

Chapter 2

Some Words About the History of Computed Tomography

We could limit the story of the beginnings of computed tomography to mentioning Allan MacLeod Cormack and Godfrey Newbold Hounsfield, the authors of this groundbreaking invention, and to placing their achievements on a timeline, from Cormack's theoretical idea in the late 1950s to Hounsfield's development of a practical device in the late 1960s. However, perhaps we should broaden our horizons and look back through the centuries to obtain a more complete view of the development of human thought and aspirations, which led to the invention of a device without which it would be difficult to imagine contemporary medicine.

This story begins in ancient times about 400 BC, when the Greek philosopher Democritus first described matter as a cluster of invisible and at the same time indivisible particles. He called these particles atoms, from the Greek, *atomos*, meaning indivisible. He also studied the invisible forces which caused attraction and repulsion. Their action was observed for example, when, after being rubbed with fur, amber attracted various small objects. Today we know that the cause of this mysterious attraction is the electric force. We can see the evidence of Democritus' research in the use of the word "electron", which in Greek means amber, to name one of the elementary particles. Now, over two thousand years later, this physical phenomenon, first observed by ancient scholars, is exploited in the modern X-ray tube.

X-radiation, used in X-ray computed tomography, is an electromagnetic wave. The English physicist Michael Faraday (1791–1867) observed the phenomenon of electromagnetism and in 1831, he formulated his famous laws of electromagnetic induction. Twenty-nine years later, in 1860, this discovery by the "father of electromagnetism" allowed another pioneer, the Scot, James Clark Maxwell, to formulate the laws, which are included in the equations that bear his name. Maxwell's equations comprehensively expressed the ideas of electricity and magnetism in their dynamic form and provided a revolutionary stimulus, which led to the development of the later technologies of radio and television and of course, radiology.

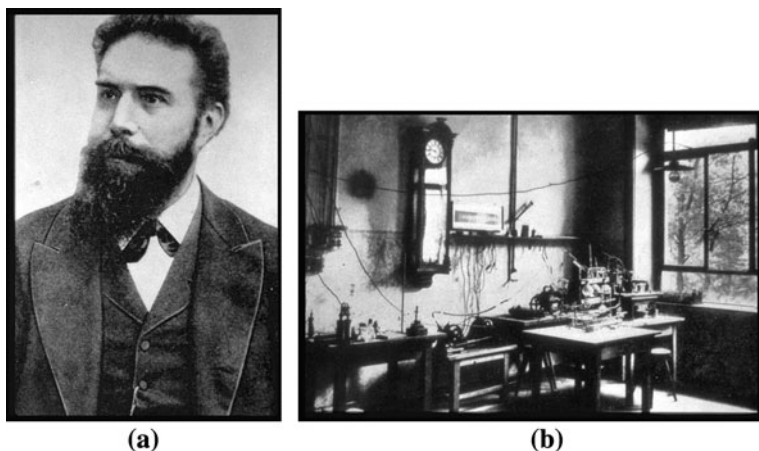


Fig. 2.1 Wilhelm C. Röntgen (a) and the room where he discovered X-rays (b)

The accidental discovery of the radiation, known today as X-radiation,¹ triggered a revolution in our knowledge of the inside of the human body. The discovery was made on 8th November 1895 by the German scientist Wilhelm Conrad Röntgen (1845–1923) (see Fig. 2.1a) and it marked the beginning of his glittering career and fame. Röntgen, at that time professor of physics at the University of Würzburg, was in his blacked out laboratory (see Fig. 2.1b) investigating the glow that occurred during electric discharges inside an evacuated glass tube, a Crookes tube. An example of a Crookes tube and ancillary equipment, similar to that used in his famous experiment, is shown in Fig. 2.2a.

Röntgen was working on the properties of cathode rays, and in particular on the determination of their range outside the tube (his description of the experiment is shown in Fig. 2.2b). During the experiment, completely unexpectedly, he observed something unusual; a screen coated with crystals of barium platinocyanide started to glow. The screen was made of fluorescent paper, which at that time was used routinely to detect ultraviolet radiation. While he was carrying out the experiment, the screen happened, by chance, to be in the laboratory within range of the radiation coming from the tube. Röntgen noticed that the screen was too far away from the source for the cathode rays to have been the cause of the glow. He was also surprised that tightly covering the tube with cardboard did not eliminate the effect; this contradicted his assumption that the glow, occurring during the electrical discharge inside the tube, was the cause of this phenomenon.

If anyone today wanted to reproduce Röntgen's experiment of the evening of 8th November 1895, he would need to follow these instructions:

¹ X-radiation (or X-rays) seemed to Röntgen to be so inexplicable and mysterious that he took inspiration from mathematicians and named it after the symbol X: the symbol of the unknown in mathematics.

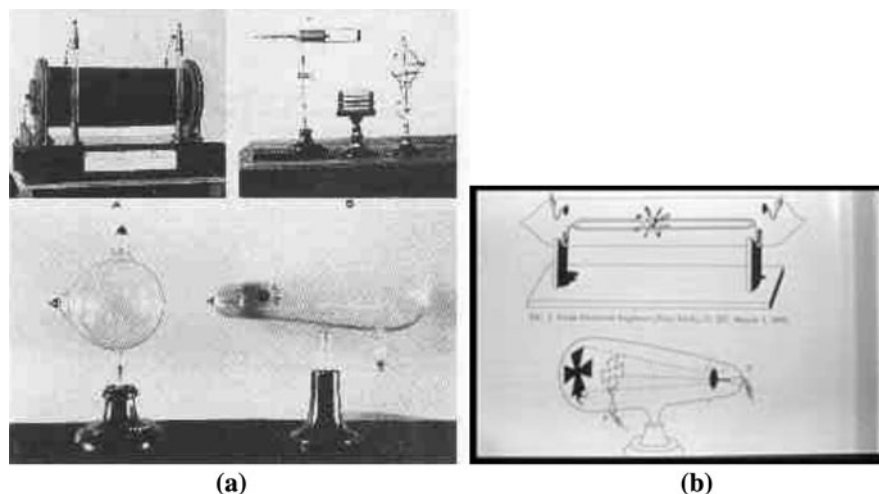


Fig. 2.2 Crookes tube from the time of Röntgen (a) and circuitry similar to that used in his famous experiment (b)

Recipe for X-rays à la Röntgen. Take an induction coil consisting of a primary coil with a few hundred turns of thick wire (the current in this coil is about 20A), a secondary coil with 200 thousand turns of thin wire, and a contact-breaker (invented by Deprez) with platinum contacts (this breaks the current in the primary coil 15-20 times a second). Transform the constant primary voltage from a 32V battery to an alternating secondary voltage of 40-60 kV. Apply this voltage to a Crookes vacuum tube which has previously been evacuated to a pressure of 0.01 Torr (mmHg) using a mercury pump. Cover the tube with blackened cardboard. Put aside a little time for pumping out the tube. This can take a number of hours, but may well extend to several days. Place a screen coated with crystals of barium platinocyanide near the cathode end of the tube. While the electric discharge is taking place inside the tube, place various objects between the tube and the screen and observe the image appearing on it. Try to resist experimenting on your own hands.

During the few days following the 8th November, Röntgen carried out a series of tests in which he placed various objects between the tube and the screen. It was then that he also noticed, clearly outlined on the screen, the skeleton of his own hand.

He was not sure however, to what extent his observations were scientifically valid, as he mentioned in letters to friends. Röntgen confided to them: "I have discovered something interesting but I don't know if my observations are correct". Nevertheless, he conducted further experiments. When, on 28 December 1895, he was finally certain that the mysterious rays really existed, he sent a report of his research to the Würzburg Physical Medical Society, in which he wrote:

If the discharge of a fairly large induction coil is put through a Hittorf vacuum tube or through a Lenard tube, Crookes tube or other similar apparatus, which has been evacuated, the tube covered with thin, quite tightly fitting, black cardboard, and if the whole apparatus is placed in a completely dark room, then with every discharge a bright flickering is

observed on a paper screen coated with barium platinocyanide, placed near the induction coil [4].

Attached to the 11-page report was the famous X-ray picture of a hand, which most probably belonged to Röntgen's wife, Bertha (see Fig. 2.3).

The report contained a detailed list of the properties of X-rays. From the point of view of the medical applications of the radiation, the most significant of these were:

- the ability of various materials of the same thickness to transmit X-rays depends to a great extent on their densities,
- the ability of samples of the same material to transmit X-rays depends on their thickness; an increase in thickness of the material decreases the transmission of the rays,
- photographic plates are sensitive to X-rays.

After the results of the experiment were reported in *The New York Times*, Röntgen's career, and that of X-rays, took off. By January 1896, the whole world knew about the wonderful discovery, and people, not just those connected with science, were overwhelmed by a peculiar "X-ray mania". Röntgen's success culminated in 1901 with the Nobel Prize, the first in history to be awarded for physics.

The technique of making X-ray photographs, to enable the observation of the internal features of a person without any surgical intervention, quickly found

Fig. 2.3 Röntgen's report on his research into X-rays—the enclosed X-ray picture of the hand of his wife, Bertha

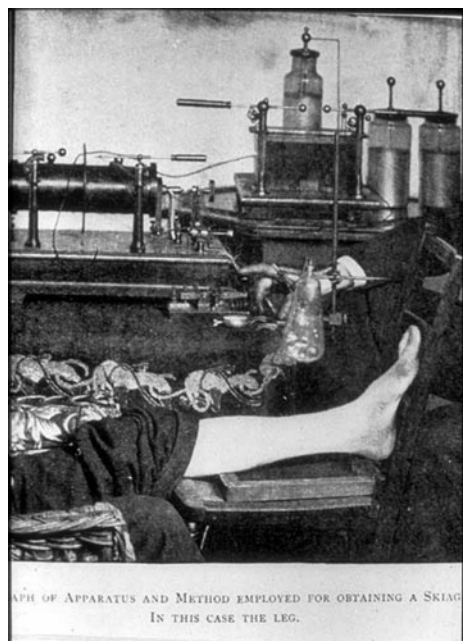


justified recognition among doctors and spread around the whole world. People began to build devices for taking X-ray pictures for medical purposes, and X-ray research developed so quickly that by 1897, William Morton had taken the first picture of a whole skeleton using X-rays. Figure 2.4 shows a picture of one of the pioneering devices in an X-ray room of the time.

We should not forget however, that Röntgen's epoch-making discovery was made possible by the inventions of several earlier innovators. Among those, we should mention the Italian Evangelista Torricelli, inventor of the mercury barometer (1643) and the German Otto von Guericke, creator of the vacuum pump. Their work contributed to William Crookes' (1832–1919) construction of the vacuum tube. This was widely known in Röntgen's time and, of course, was used by him in his first experiments. Other elements of the equipment used by Röntgen came directly from the ideas of Gaston Planté, the designer of the electric battery that Röntgen used as his source of electrical energy.

Over the years, the design of X-ray equipment was refined to obtain better and better two-dimensional images of the inside of the human body. The American Thomas Alva Edison (1847–1931), for example, made a significant contribution to the development of medical imaging techniques. He was, among other things, the author of many improvements to the design of X-ray tubes. The German Hermann von Helmholtz (1821–1894), on the other hand, investigated the nature of X-rays; he was interested in the mathematical equations describing their properties and in measuring their penetration through different materials.

Fig. 2.4 X-ray room from the early years of radiography



The initial euphoria surrounding the diagnostic possibilities of X-ray pictures gradually gave way to a realisation of the limitations of body imaging methods in only two dimensions. In the year after the discovery of X-rays, E. Thompson was already attempting to obtain a three-dimensional X-ray image using stereoscopic techniques. The solution he proposed involved taking two X-ray pictures, displaced with respect to each other, of a patient who remained motionless. The diagnostician could then use a stereoscope to view the images with depth perspective.

At this point, it is worth mentioning that Poles also made their contribution to the improvement of X-ray imaging techniques. In particular, the experiments of Doctor Karol Mayer from the Krakow Clinic of Internal Medicine are acknowledged as a prelude to tomography. In 1916, he obtained stratigraphic images using a moving X-ray tube and a stationary film cassette, a method which resembles the process of scanning by computed tomography. Carlo Baese patented a similar imaging method in 1915 and described it in his paper *Methods and equipment for the location of foreign bodies in the human body by use of X-rays*. The technique devised by Baese depended on the simultaneous movement of tube and film cassette.

In 1922, the CT scanner came still closer to fruition; A.E.M. Bocage obtained a patent entitled *Methods and equipment for obtaining radiological images of cross-sections of the body not obscured by tissue structures in front of or behind the cross-section*. During the same period, B.G. Ziedses des Plantes conducted research into his concept of planigraphy, which was put into practice by Massiot in 1935.

A further step along the road towards contemporary scanners was the use, by the German doctor Willy Kuhn, of gamma radiation to obtain a layered image of tissues, in 1963.

The discovery of X-rays was a necessary but insufficient condition for the rise of computed tomography. Its design also depended on the development of computational techniques, which enabled the building of the computer, a device having fundamental significance for modern imaging techniques.

Perhaps we could think of the “computer” story as having started with the human hand, undoubtedly the first calculating device. By means of an ingenious system of counting, using the fingers, the early peoples of Europe and the Near East could calculate up to 9999. The Chinese even pushed the upper limit of calculation to ten billion. The results of calculations were recorded in various ways such as by making cuts in animal bones and in wooden tablets. The Incas used a so-called *kipu*, that is, a system of strings with knots on them. However, people were soon dissatisfied with such an approach to calculations; they needed instruments that were capable of carrying out complicated arithmetic and even of interpreting the data obtained.

One of the first “calculating machines”, consisting of a tablet and stones, was the abak; this would be familiar to the ancient Greeks and Romans. Its operation was very straightforward. A series of columns of stones² were arranged on the

² It is not by accident that the word calculation has its roots in the Latin word for *pebble*—*calculus*.

tablet and the stones moved to perform the arithmetical operations. It is interesting that in China they still use an abacus which they call the *suan-pan*, based on similar principles.

In the 17th century, a mathematician from Scotland, John Napier, well-known today as the creator of logarithm tables, built a system for the multiplication of numbers, a set of rods of square cross-section known as *Napier's bones*. To use them to multiply, it was necessary to sort through the rods to find the appropriate digits, place the rods next to each other in the appropriate order and then read off the result. In about 1630, the German Wilhelm Schickard, amongst others, mechanised this idea using systems of cogs and dials.

Further innovations were introduced by some of the most outstanding figures in the world of science. Among these was Blaise Pascal (1623–1662), who designed a machine to perform addition and subtraction. Contemporary computer scientists have shown their appreciation of his services to computational technology by naming one of the most popular high-level computer languages after him. At this point, it is impossible not to mention Gottfried W. Leibniz (1646–1716), who significantly reduced the degree of complexity of his predecessors' calculating machines by introducing a drum with teeth of unequal length. The next step in the evolution of calculating machines was the arithmometer, examples of which were built independently by F.S. Baldwin and W.T. Odhner; the mechanics of calculating machines reached their zenith with these devices.

Today's computers owe their computational power to progress in the fields of electricity and electronics. Scientists designed prototypes of new components which were soon manufactured and applied practically. Particularly noteworthy here are the inventions of the electronic valve (produced by the Philips company in 1917), the transistor (developed by the Americans John Bardeen and Walter H. Brattain in 1948) as well as the integrated circuit (developed by a group of researchers at Intel under the direction of Ted Hoff in 1969). These innovations might well have contributed only to the improvement of the calculating function of existing instruments, if it were not for the appearance of the English mathematician, physicist and philosopher Alan Turing.

Turing (1912–1954) transformed the ordinary calculating machine into a device that could be regarded as a prototype computer. In his paper *On Computable Numbers with an Application to the Entscheidungsproblem* [5], he discussed the possibility of building a programmable calculating machine. He considered three factors: logical instructions, the equivalent of today's microprocessor instructions; a thought process, in effect an algorithm; and a "machine". Turing argued that it was possible to write down an analytical thought process as a finite series of simple instructions, and then to execute these using the machine. He reasoned therefore that every process, which could be expressed logically, could be implemented by means of tables described in his work, these constituting the essence of the Turing machine.

The universal Turing machine contained the idea of creating a device, which knew a "code" that it could use to record each computational procedure. It was now only a step away from the creation of a computer programming language. It is

not by accident that the word code has been used at this point. During World War II, Turing became an expert in cryptography while engaged in decoding German Enigma cipher machines. This kind of experience was undoubtedly to be of great help in his work on computing languages.

It is worth commenting on the significant contribution to the process of decoding the famous Enigma cipher system made by the Polish mathematicians: M. Rejewski, J. Różycki, and H. Zygalski. It was they who broke the code of the early versions of Enigma.

The first computer in the world to be officially recognised as such is the ENIAC machine (*Electronic Numerical Integrator and Calculator*) from 1946. In fact, the first computer was three years older and was built during the war at the Bletchley Park centre, by a group under the direction of Max Newman. The existence of the computer, called Colossus I, was kept secret until 1976. It is worth remembering that the first computers were far from perfect. They contained about 18 thousand very unreliable valves; this meant that the time that the computers were out of commission considerably exceeded the time that they worked. Over the years, engineering advances and progress towards the miniaturisation of components in computers led to the development of microcomputers.

It is at this point that the two separate strands of discovery and invention come together; the path leading to the discovery and exploitation of X-rays meets that leading to the refinement of computational techniques. Without this convergence, there would probably not have been computed tomography today.

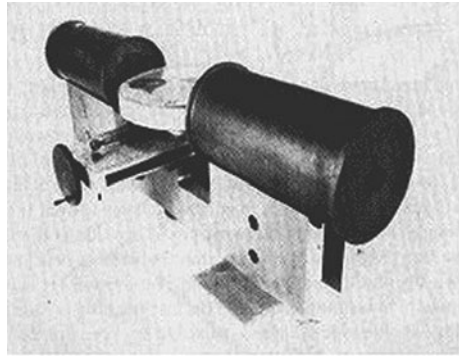
The two people generally credited with inventing computed tomography were awarded the Nobel Prize for Physiology or Medicine in 1979: Allan MacLeod Cormack (1924–1998) and Godfrey Newbold Hounsfield (1919–2004). Although the Norwegian Abel conceived the idea of tomography significantly earlier (in 1826), and then the Austrian Radon developed it further,³ it was only the solution proposed by Cormack and Hounsfield that fully deserves the name computed tomography.

Born in South Africa, Allan MacLeod Cormack first encountered issues associated with tomography during his work at the Department of Physics at the University of Cape Town; he was working on the measurement of the X-ray absorption of various body tissues. He later moved to Harvard University and, in 1956, began work on the problem of image reconstruction of X-ray projections. First, he solved the problem theoretically and then confirmed the results of his research experimentally using cutlets of horsemeat and pork, and apparatus that he had built himself. Figure 2.5⁴ shows the apparatus which Cormack used for his first experiments in 1963.

³ The Radon transform forms the basis of methods of image reconstruction from projections, the fundamental mathematical problem in computed tomography.

⁴ The Homepage of the Japan Industries Association of Radiological Systems (JIRA) and Sumio Makino: *Key words for success or failure of enterprises—From case study of X-ray CT business*, Japan Planning Center.

Fig. 2.5 Tomographic device built by Cormack in 1963



Cormack published the results of his research in an article entitled *Representation of a Function by its Line Integrals*, in *The Journal of Applied Physics* and later in *Physics of Medical Biology* [2].

As a theoretical physicist, Cormack was not concerned about the practical application of his research. It was the work of the Englishman Godfrey Newbold Hounsfield, employed at the Central Research Laboratories of EMI Ltd., which led to the construction of the first CT scanner; Hounsfield and his creation are shown in Fig. 2.7a.⁵ During World War II, Hounsfield had worked on the technical development of radar air defence systems; this undoubtedly influenced his later achievements in the field of tomography. In 1967, independently of Cormack, he began his research on tomography, initially using gamma radiation, which has similar properties to X-radiation. Hounsfield developed a different approach to the problem of image reconstruction from that of his predecessor and he used the power of the computers available at that time to carry out the complicated calculations needed. In this way, the concept of computed tomography found its practical expression. A photograph of the CT scanner, which Hounsfield used in the laboratory, is shown in Fig. 2.6a.

The first laboratory tests revealed the great complexity of the technical problems facing the builders of the scanner; because of the low output of the gamma ray source (Americium, Am) individual exposures took a long time, so scans took as long as nine days. The first experiments were carried out on a human brain prepared in formalin, the brain of a living calf and the kidneys of a pig and it was difficult to differentiate the healthy tissues from the unhealthy. Nevertheless, after about 28 thousand measurements and a process of reconstruction taking about 2.5 hours, an image was obtained with enough contrast to enable the observation of the differences between the tissues of the brain. The resolution of the image was 80×80 pixels (see Fig. 2.6b). Hounsfield finally patented his device in 1968.

In order to confirm the results of his initial research, further experimental work was necessary, this time using living tissues. Hounsfield also took the opportunity

⁵ In 1958, Hounsfield was, among other things, leader of the group, which built the EMIDEC 1100, the first computer in Great Britain to be made entirely of OC72 transistors.

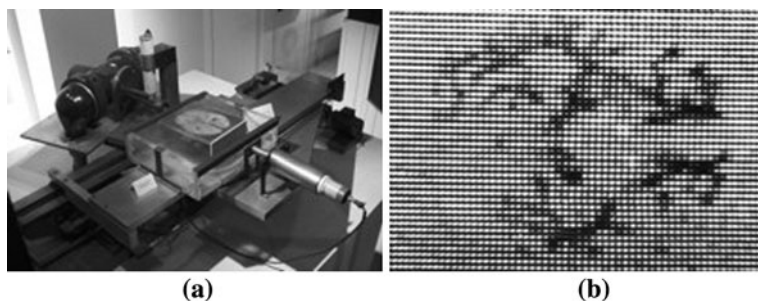


Fig. 2.6 Laboratory scanner used by G.N. Hounsfield (a) and an image of a preserved brain, obtained using this equipment in 1968 (b)

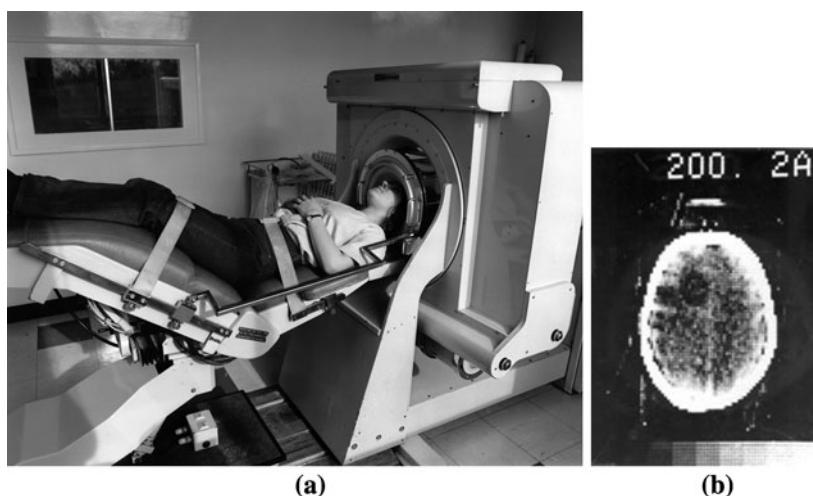


Fig. 2.7 The EMI Mark I scanner (a) and a transverse image of the brain (b)

to refine the design of the scanner. As a result, he was in a position to begin the clinical test phase, during which an X-ray tube replaced the source of gamma radiation. This shortened the time spent taking the measurements to nine hours. The actual process of image reconstruction was reduced to 20 minutes.

In September 1971, with the participation of the neurologists James Ambrose and Louis Kreel, an improved prototype scanner, the EMI Mark I, was installed at the Atkinson Morley's Hospital in Wimbledon (CT scanners at that time were known as EMI-scanners; see Fig. 2.7a). Because of the small size of the opening in which the scan was carried out, this apparatus could only be used to produce images of the head. In order to reduce the range of radiation intensities registered by the detectors, the head was placed in a rubber membrane filled with water.

The first tomographic examination of a patient took place on 1 October 1971. It was of a woman with a suspected brain tumour. On the image obtained, it was

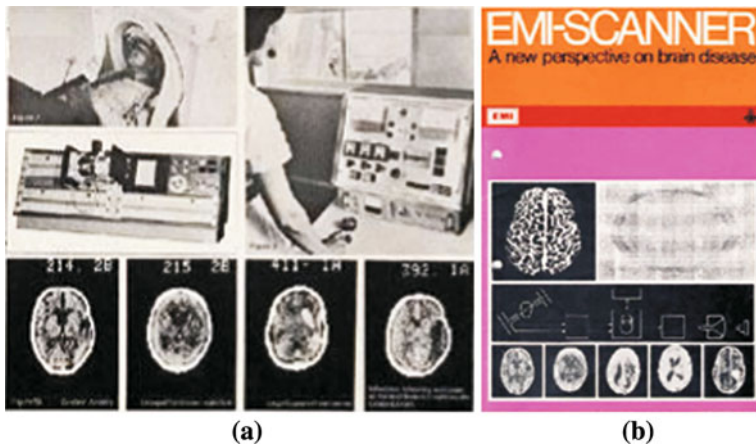


Fig. 2.8 The EMI scanner with instrumentation and images obtained with it (a), and the front cover of a company brochure describing the new technology

possible to differentiate clearly between the physiological areas of the brain and the round, darker pathological area where a cyst was developing (see Fig. 2.7b).

The basic parameters of the scanner used at that time were as follows:

- scan time: about 4.5 min,
- reconstruction time: 20 s,
- cross-section thickness: 13 mm,
- image matrix: 80×80 pixels, where each pixel represented an area 3×3 mm.

In his first scanner, Hounsfield used a reconstruction algorithm, which is known today as the algebraic reconstruction technique (ART).

In April 1972, at a seminar at the British Institute of Radiology, Hounsfield formally presented the results he had obtained using the EMI scanner, and descriptions of the device appeared in many publications, including for example in the *British Journal of Radiology* [1, 3].

After these first successes, Hounsfield's group continued its research at the Atkinson Morley's Hospital and at The National Hospital, Queen Square in London. At this point, the fascinating story of the development of computed tomography began to gather momentum; numerous neurologists, radiologists, physicists, engineers and data processing specialists all started working on methods of obtaining and interpreting tomographic images.

By the end of 1973, the first commercial CT scanner was on the market; this was the EMI CT 1000, a development of the Mark I computer (see Fig. 2.8).⁶ Due to the increased pace of development, in the course of 1973, the time to acquire an

⁶ The Homepage of the Japan Industries Association of Radiological Systems (JIRA) and Sumio Makino: *Key words for success or failure of enterprises—From case study of X-ray CT business*, Japan Planning Center.

image was reduced to 20 s. Next, the number of detectors was increased to 30; this allowed the acquisition of a reconstructed image with a resolution of 320×320 pixels.

From the very beginning, computed tomography was commercially significant. Six EMI CT 1000 models were sold in 1973, two of them to the United States, and

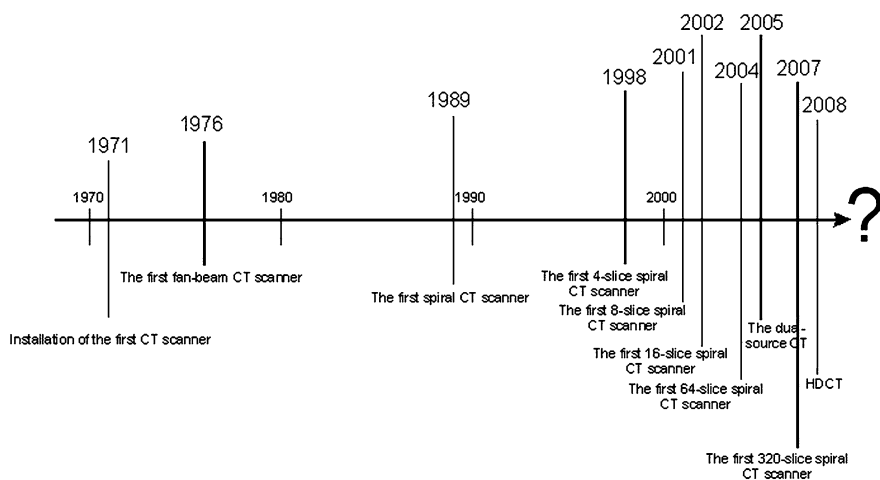


Fig. 2.9 Turning points in the history of computed tomography

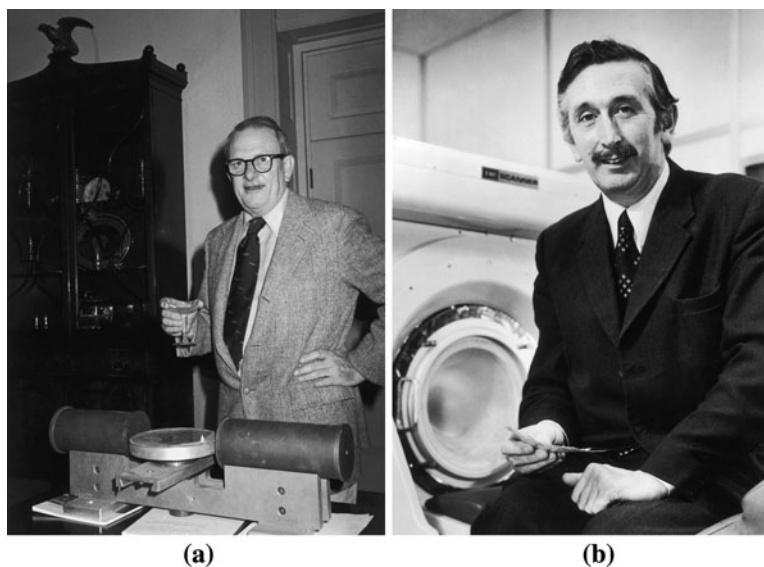


Fig. 2.10 Co-creators of computed tomography: Allan MacLead Cormack (a), Godfrey Newbold Hounsfield (b)

each for the not inconsiderable sum of approximately £100,000. In the course of the following two years, the market for CT scanners reached a value of about £40,000,000.

In 1974, competition for the EMI scanner appeared in the form of designs by such firms as Neurscan (head scanner) and Disco (whole body scanner). The year 1975 brought an avalanche of different models. Unfortunately, the production capacity of EMI did not allow it to hold on to its leading position, which was soon taken by such giants as Technicare and General Electric, who quickly took a major share of the scanner market. Manufacturers from continental Europe, such as Siemens and Philips (in 1974 and 1975, respectively) soon followed in the footsteps of the Americans. They all joined in the race to capture as much of this very important medical technology market as possible.

If we compare the first scanners with today's successors, it is striking how much progress has been made in their design and manufacture in such an extremely short time. Contemporary CT scanners can scan in a few hundred milliseconds and reconstruct an image of 2048×2048 pixels. The most important events in the history of the development of computed tomography are shown on a timeline in Fig. 2.9.

Finally, it is also interesting to note that the two people, who are recognised by historians of science as the fathers of computed tomography (see Fig. 2.10a and 2.10b), only met each other for the first time in 1979 at the presentation ceremony, where they jointly received the Nobel Prize in Psychology or Medicine.

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