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*To my Parents*

# Preface

This book is an attempt at a comprehensive treatment of those medical imaging techniques commonly referred to as Computed Tomography (CT) and sometimes known as Computerised Tomography, which rely on X-rays for their action. As this is a place to explain my reasons for writing the book, I would like to begin by assuring the reader of my passion for the medical technology discussed here. My main motivation in publishing this work was a desire to share with the widest possible readership my fascination with the topic. I would expect the target audience for this account to be primarily academics, students and technicians involved with biomedical engineering, as well as doctors and medical technicians concerned with medical imaging. The structure and content of the book place particular emphasis on issues related to the reconstruction of images from projections, a key problem in tomography. This reflects my area of interest in the field. Other problems will be treated as technical and physical background to the reconstruction algorithms, in so far as is necessary for an understanding of how they work (and perhaps a little more). The reconstruction algorithms covered relate to all the basic designs of tomographic equipment, from the first Hounsfield scanner to the most recent spiral CT devices for reconstructing images in three dimensions. I hope that the summaries of various practical implementations of the algorithms will help people to test the individual reconstruction methods for themselves. The final chapter contains an account of a virtual test environment so that those without access to physical measurement data from a real scanner can carry out these tests. Perhaps it is a good point here to wish you the best of luck.

There is another reason for engaging the reader at this point, in addition to spreading enthusiasm for the subject. It is to thank those particularly who have made significant contributions to the conception of "the work". I would like to start with my lecturer Professor Ryszard Tadeusiewicz. It was at his lecture that I first heard about the reconstruction problem. It was then, perhaps thanks to his eloquence, that I was quite simply struck by the "beauty" of the problem. The second person who, in my academic life, had a decisive influence on the direction of my research was Professor Leszek Rutkowski. He, as my academic supervisor, always gave me enough freedom to choose the direction of my own interests.

However, I also cannot forget those individuals and institutions that, during the writing of this monograph, enabled me to bring the project to fruition. Amongst these I would like to stress the contribution of Dr. Marek Waligóra from the Private Health Care Group “Unimed” in Czestochowa, who provided me with the tomographic images contained in the book, and offered advice on all contentious medical issues. I would like to thank Mr Marcin Gabryel for his assistance in preparing the program listings included in the book. These should prove very useful to those wishing to test the reconstruction algorithms described here. I would also like to offer my special thanks to Japan Industries Association of Radiological Systems (JIRA) and Sumio Makino for allowing the publication of historical photographs related to the development of computed tomography techniques. A significant role was also played by Ms. Claire Protherough, on behalf of Springer Publishing. She showed great patience with such an ill-disciplined author as myself and took such care during the editorial work on the publication. This book would probably not have arisen at all without Mike Butynski, who not only translated the text from the Polish language but also, thanks to his physics background, helped me with many of the basic problems that arose during the writing of this monograph. Thank you, Mike, for the heart that you put into the book. To others not mentioned here by name, but who helped with this work, I apologise and ask for understanding.

In conclusion, I would like to hope, dear reader, that you are willing to spare the book a moment of your attention and not regard it as time ill spent.

Częstochowa, March 2010 Robert Cierniak

# Contents

# Chapter 1
# Introduction

Only a few devices in the rich arsenal of medical equipment can match the popularity of the computed tomography scanner (or CT scanner). Its invention undoubtedly initiated a revolution in diagnostic technology by allowing us to look inside a person and obtain a very clear anatomical image without violating the outer surface of his body, in other words, non-invasively. Throughout the industrialised world, it would be difficult to find anyone who was not familiar with CT scanning either personally or indirectly, perhaps via an acquaintance or a popular science television programme.

Anyone who encounters CT is amazed by its research possibilities and its diagnostic precision. However, the CT scanner is more than just a collection of technical solutions or an example of a successful implementation of long-term biomedical engineering research. This wonderful instrument unquestionably represents the embodiment of the power of human thought and the proud spirit of man, who throughout the ages has worked on the problem of how to look inside his earthly form without the use of a scalpel and without causing haemorrhaging. When we stand before such a complex machine, we find ourselves asking: where does this seemingly inconceivable idea come from, this bloodless "cutting" of a person slice by slice, then to reassemble the slices to describe in detail the result of this incredible journey deep into the human body? It is worth therefore looking a little closer at this piece of medical history, to have a more complete understanding of the field of tomography.

The examination of a person's anatomy, as a preliminary to performing various diagnostic procedures, is a technique that has been used for centuries. However, people have not always been convinced that it was necessary to know about the structure of the human body, let alone about the physical diagnosis of internal illnesses. The belief in a link between the body and the suffering of sick people probably arose by the way of observation of the changes that occurred in the appearance of people afflicted with various kinds of illness. This also probably aroused a curiosity about the structure of the human body, the operation of its individual parts, and the links between symptoms and the pattern of pathology. A number of historical sources indicate that people first investigated the internal

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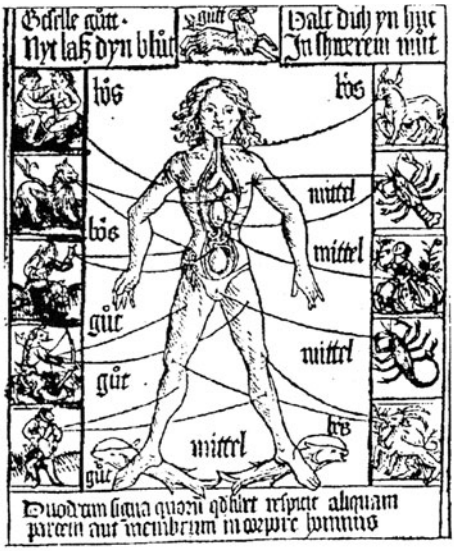

**Fig. 1.1** The transcendental human

structure of the body through human dissection, a process that aroused ambivalent emotions.[1] Dissections were probably already being performed in ancient times by scholars such as Alcmeon, Erasistratus, Galen and Herophilos of Alexandria.

In the middle ages, there was a reluctance to continue this earlier work and so there was a reduction in the number of such procedures performed. At that time, people perceived the human body to be the seat of the soul and thus the property of the Creator. They endowed it with a kind of inviolability clause and surrounded it with a special taboo. It was forbidden to carry out any kind of human dissection, thereby removing the only possible source of knowledge about the human anatomy at that time. Until the sixteenth century, therefore, the only available description of the inside of a person was the ancient work of Galen *De usu patrium*, based on which people created a variety of ideas about the human body, its nature and structure (see Fig. 1.1).

A fundamental shift in the perception of the body and knowledge of anatomy came with the renaissance. The new ideological and philosophical trends of this period very much favoured anthropological research. It is significant, for those interested in human affairs, that it was at this time that geographical exploration was being carried out on a large scale. In the course of their distant journeys, travellers discovered new lands, previously unknown animal and plant species, and, in the eyes of people from the Old World, strange peoples with strange customs and different attitudes to the body. These journeys had a great effect on European imagination and consciousness. Differences between peoples not only

[1] The word tomography comes from the Greek words *tomos*, meaning slice, and *graphia*, meaning writing or description.

aroused curiosity but also induced a deeper reflection on their own organism and its structure.

At the turn of the fifteenth and sixteenth centuries, people began to perform dissections openly. Yet secret dissections had already taken place earlier, in fifteenth century Florence. Leonardo da Vinci carried out 30 such procedures in 1470, producing descriptions and drawings. However, it was Andreas Vesalius, professor of medicine at the University of Padua, who profoundly transformed our way of thinking about the nature of man. In 1543, he published his work *De humani corporis fabrica*. It signalled a revolution in the understanding of man and his body. Anthropologists started to think of homo sapiens exclusively as an arrangement of bones and muscles, disregarding those elements of human nature, important to medieval scholars, which were supposed to emphasize the relationship of the human being with the Transcendent. The renaissance conception of man as a carnal being was dominant for many centuries. The development of empirical investigation of the body and the observation of variations in the structure of tissues permitted the drawing of conclusions about the normal and abnormal functioning of the human organism. This, in turn, led to the evolution of the field of medicine known today as pathophysiology.

Of course, pathophysiology owes a great deal to a certain accidental discovery by Wilhelm Conrad Röntgen at the end of the nineteenth century, that is, to the discovery of X-rays. Thanks to pictures taken using röntgen radiation, it was now possible to look at the internal organism of a person without violating the outer surface of his body (see Fig. 1.2). The use of X-ray apparatus to diagnose many serious illnesses and complex post-traumatic complications quickly became standard clinical practice. This type of apparatus still forms the basic equipment of departments of imaging diagnostics in hospitals, and devices making use of X-rays in varying degrees find their application in operating theatres, dental practices or even mobile mammographic screening units. Moreover, although it soon transpired that X-radiation is harmful to the human organism, this did not alter the fact that its impact on our understanding of the human interior was nothing less than

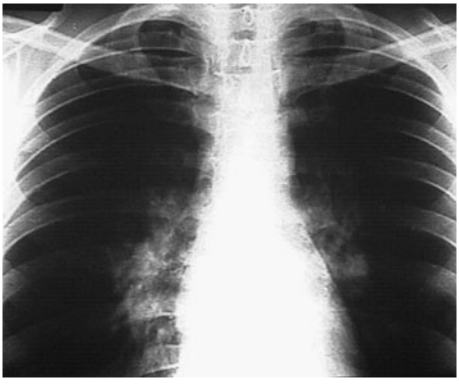

**Fig. 1.2** X-ray picture of a chest

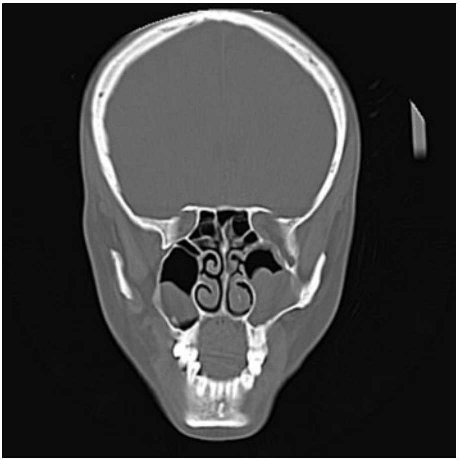

**Fig. 1.3** Tomographic image of the sinuses in the frontal plane

astonishing. With time, one of the more important applications of this radiation turned out to be CT.

If we compare the use of X-ray techniques in medicine to the revolution that brought about the industrial age, then we can certainly argue that the formulation of the principles of computed tomography and the design of the CT scanner is evidence of the arrival of a new period in the history of knowledge and technology: the third phase, the information age.[2] The arrival of a new era inevitably involves the enrichment of familiar earlier technologies with new ideas and their practical application. In the case of CT, this has meant the application of not only X-rays but also of the mathematical algorithms that allow the reconstruction of an image of any given cross-section of a person's body. By suitably arranging a set of these cross-sections, it is possible to visualise, in three dimensions, the anatomical structure of any part of a human body. A spatial image such as this is of enormous help in medical diagnosis. An example of a tomographic cross-section is shown in Fig. 1.3.[3]

Tomographic examination is currently one of the basic techniques of medical diagnosis. Indeed, the significance of tomographic techniques in contemporary medicine is clearly demonstrated by the fact that when this type of apparatus in a hospital breaks down, doctors will avoid making a definitive diagnosis until an examination can be carried out in another centre.

This book is an attempt at a comprehensive and detailed portrayal of the subject of X-ray CT, beginning with its history, followed by its physical and technical concepts, its parameters and principles of operation, and concluding with methods of solving the image reconstruction problem. Much space is devoted to this last issue because it is of fundamental significance for the operation of the equipment,

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[2] Toffler A.: *The third wave*. Bantam Books, New York, 1980

[3] Image made available by the Private Health Care Group "Unimed", Czestochowa, Poland.

whereas a more modest amount of space is devoted to the section discussing the physical and technical concepts. The aim of the chapters on the technical aspects of CT scanners is to raise awareness of the nature of the image reconstruction problem. Chapters 3 and 4 therefore are concerned with topics relating to the construction of CT scanners and the physics of their operation. This then allows us to formulate the reconstruction problem for every type of projection system.

Chapter 9 completes the remaining two parts of the work, discussing the technical parameters describing practical CT scanners, together with methods and procedures for determining values that indicate the quality of the reconstructed image.

The fundamental issue of image reconstruction methods has been organised by taking into consideration the two most important approaches: transformation (analytical) reconstruction methods and algebraic reconstruction techniques (ART). The first of these methods is covered in Chaps. 5, 6 and 7, while the second is covered in Chap. 8.

The prevalence of certain transformation reconstruction methods in practical scanners has meant that Chaps. 5, 6 and 7 are dominated by discussion of algorithms. Chapter 5 also considers issues that are fundamental for other approaches to solve the reconstruction problem. ART algorithms are considered in Chap. 8. Chapter 10 contains descriptions of standard methods of obtaining projection values using mathematical modelling. These are extremely useful for carrying out computer simulations of various types of projection systems.

Finally, I hope that you will share, at least to some degree, my passion for the subject of this book and that you will kindly forgive any possible mistakes that you may find. As the medieval scribes used to say, "God did not create this, but the hand of a sinner". Following their example and after wishing you a fruitful read, there only remains for me to say:

> I beg you dear reader if you find any mistake or shortcoming [...] don't despise me because of my human frailty, but forgive me all and that shortcoming or error correct.[4]

[4] *The Liturgikon*, pp. 1727–1738, Supraśl, Poland

# 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.

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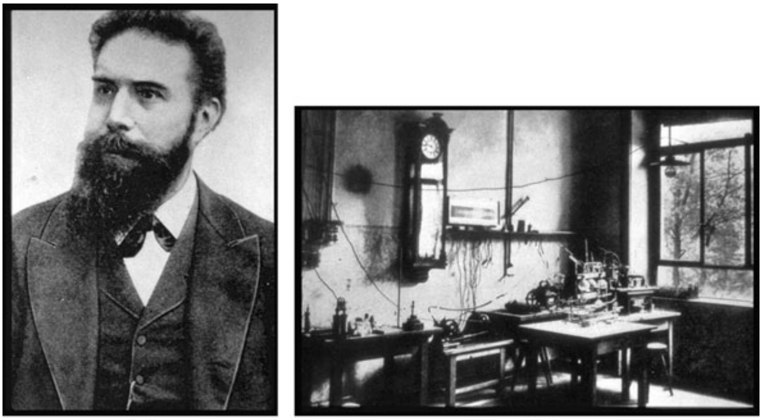


(a) (b)

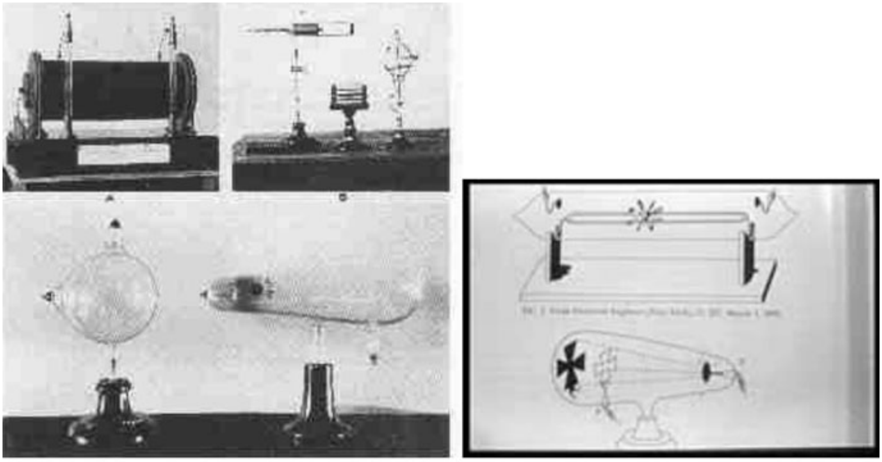
**Fig. 2.1** Wilhelm C. Röntgen (**a**) and the room where he discovered X-rays (**b**)

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 the 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.



(a) (b)

**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 á 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 Plant, 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.

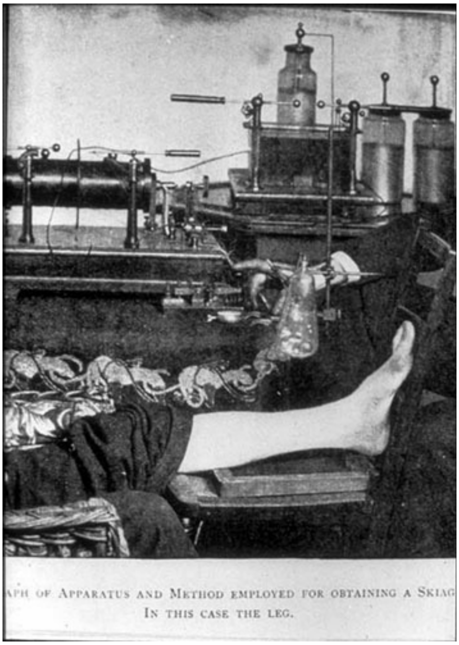



**Fig. 2.4** X-ray room from the early years of radiography

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 stones[2] 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 2.5[4] 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.

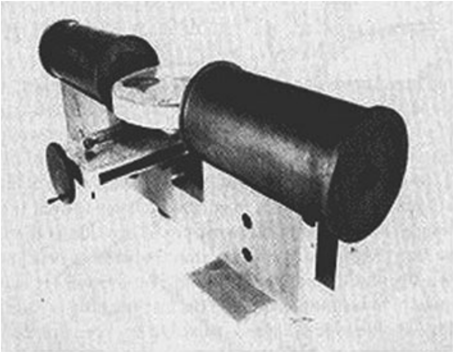


**Fig. 2.5** Tomographic device built by Cormack in 1963

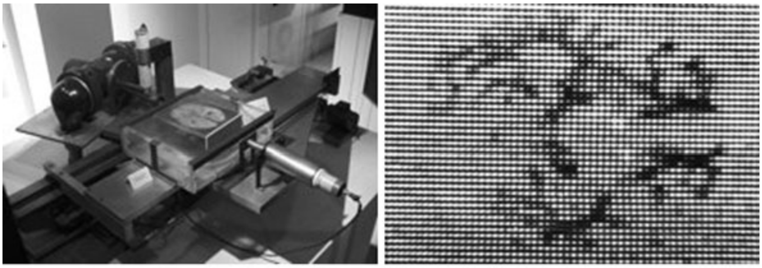
Cormack published the results of his research in an article entitled *Representation of a Function by its Line Integrals*, in *The Journal of Applied Physics* and later in *Physics of Medical Biology* [2].

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 $80 \times 80$ pixels (see Fig. 2.6b). Hounsfield finally patented his device in 1968.

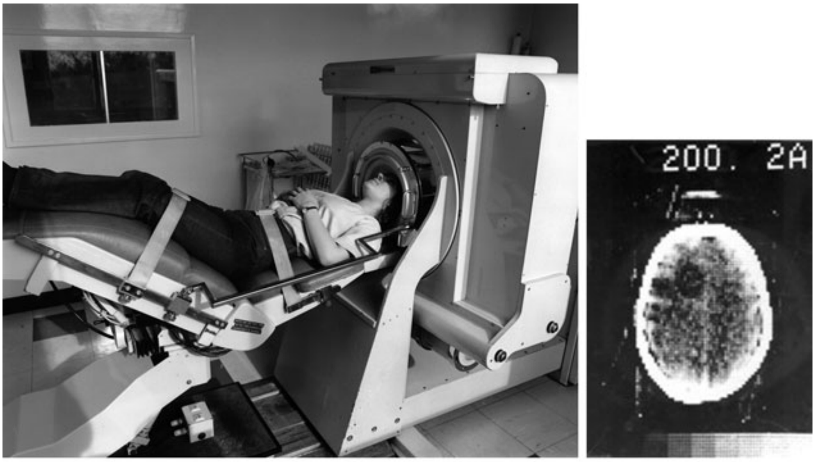
In order to confirm the results of his initial research, further experimental work was necessary, this time using living tissues. Hounsfield also took the opportunity

[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.



(a) (b)

**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**)



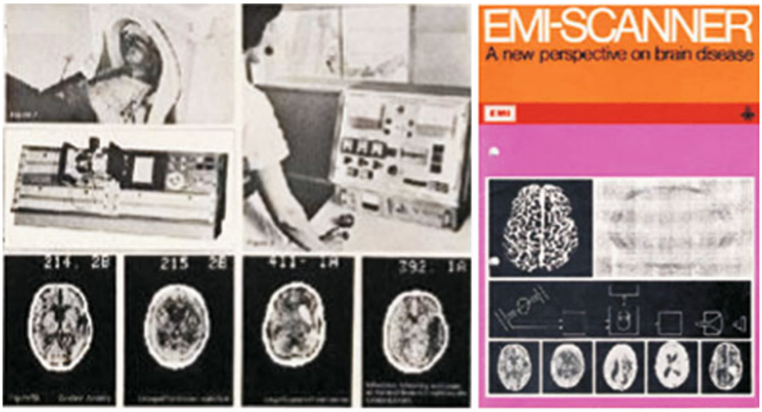

(a) (b)

**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




(a) (b)

**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

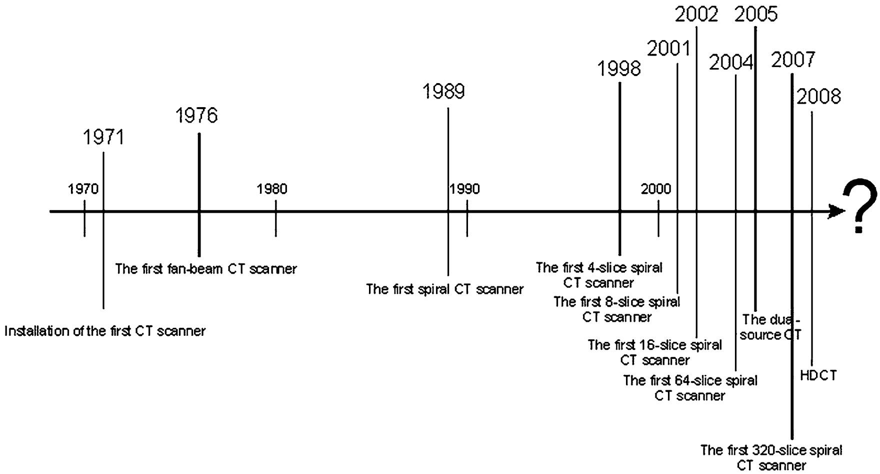



**Fig. 2.9** Turning points in the history of computed tomography

(a) (b)

**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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# Chapter 3
# Technical Concepts of X-ray Computed Tomography Scanners

Medical examinations using computed tomography are currently standard hospital practice. Back in the 1980s, its use was relatively rare, and was available only in a limited number of specialised medical centres. Today it is hard to imagine medical diagnosis without it.

Nowadays, hospitals in most major cities are equipped with CT devices. They are deployed, taking into account the prevailing demographic situation, so that optimal use is made of the equipment and the time needed for a patient to reach a centre is minimised. Computed tomography is used in the diagnosis of many conditions, both chronic and acute.

The installation of a CT scanner requires complex preparatory work. For a medical centre to be able to carry out on-site tomographic examinations, it must first adapt a suite of rooms for the purpose. The CT room must meet several requirements

- it must have floors with adequate load-carrying capacity,
- its walls must be constructed of X-ray absorbing material (this is usually a barium (Ba) plaster),
- the floor should be lined with material that is both anti-slip and antistatic.

Separate rooms should be provided for the CT scanner and for the radiographers; the rooms must be separated from each other by special window-glass (containing lead, Pb), to protect against X-rays. In addition, a suite of CT rooms must comply with all the health and welfare regulations, which are typically required for units carrying out medical X-ray examinations. A typical CT suite showing the location of the various elements of the scanner is illustrated in Fig. 3.1.

We can consider the CT scanner as being composed of two layers: the computer layer and the physical layer. The computer layer consists of the operating system[1] responsible for running the tomography application, file management and communication with external devices; and the tomography application itself. The latter

[1] As a rule, the UNIX operating system.

R. Cierniak, *X-Ray Computed Tomography in Biomedical Engineering*,
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