems was producing small detector elements with uniformity of sensitivity among the elements. With solid state each element is independent, unlike the gaseous detectors that shared common pressure. Solid state detector technology developed and evolved with the scintillation based detectors becoming a significant contribution.

It was the development of solid state detector arrays consisting of small individual detector elements that was to bring one of the major revolutions in CT: the transition from single-slice to multiple-slice acquisition, and beyond.

Multi-row Detectors and Multi-slice Imaging

Arrays of both solid state and xenon detectors used with fan beams was the enabling technology for the third, fourth, and fifth generation scanners and provided significantly faster acquisitions with respect to the earlier generations.

The next major advancement was the development of detector arrays consisting of *multiple rows* of detector elements as illustrated in Fig.24.

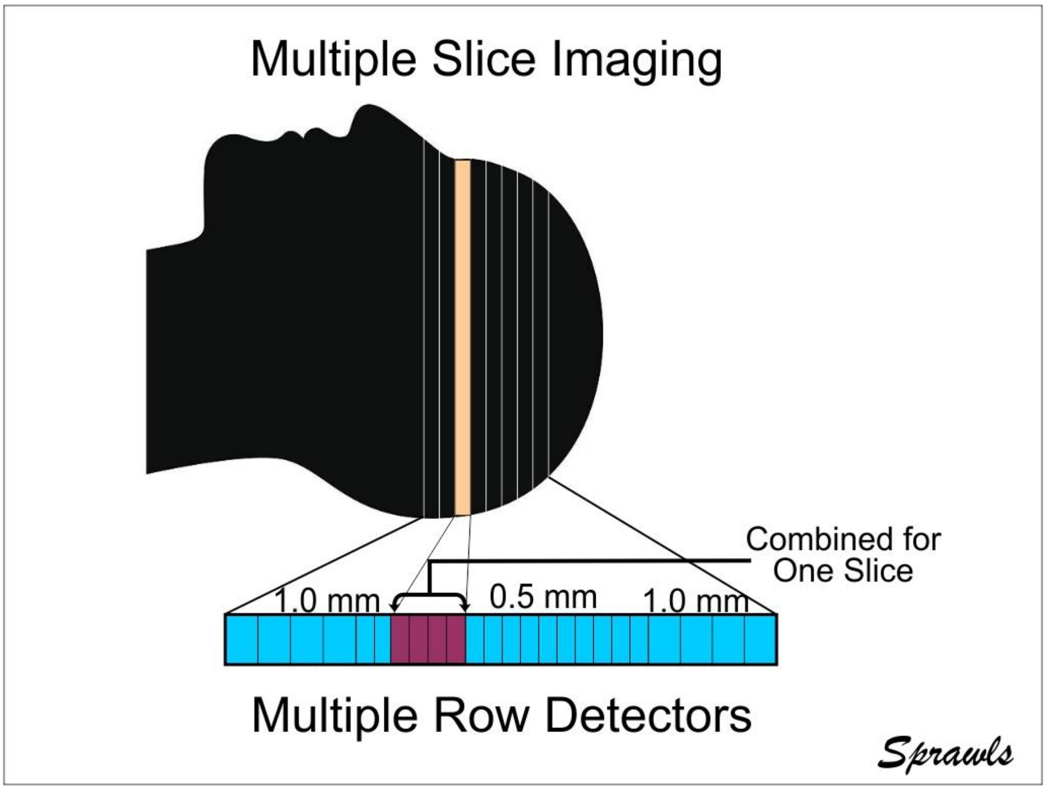

Fig. 24. Multiple Row Detectors and Multiple Slice Imaging

The immediate advantage was the ability to scan and acquire data for several or multiple slices simultaneously. This provided a significant reduction in acquisition time for a procedure. The various manufacturers had slightly different designs with respect to size and number of detectors, in general similar to that shown in figure 24. The number of rows in the designs ranged up to 64. Some designs included smaller detectors in the center that could be selected to produce thinner slices and increased image detail.

Adaptive Arrays

A valuable feature of multiple row detectors was the ability to electronically select and combine several detectors for each slice. This provided the opportunity to adjust and optimize slice thickness for specific clinical procedures.

XII. SPIRAL AND HELICAL SCANNING

One of the major steps and evolutionary events in computed tomography was the invention and development of spiral or helical scanning by Willi Kalender, introduced at the RSNA 1n 1989. Dr. Kalender, Fig. 25, was a major contributor to the development of computed tomography physics and technology throughout his career.

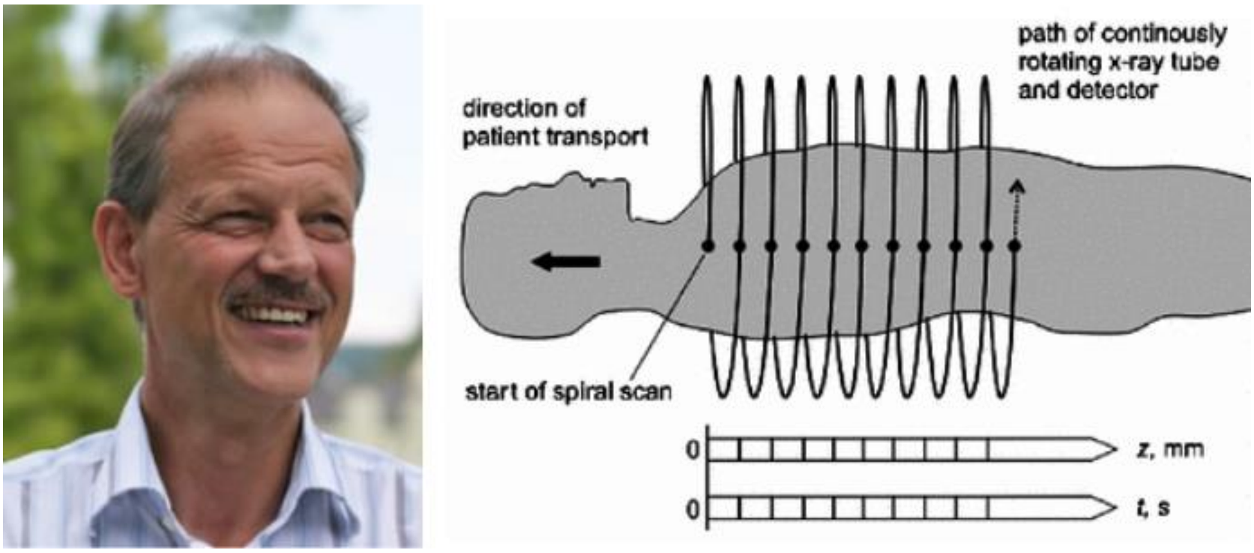

Fig. 25. Dr. Willi Kalender and diagram illustrating the spiral scanning process.

All of the CT methods up until then (1989), including single- and multi-slice scanning, had one thing in common: the thickness and location of each imaged slice within the body was determined during the scanning and data acquisition phase. The relation of the scanning x-ray beam to the long (head to foot) dimension of the human body was fixed, or not moving, as each individual slice was scanned and data was acquired. This produced a data set for each slice. After scanning and acquiring data for a specific slice the body was moved to the next slice position. This was sometimes described as the "scan and step" method where the data for a body section was acquired step by step with a data set for each individual slice. The evolutionary and valuable feature of the spiral method was the acquisition of data in one continuous *volume data set* as illustrated in Fig. 26.

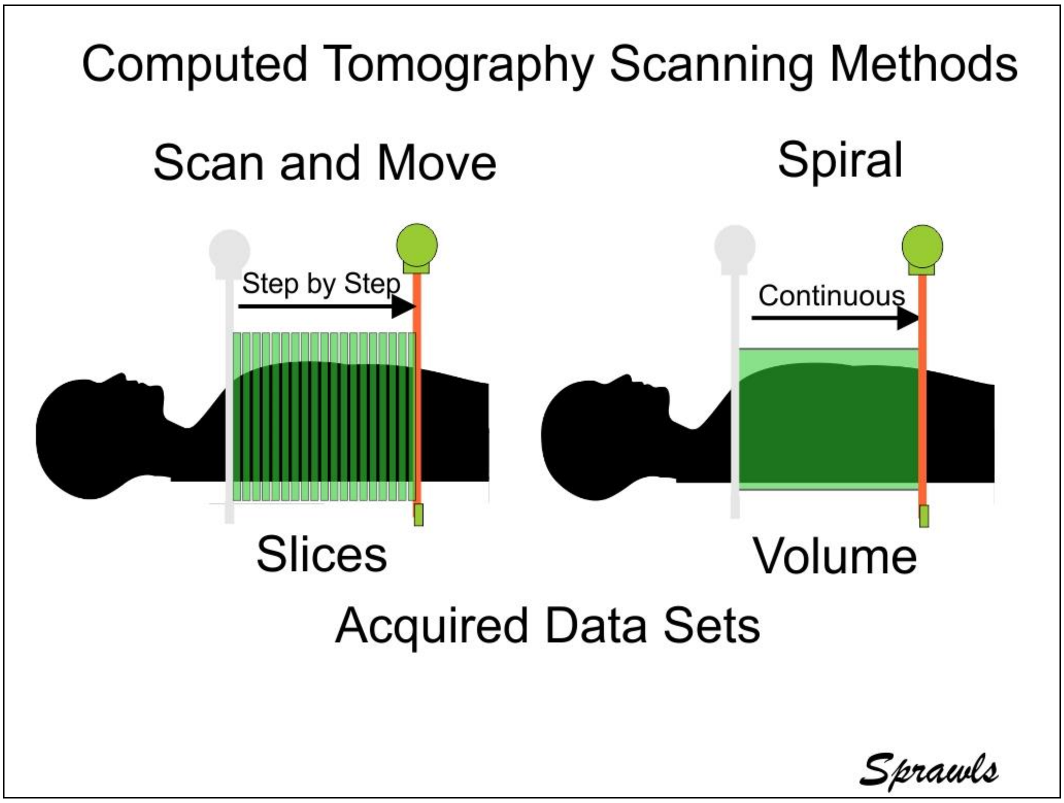

Fig. 26. Comparing scanning methods and acquired data sets.

There were many advantages of spiral scanning and continuous volume data sets over the slice data sets with the other scanning methods (Ref. 14). It overcame the problem of mis-registration of the acquired data with respect to anatomical location. The volume data sets could be used for the reconstruction of three-dimensional (3D) and multiplane images that were especially valuable for angiography and evaluation of vascular diseases. It also revolutionized tomographic (slice) imaging. Rather than the tissue slices being defined (thickness and location) during the acquisition process, they are formed during the reconstruction process from the volume data with the ability to adjust factors including thickness, location, and orientation of the slices. A possibility with the volume data set acquired with spiral scanning was being isotropic with the same detail (spatial resolution) in all directions. This is compared to conventional slice scanning where the slice thickness (one dimension of the voxel) is fixed during the acquisition and is usually larger than the voxel dimensions in the plane of the image.

The Pitch

With the ability to produce data with high detail in the axial direction there were limiting factors. These include the detector and focal spot size effects as in slice acquisition and the additional factor of “how fast” the body is moved through the x-ray beam in the axial direction.

The critical factor that impacts both image quality and radiation dose is the distance the x-ray beam is moved along the length of the body during one rotation in relation to the width of the x-ray beam. This is defined as the *pitch.* It is an adjustable protocol factor with spiral scanning and data acquisition that plays a major role in the optimization of CT imaging procedures and is illustrated in Fig. 27.

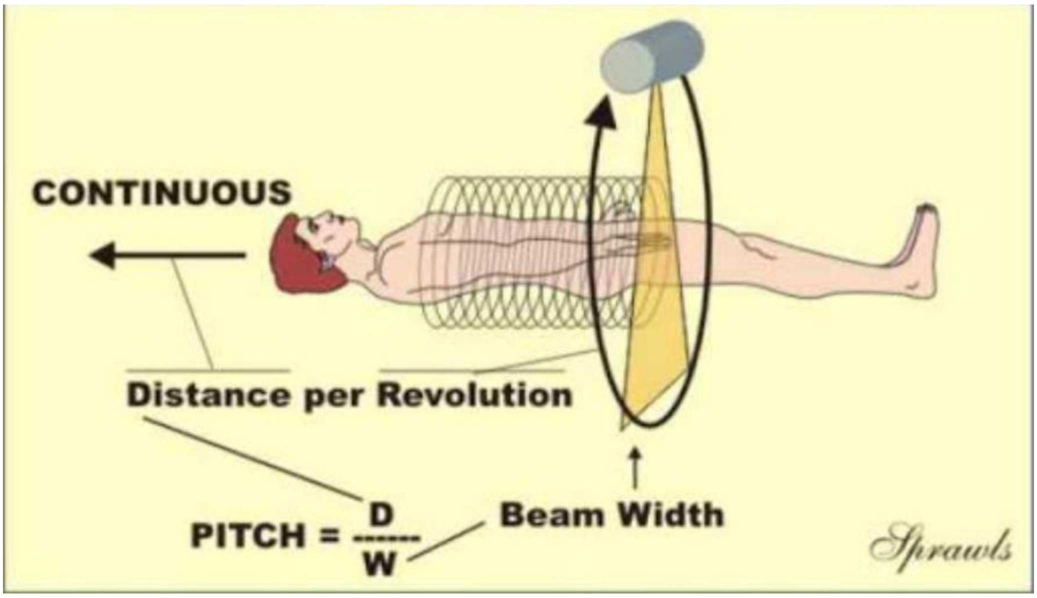

Fig. 27. The concept of the pitch factor shown here for scanning with a single slice beam.

The pitch is a protocol factor that controls and is adjusted before each acquisition scan. The selected value has a significant effect on the three major factors--scan speed, image quality, and radiation dose to the patient. It is a critical factor in optimizing an imaging procedure, especially the balance of image quality and dose.

A significant characteristic of spiral scanning is the determination of the thickness of the tissue slice in the image which has a significant effect on image quality. With the previous generations and methods the slice thickness was determined at the time of acquisition by the active thickness of the x-ray beam as determined by the focal spot and detector sizes. With spiral scanning the slice thickness is not determined, but is *limited* by the x-ray beam thickness. If thin slices (for image detail) are to be produced during reconstruction the data must be acquired with thin x-ray beams. The blurring produced by beam thickness limits the ability to reconstruct thin slices with good quality.

The continuous movement of the patient body during spiral scanning has the effect of blurring the data in the axial direction and this carries over to the reconstructed image. The selected pitch value controls this blurring. Increasing the pitch provides the advantages of faster scanning and reduced radiation dose to the patient. This must be balanced against the reduction of image quality in the slice thickness direction.

Technical Requirements for Spiral Scanning

Spiral scanning required the development of a system more advanced and different from previous types to provide for continuous and many rotations around the patient body. This was achieved with the use of slip ring technology as illustrated in Fig. 28.

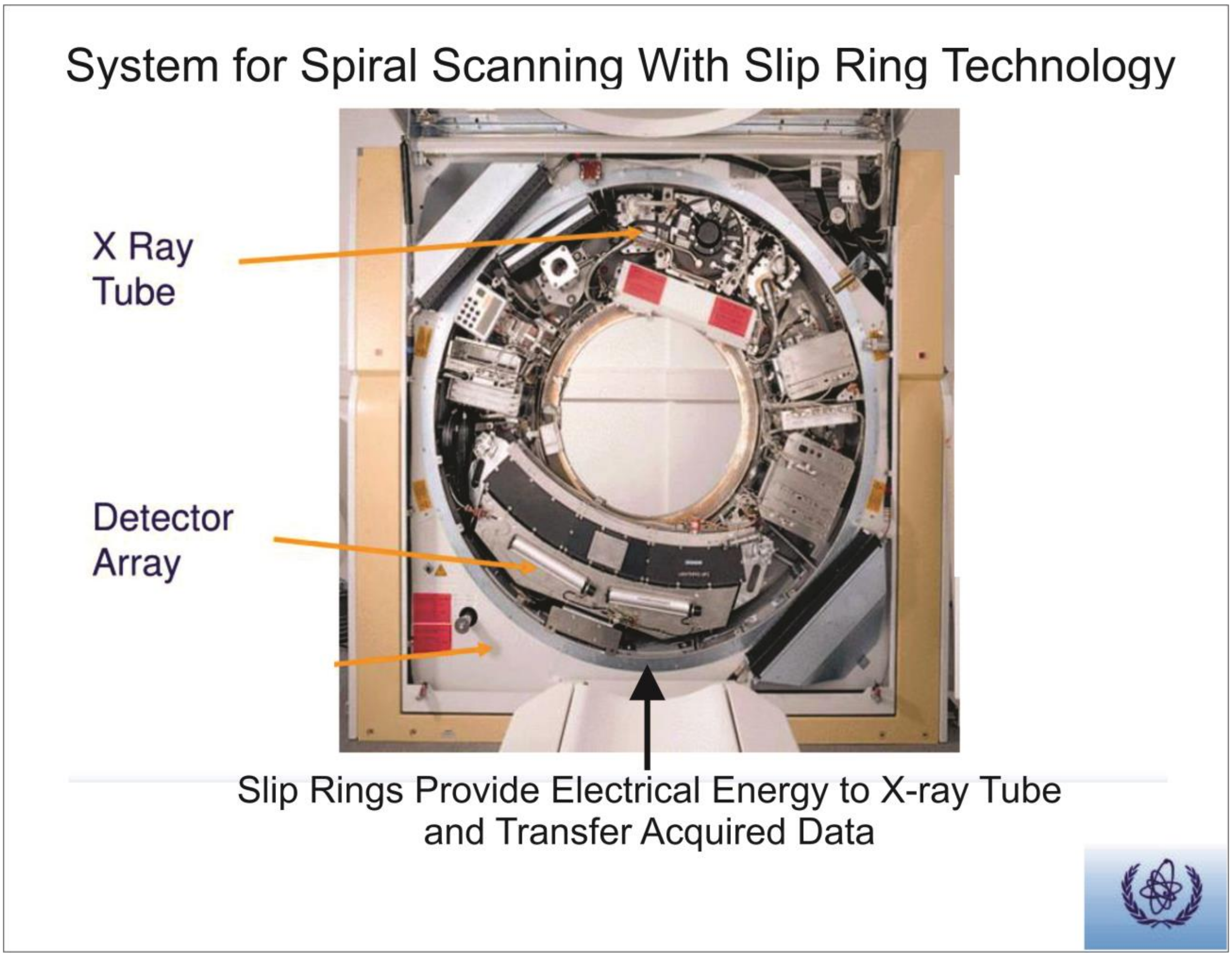

Fig. 28. A scanner using slip ring technology to provide for continuous rotations around the patient's body.

The slip rings are a set of stationary circular electrical/electronic contacts surrounding the rotating components that include the power supply and x-ray tube in addition to the detectors and acquisition data electronics. These connect to the slip rings through sliding contacts during the rotation.

Reconstruction Requirements for Spiral Imaging

One of the major features and values of spiral CT is the ability to produce images for slices created during the reconstruction process from a volume data set. This is different from the other CT methods in which a data set is fixed or confined to each slice during the acquisition phase. A requirement for reconstructing images from data acquired with spiral scanning is *interpolation* from the spiral pathway of the x-ray beam and data acquisition to a slice within the body with a specific location, thickness, and orientation.

XIII. SUMMARY AND THE SIMULTANEOUS DEVELOPMENTS

Our objective with this article is to follow the innovations and developments of the technology for CT systems that provided imaging capabilities for a wide range of clinical applications and are the general purpose systems in most hospitals and clinics, from the early inventions and developments up through the revolutionary spiral scanning process. This has been a step-by-step process moving through multiple generations with a focus on reducing acquisition time (from minutes to sub-seconds) with increased image quality and more dose-efficient and optimized procedures. This progress has benefited from developments in other fields including detector technology and digital computing capabilities.

Along with the developments of the general purpose CT systems which have been our subject there are many other innovations that contribute to a wider range of clinical applications and improved radiation dose management.

Image Reconstruction

Mathematical image reconstruction that is the foundation of CT has evolved with many innovations including an extensive range of filters/algorithms for optimizing reconstruction. Iterative reconstruction was a major innovation that made it possible to produce images of adequate quality with reduced radiation to patients.

Radiation Dose Management

An ongoing effort, especially by physicists, has been the development of methods and procedures for determining and specifying radiation dose to patients and incorporating that into clinical practice as features of modern CT systems. This has been especially significant because a CT procedure compared to radiography requires higher exposures to produce quality images.

Cone Beam Acquisition

The development of flat panel detectors as used in digital radiography provided the opportunity for an even larger acquisition area beyond the well-established multi-row detector configurations. One advantage was an acquisition covering the full anatomical region from each x-ray beam position as illustrated in Fig. 29.

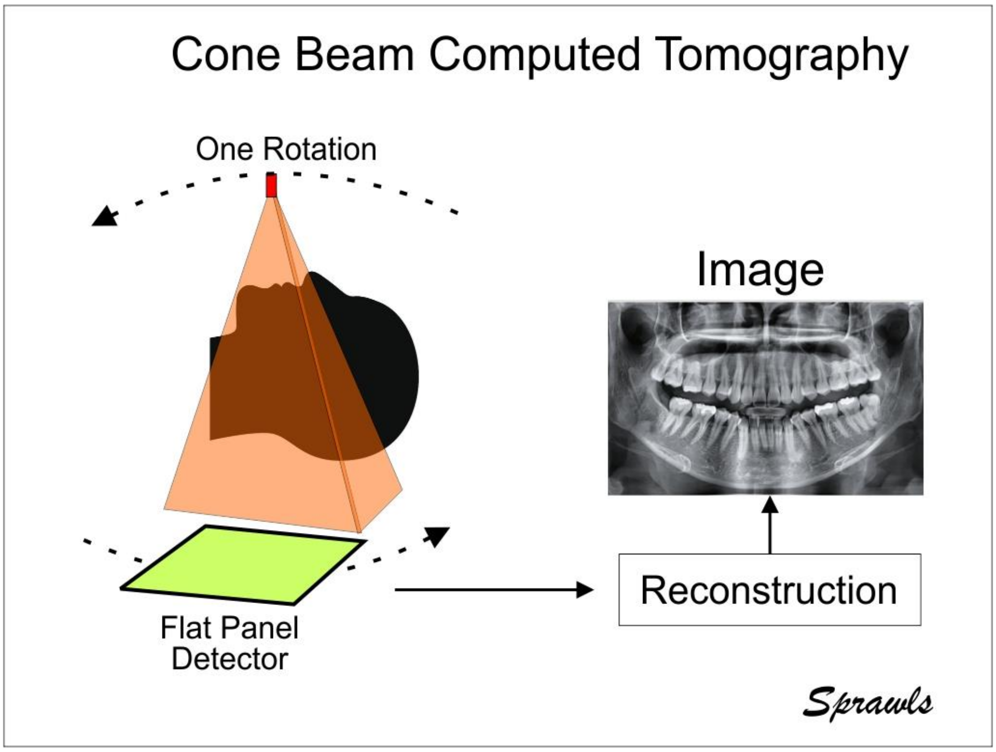

Fig. 29. The concept of cone beam computed tomography.

The cone beam technology was not to become a "next step" in advancing general purpose CT for most clinical applications throughout the human body but enabled the development of specialized CT systems for applications not provided for by general purpose scanners. Two of these systems were for dentistry and breast imaging.

Dual Energy Acquisition

The revolutionary characteristic and contribution of CT to medical imaging was its high contrast sensitivity and ability to produce visible image contrast from small physical differences (physical contrast) among soft tissues. This physical contrast is primarily differences in physical density with some contributions from differences in atomic number (Z). One approach to enhancing contrast is to scan and acquire data with two different x-ray spectra. Contrast is derived from the difference in x-ray attenuation at the different x-ray energies. Several different methods have been used to produce scanners with dual-energy capability. These include two separate x-ray tubes, switching the KV applied during a scan, and spectral selective detectors.

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BIOGRAPHIES

The history of technological developments in computed tomography includes the biographies of those who made major contributions. The innovations and developments over the first fifty years are from the efforts of many physicists, engineers, and physicians often working in collaborative teams in both academic and commercial laboratories. Their contributions are documented and preserved in the scientific literature. Here we provide short biographies of four who made major contributions that have been described in this publication.

Allan MacLeod Cormack

Allan Cormack was born in South Africa in 1924, and after completing the Bachelor and Masters degrees at Cape Town went to St. John's College, Cambridge, as a Research Student.

"I worked at the Cavendish Laboratory under Prof. Otto Frisch on problems connected with He^6. While I made some progress on these problems I did not complete them because of the following circumstances. I had met an American girl, Barbara Seavey, in Dirac's lectures on quantum mechanics, and a year and a half later I wanted to marry her, but I was broke. An inquiry at the Physics Department at Cape Town elicited not only the information that there was a vacancy there, but also a telegram offering me a position as Lecturer. So in 1950 I returned to Cape Town with a bride but no cyclotron, and so no further work on He^6."

In his new position he also served as a part-time medical physicist in the radiology department in Cape Town. This was his introduction to the use of radiation for both diagnosis and treatment of cancer patients. He became concerned with the deficiencies with images and applications for radiation therapy planning and began research and a series of experiments to find some solutions.

Sir Godfrey Newbold Hounsfield

He was born in 1919 and reared near a village in Nottinghamshire and enjoyed the freedom of the rather isolated country life. At a very early age he became intrigued by all the mechanical and electrical gadgets which even then could be found on a farm: the threshing machines, the binders, the generators. The period between his eleventh and eighteenth years was special because this was the time of his first attempts at experimentation, which might never have been made had he lived in a city. "In a village there are few distractions and no pressures to join in at a ball game or go to the cinema, and there was freedom to follow the trail of any interesting idea that came my way." He constructed electrical recording machines; made hazardous investigations of the principles of flight, launching himself from the tops of haystacks with a home-made glider. He almost blew himself up during exciting experiments using water-filled tar barrels and acetylene to see how high they could be waterjet propelled.

During this time he was learning by the hard way many fundamentals in reasoning. At the Magnus Grammar School in Newark they tried hard to provide a broad education but he responded only to physics and mathematics with any ease and moderate enthusiasm.

Aeroplanes were a special interest and at the outbreak of the Second World War he joined the RAF as a volunteer reservist. He took the opportunity to study the books which the RAF made available for Radio Mechanics. After sitting a trade test he was immediately taken on as a Radar Mechanic Instructor and moved to the then RAF-occupied Royal College of Science in South Kensington and later to Cranwell Radar School. At Cranwell, in his spare time he sat and passed the City and Guilds examination in Radio Communications. While there he also occupied himself in building a large-screen oscilloscope and demonstration equipment as aids to instruction, for which he was awarded the Certificate of Merit.

At that time his work was appreciated by Air Vice-Marshal Cassidy who was responsible for his obtaining a grant to attend Faraday House Electrical Engineering College in London, where he received a diploma.

From Hounsfield's Autobiography
"I joined the staff of EMI in Middlesex in 1951, where I worked for a while on radar and guided weapons and later ran a small design laboratory. During this time I became particularly interested in computers, which were then in their infancy."

Robert S. Ledley

Robert Ledley was born in Flushing, Queens in 1926. He studied physics at Columbia hoping that would be his career. However, his parents, worried about the scarcity of jobs in the field, urged him to become a dentist. After receiving his D.D.S. from New York University in 1948, he enrolled as a graduate student at Columbia to study physics. He received his master's degree in physics in 1950.

After his discharge from the Army, he went to work in Washington at the National Bureau of Standards' Dental Materials Section, where he also helped his wife get a job, as a programmer on the Standards Eastern Automatic Computer, or SEAC. It was she who introduced him to computers. Before long he was working directly with the SEAC and focusing on the role that computers might play in solving biomedical problems.

In 1956, Dr. Ledley was hired as an assistant professor of electrical engineering at the George Washington University School of Engineering and Applied Science. That year, he began to collaborate with Lee B. Lusted, a radiologist and electrical engineer, on developing ways to teach physicians and biomedical researchers to use electronic digital computers in their work. In 1960 he founded the National Biomedical Research Foundation, a nonprofit organization dedicated to promoting the use of computing methods among biomedical scientists.

Willi Kalender

Please See: https://en.wikipedia.org/wiki/Willi_A._Kalender#Career

Contacts of the corresponding author:

Author: Perry Sprawls
Institute: Emory University and Sprawls Educational Foundation
http://www.sprawls.org/

Email: sprawls@emory.edu