F. Jensen[1])

100 years of X-rays

The phenomenon that Wilhelm Conrad Roentgen, soon after his discovery, referred to as 'A New Kind of Rays' has, as we now know, existed since the beginning of the universe. It has been involved in all stages of the development of the cosmos right up to the present day. However humans were unaware of the existence of these rays.

Since their discovery, one hundred years ago, human beings have been able to create these rays artificially, modify them, and make appropriate use of them. Over the intervening century, many applications have extended into very different areas of our lives, and have gained in significance. Even today, this development is still in full swing.

The discovery

Roentgen described the discovery of the hitherto unknown rays as happening by chance. He had not been searching for them, as one might on the basis of a theory, or hypotheses derived from the theory. When he discovered them, on 8 November 1895, he was engaged in investigating the problems of gas discharge in evacuated glass vessels (Hittorf and Crookes tubes) and the associated emission of cathode rays (cathode rays are electrons, released by gas ions when they impinge on the cathode).

Roentgen's outstanding achievement is his thorough research into the *cause* of the incidental observation, during his experiments, of the fluorescence of a barium platinocyanide screen, which happened to be nearby, and which was shielded by black cardboard from the light produced in the discharge tube.

In a few days of systematic experimentation Roentgen had investigated the astounding

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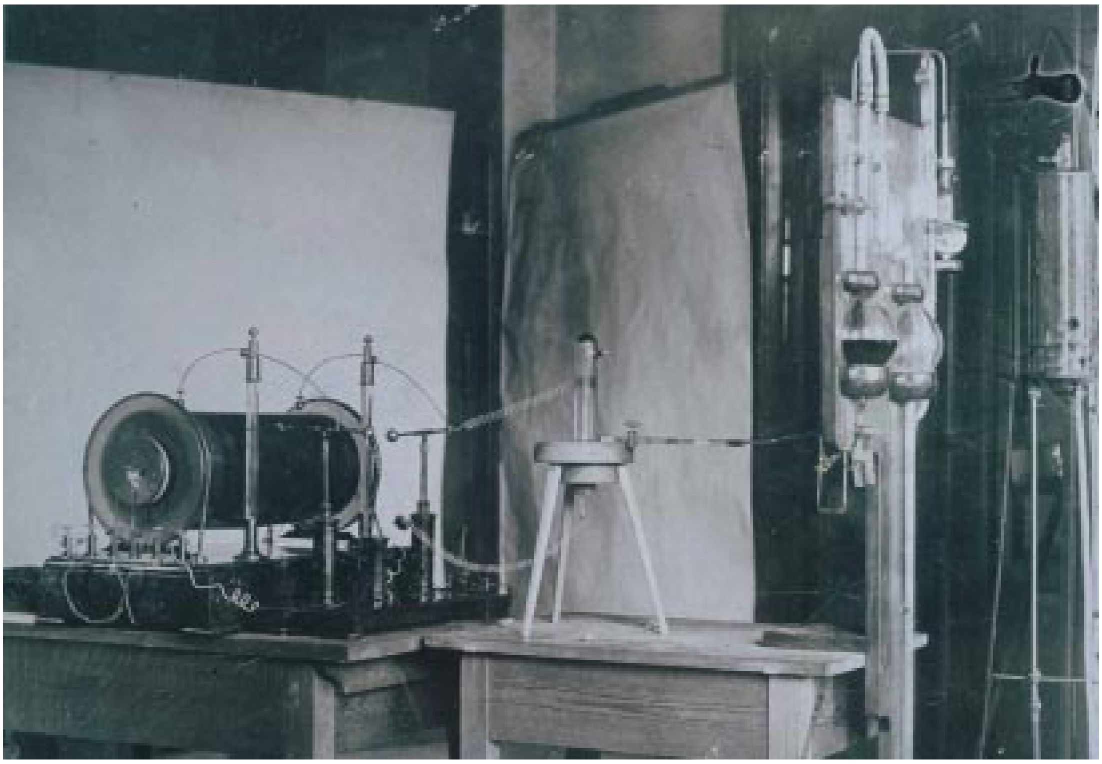

Fig. 1. Reconstruction of Roentgen's original experiment, at the time of the original discovery.

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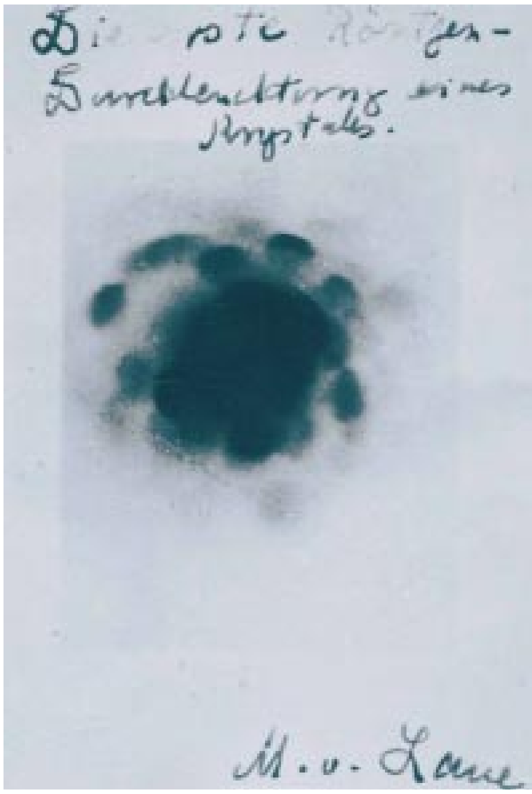

Fig. 2. Radiograph of Mrs Roentgen's hand.

Fig. 3. Interference due to diffraction in a crystal lattice (1912).

manifestation so thoroughly that the first publication of his classic paper 'Ueber eine neue Art von Strahlen' (On a New Kind of Rays) could be handed in to the Würzburg Physico-Medical Society on 28 December 1895. The text already described, with admirable completeness and clarity, the most significant characteristics of the radiation which would be of importance for their later application:

- the point from which the X-rays are emitted was described as that position 'where the cathode rays impinge on the glass wall of the discharge apparatus'
- the propagation of the rays in straight lines, the different absorption in various materials and the production of shadow images from within opaque materials were reported
- shadow images could be made visible and recorded by means of the fluorescence of various substances (not only barium platino-cyanide) and the blackening of photographic plates
- the rays are invisible to the human eye (at least in the intensity available at that time), and their propagation cannot be influenced by magnetic or electrical fields.

As early as March 1896, a second communication followed with an extensive report on the fact that 'gases irradiated with X-rays acquire the property of discharging an electroscope. The efficiency of radiation production of various anode materials was also described.

The third and final communication by Roentgen appeared in May 1897. It contained reports on the phenomena of scattering, measurements of the radiation intensity using a photometer, and the directional distribution of the intensity in the X-ray beam. The penetration of the rays as a function of the vacuum in the discharge tube was described, as well as the hardening of the radiation after passing through the first absorbent layers.

Roentgen issued no subsequent reports on further investigations into the rays and, apparently, he did not concern himself with technical developments for the production of X-rays or their practical application.

Roentgen's interest in physics lay in many other areas. Among his sixty publications, some of which were of fundamental importance, only the three cited here were on the 'new kind of rays', while a further three communications were on the electrical conductivity of crystals and the way in which it is affected by radiation.

The many scientists who subsequently concerned themselves with the new rays added nothing of significance to the properties described by Roentgen for the next ten years.

The spread of the discovery

The report on the discovery of the 'mysterious' rays created a great sensation, and spread rapidly. Actually 'working with X-rays' also attracted great interest and became widespread in many countries within a very short time. Roentgen's original communication was available as a preprint by new year 1896, and was published on 28 January. The first report in the press appeared on 5 January 1896 in Vienna, and days later in Würzburg and Berlin, as well as in England and the USA.

As the necessary apparatus was already available in many laboratories, X-ray exposures were made in many places within the first few weeks following the initial report.

Of all the properties of X-rays, the ability to make the invisible visible was, understandably, the most fascinating. For this reason the principal theme of further investigations and publications was, for several years, images of anatomical and technical objects.

Today, one hundred years later, the production of fluoroscopic images and radiographs is still the most frequent and best known use of X-rays, albeit it with significant improvements in the technical means, and a corresponding increase in the information content.

X-rays in science, technology and medicine

The investigation of X-rays and their application has increased our knowledge in many fields, and has had a positive effect on our lives. The increase in knowledge applies to our understanding of the composition and structure of matter, as well as the structure and development of the universe.

Many important advances in technology are due to the application of X-rays, and the same is true of developments in modern biology. The development of medicine during this century would have been unthinkable without the fundamental knowledge of both anatomy and physiology that has been gained by the use of X-rays, and for many decades radiology has played a significant role in medical diagnostics. Many examination and treatment techniques which are now part of routine practice have their origins in the application of X-rays to human beings. These aspects will be dealt with briefly below, within the limitations imposed by the scope of this article.

The structure of matter

In 1912, as part of his investigations into the nature of X-rays, M. von Laue instigated experiments on diffraction and interference in crystal lattices, which were successfully continued by his colleagues W. Friedrich and P. Knipping. The investigations demonstrated the wave-like nature of the rays. On the other hand, the diffraction and interference patterns also yielded information on the structure and composition of the crystals used. The techniques were further developed W.H. Bragg, W.L Bragg, P. Debye, P.H. Scherrer and others. Their work led to the development of fundamental methods for crystal structure analysis and X-ray spectrum analysis. Such investigations, together with the measuring systems developed for them, provided important new knowledge and techniques for routine analysis. Scatter and interference investigations with X-rays also provided the basis for the model of the atom developed by N. Bohr and E. Rutherford. However, the investigations into scatter by A.H. Compton could only be explained if the rays were composed of discrete particles. This provided the starting point for the development of the hypothesis of wave-particle dualism in physical phenomena, as well as for the theories of relativity.

More recently, it has even become possible to observe the interior of cells and the chromosomes with the aid of an X-ray microscope. This has a superior resolution to that of the optical microscope but, unlike the electron microscope, it does not affect the object observed. In this case, diffraction gratings are used to create the image.

Cosmology

Our knowledge of the macroscopic world also owes much to work done with X-rays. In the energetic processes that take place in stellar material, the effects produced include the emission of X-rays. Due to the atmosphere, these rays do not reach the surface of the Earth, but they can be measured via space probes and satellites. Analysis of the radiation provides information on the elementary processes taking place in the stars, and the composition of the matter present there. Many objects in space, from which no visible light reaches us, are detected by X-ray telescopes in which the X-rays are focused by means of reflective surfaces. Since satellites have become available, X-ray astronomy has yielded particularly rich data for cosmology.

X-rays, as a tool or aid, have also provided important knowledge and progress in other fields, including metallurgy, geology, archeology and even research into art objects.

Security in technology

The first demonstrations with the newly discovered rays, even in 1895, showed images of a set of weights in a closed wooden box. From this beginning, the concept of nondestructive testing of materials was developed, with

Fig. 4. Radiography of critical components to ensure freedom from cracks and cavities.
a. *Automated fluoroscopic inspection.*
b. *Compton backscatter measurement.*

4a

4b

apparatus and ancillary equipment specially designed for the purpose. Critical components with respect to safety (beams, welds, vehicle and aircraft parts) began to be regularly tested to ensure their perfect condition (exclusion of cracks and cavities). Fluoroscopy and radiography were performed, in part, with automatic evaluation. Checking the contents of freight and baggage in air travel is a further, present-day example in security applications. In many cases nowadays, radioactive emitters and ultrasound are also used for materials testing. These alternative methods have their advantages in certain applications, but the impulse for their use began with the work with X-rays.

Radiation biology

The science of the effects of ionizing radiation on cells, tissues and organisms has its origin in extensive investigations with X-rays, to which we owe important knowledge with respect to cell growth, radiation damage, mutations and genetics.

Radiation biology provides the scientific basis for both radiation therapy and radiation protection.

Radiation therapy

Skin damage arising from careless use of X-rays led to very early recognition of their harmful effect on human tissue. For this reason, doctors tried in the first years after their discovery to use X-rays for the treatment of skin diseases. Apart from a few incidental results, there was very often damage as well, due to the lack of any concept of correct dosage, and the absence of possibilities for accurate dose measurement.

In 1902, Holzknecht succeeded in using the discoloration of crystals under the influence of radiation as a method of dose measurement.

In 1902/3 a number of physicians began the systematic use of radiation for the treatment of carcinoma. In principle, however, significant results only began to be achieved in the course of time, after the necessary experience had been gained with respect to the 'correct' dosage, exact dosimetry, and suitable methods for accurately applying the required radiation dose to the focus of the disease, while to a great extent sparing the surrounding healthy tissue.

Today, there are tried and tested techniques available for dose measurement with ionization chambers, as well as solid-state dosimeters.

The following methods have been successfully employed for achieving the desired dose distribution:

- variation of the penetration in the tissue by selection of the radiation energy with the aid of tube voltage and radiation filtration, as well as by varying the focus-skin distance
- crossfire and moving-beam irradiation
- intracavitary application, i.e. positioning the radiation source close to the lesion by using body-cavity tubes or small radioactive sources
- the use of alternative radiation sources with suitable energies and radiation types (gamma emitters, particle accelerators).

Specialized therapy systems have been developed to meet the requirements of increasingly sophisticated applications:

- brachytherapy systems, with low tube voltage and a thin output window, used at extremely short focus-skin distances to treat lesions lying close to the skin surface
- systems with rod-anode tubes for treatment within body cavities
- X-ray systems for deep therapy at tube voltages up to 250 or 300 kV, operating at greater focus-skin distances
- systems for moving-beam therapy
- systems for curie teletherapy with radium, cobalt 60 or caesium 137
- particle accelerators (linear accerator, Betatron) operating at 6 to 25 MeV.

Systems for irradiation with neutrons, protons or pions have so far had no widespread practical application.

From the first attempts to use the damaging effect of ionizing radiation on tissue for the treatment of disease, with all the associated problems, radiation therapy has developed into a method for treating cancer which is successful in many cases. In addition to the highly developed technology of the treatment system listed above, a significant proportion of the success can be attributed to:

- radiobiological research
- exact localization and treatment planning
- and the combination with surgical procedures and/or chemotherapy.

X-ray diagnostics

Immediately after the announcement of the discovery of the new rays, the sensational first exposures of a human hand led to a surge of investigations into their diagnostic possibilities among physicians in many countries. In the meantime, the 'images from within the body' have made a major contribution to health care and the medical treatment of mankind.

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Fig. 5. The Philips SL20 linear accelerator.

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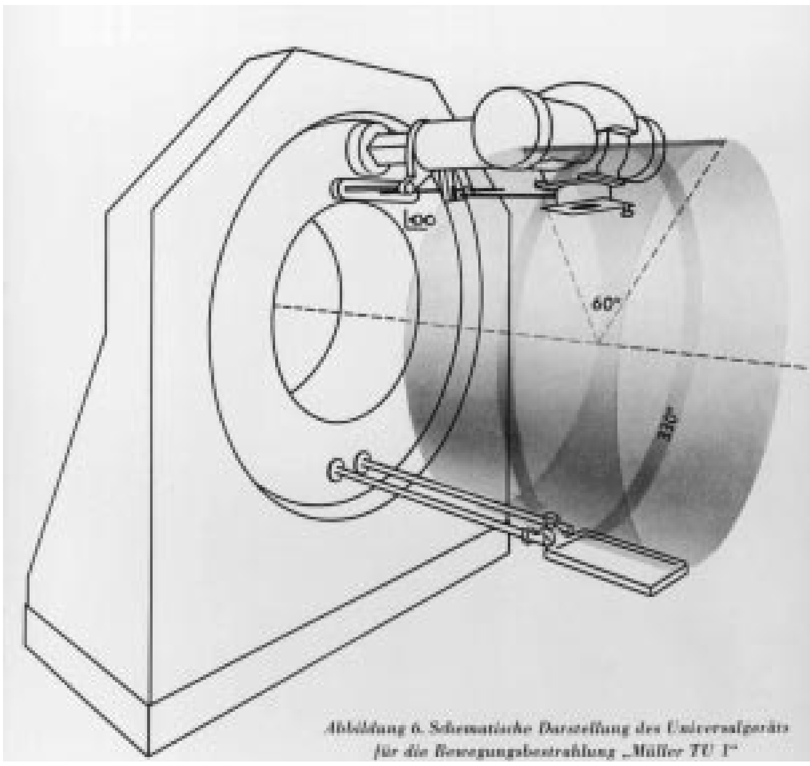

Fig. 6. The TU1 therapy unit.

Fig. 7. High-resolution exposure of a hand.

7

This most frequent application of Roentgen's discovery is also the one that has made the deepest impression on the consciousness of the general public.

X-ray diagnostics has also provided the impetus for the development of diagnostic imaging in the widest sense, with techniques for image acquisition based on other 'probes' such as ultrasound and magnetic resonance.

Development of the technical requirements

The way for the evolution of X-ray diagnostics was prepared by a spectacular improvement in the diagnostically useful information in the image, the possibility of reducing the dose required for individual applications, and the successful adaptation to new diagnostic requirements, with well thought-out examination methods and dedicated workstations. This can be illustrated by a few examples of major advances.

X-ray tubes

The original requirements with respect to improving the quality of the images were aimed at sharpness, contrast, and the differentiation of slight differences in tissue density. In addition, due to the low intensity of the available radiation, the exposure times were significantly too long.

By making numerous improvements and inventions with respect to the original gas-discharge tubes, manufacturers and users developed these tubes - in which X-rays occurred as a chance 'by-product' - into effective X-ray tubes.

In other words, radiation geometry, radiation output and radiation quality all had to be matched more closely to the requirements of imaging.

The technical answers to these various demands were to focus the emission from the cathode, which was previously diffuse, to construct special anticathodes or anodes out of suitable material for a high radiation output, and to provide cooling of the anodes.

Other significant steps were the transition from the ion tube (using the original gas-discharge principle) to the heated cathode tube (W.D. Coolidge, 1913), the line focus (O. Goetze, 1918) and the rotating anode (A. Bouwers 1929).

Further improvements to the X-ray tube were the use of filters to influence the radiation energy, the use of collimators to limit the useful X-ray beam, and mounting the tube in a lead-lined and oil-filled housing for protection against undesirable radiation and high voltage insulation, as well as for improved and problem-free application.

In this way the use of suitable materials and mechanical construction resulted in improvements in the image information, as can be seen by comparing Figures 2 and 7. In addition, the exposure times are now in the range of hundredths of a second, rather than the several

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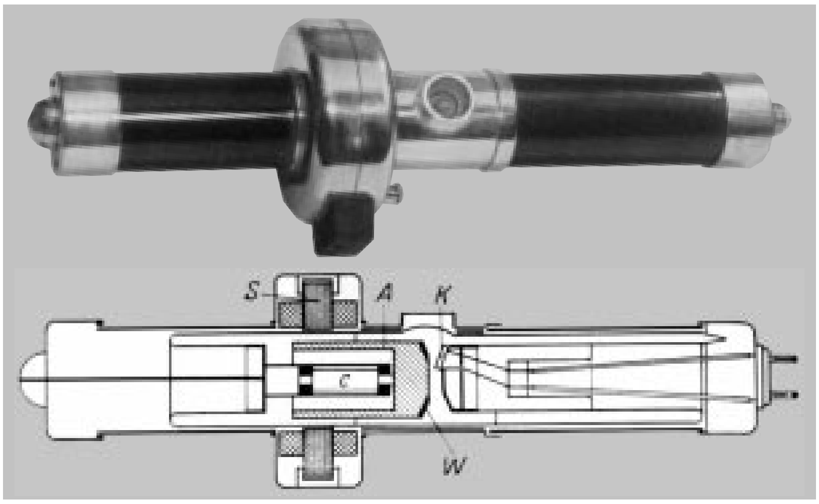

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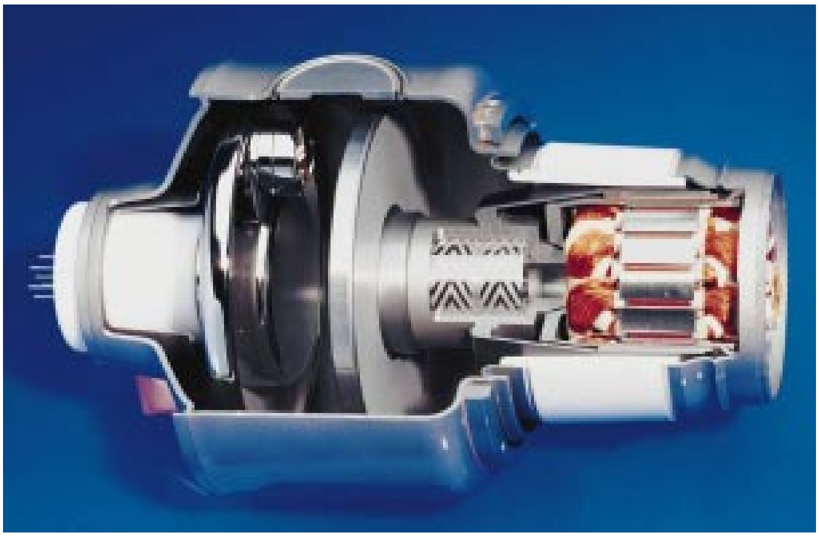


8d

Fig. 8. Stages in the development of the X-ray tube.

a. *Ion tube.*
b. *The first Rotalix tube (1929).*
c. *Super Rotalix tube.*
d. *MRC metal/ceramic tube.*

minutes required with the old ion tubes of the early days.

Figure 8 shows some typical examples of stages in the development of the X-ray tube.

Generators
The original spark induction coil was not really suitable for supplying and controlling efficient X-ray tubes. The requirement for rectified high voltage with minimum ripple, accurately defined voltage levels and exact and very short switching times, led to the construction of high-voltage generators with advanced electronic switching.

These allowed optimum exposures to be achieved with respect to output, the shortest exposure times, tube loadability and simple operation.

Image detector
The high standard of image information achieved today, with ever-lower dose requirements, would be unthinkable without

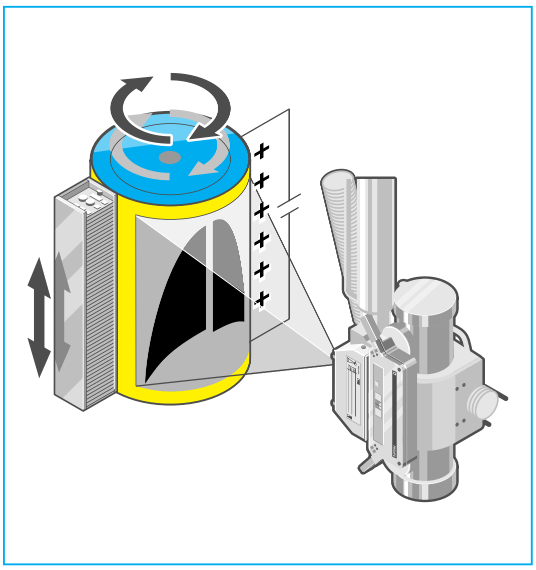
Fig. 9. A specialized diagnostic X-ray system: the Integris system for angiography.

Fig. 10. The Thoravision system.
a. *The complete system.*
b. *The selenium detector drum.*

9

10a

10b



corresponding progress with respect to the image detector.

When the images of the original fluorescent screen, which in many respects were very inadequate, are compared with those obtained with the aid of high-resolution image intensifier/TV systems, it is clear that they not only offer more details with less dose, but also allow better working with patients under good lighting conditions.

It is only in this way that examination technology and procedures can be adapted to the increasingly divergent demands of diagnosis.

In radiography, the results have been vastly improved with the use of high-resolution and highly sensitive film-screen combinations, and with the new possibilities offered by image intensifier fluorography.

Completely new ways of image acquisition, evaluation and communication of the image information are provided by electron-optically readable luminescent storage screens or - very recently - by the use of selenium detectors. In these image detectors, a latent X-ray image is stored, and then read out digitally, point-by-point, and processed by appropriate algorithms in such a way that the exposure range and detail rendition can be optimized within a very wide range.

Figure 10 shows an example of a modern system for chest exposures: the Philips Thoravision. This system has a selenium detector that offers all the advantages of higher detail rendition, together with a wider exposure latitude and immediate availability of the images.

Changes in medical diagnostics under the influence of X-ray images

The spectacular improvements in image quality allowed X-ray images to rapidly become an indispensable aid to medical investigations. The specialized knowledge required soon made medical radiology an important professional discipline in its own right. This discipline has developed under the complementary influences of medical requirements and their technical solutions, but also under the influence of new possibilities offered by the technology and the development of corresponding new examination procedures.

Specific areas of application appeared very early on, for example in skeletal examinations, chest examinations and gastro-intestinal examinations. Special workstations were created for these examinations, to make them easier for both the doctor and the patient, as a result of which the number of examinations that could be carried out also increased.

Diagnostic examinations of the skeleton have retained their importance right up to the present day.

Chest examinations lost some of their share of the applications for a time, due to control of the problem of tuberculosis by intensive preventive examinations and the availability of effective medication, but are now growing in importance again.

In gastro-intestinal work, endoscopy has replaced X-ray in many cases. On the other hand, as before, X-ray examinations are being applied in many other specialties with their own, dedicated workstations, such as urology, neurology, paediatrics and others.

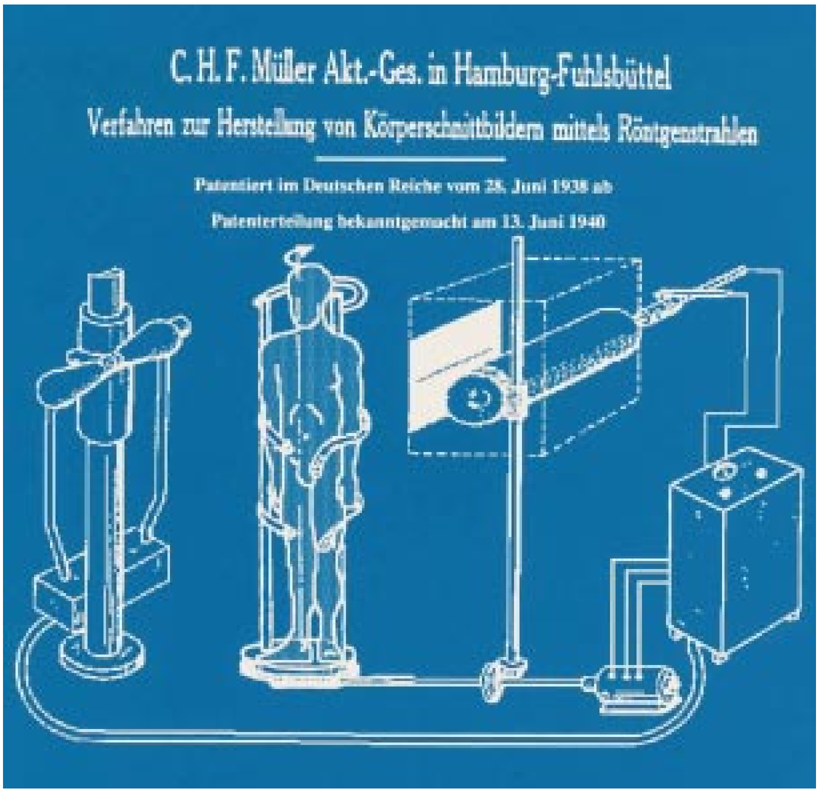


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Fig. 11. Sketch from G. Frank's patent application, showing reconstruction of a cross-sectional image from a large number of absorption values, obtained with a finely collimated beam in many different directions.

In this review, two aspects must be given special prominence: the introduction of reconstruction techniques for slice images, and the stimulation of completely new possibilities for examination and treatment.

Reconstruction techniques for slice images

Creating images of the interior of the body by reconstructing a cross-sectional image from a large number of absorption values, obtained with a finely collimated beam in many different directions, rather by 'projection of a shadow image' was a new and pioneering idea.

This very original idea was, in fact, described as long ago as 1938, by H. Franke in a patent application for C.H.F. Müller GmbH: the company that later became Philips Medizin

Systeme. In this proposal the absorption values would be recorded and reconstructed by an analogue photographic technique. For methodological reasons this did not lead to satisfactory results, and was therefore not realized in practice.

It was not until forty years later that progress in measuring and computer techniques allowed Hounsfield to arrive at a practical solution. Digital measuring techniques and computerized reconstruction of the layer led to the first results. In a very short time refinements in the acquisition technique, suitable algorithms and faster computers provided previously un-

12b

12a

12c

13a

13b

Fig. 12. Computed tomography (CT).
a. *Philips Tomoscan SR 7000 CT system.*
b, c. *CT images showing high tissue discrimination and detail recognition in the abdominal region and the spine.*

Fig. 13. Magnetic resonance imaging (MRI).
a. *Philips Gyroscan NT MR system.*
b, c, d. *MR images showing the improved representation of soft tissues.*

dreamed of images of soft tissue.

For this reason, computed tomography rapidly became of paramount importance in neuroradiology and examinations of the internal organs. Costs, as well as stress and risks for both patient and examiner, could be significantly reduced. Diagnoses of changes in soft tissue could be made with greater certainty with a reduced quantity of contrast medium, or even without contrast medium (Fig. 12).

New possibilities

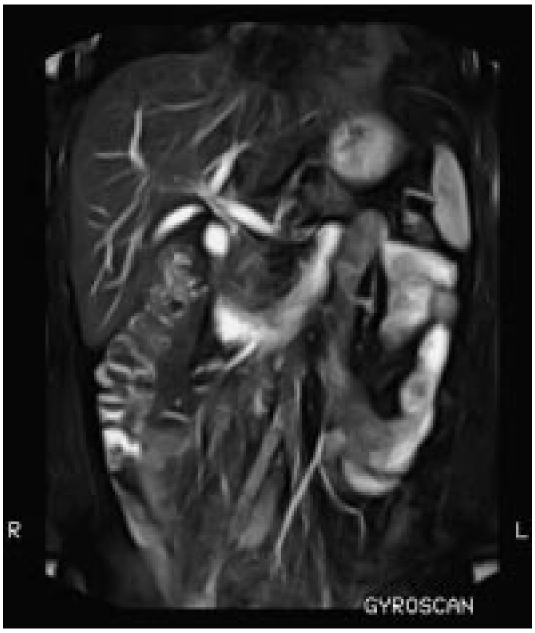
Just as computed tomography benefited from parallel developments in measuring techniques, software and computers, the methods were also successfully employed in other techniques.

Under the impetus of the preparatory work done on slice image reconstruction in computed tomography, the phenomena of nuclear magnetic resonance, which had been used in chemical anlysis since 1946, could be developed into magnetic resonance imaging (MRI). This technique has been in routine clinical use since the beginning of the 1980's, and has partly replaced CT due to its even better representation of soft tissues (Fig. 13).

The same reconstruction principles are also used in even newer techniques, such as the imaging of tiny electrical currents in the brain or heart (SQUID), which is now entering practical application (Fig. 14).

An additional significant contribution is made by the advances in computer image processing. Reconstruction in new planes and

13c



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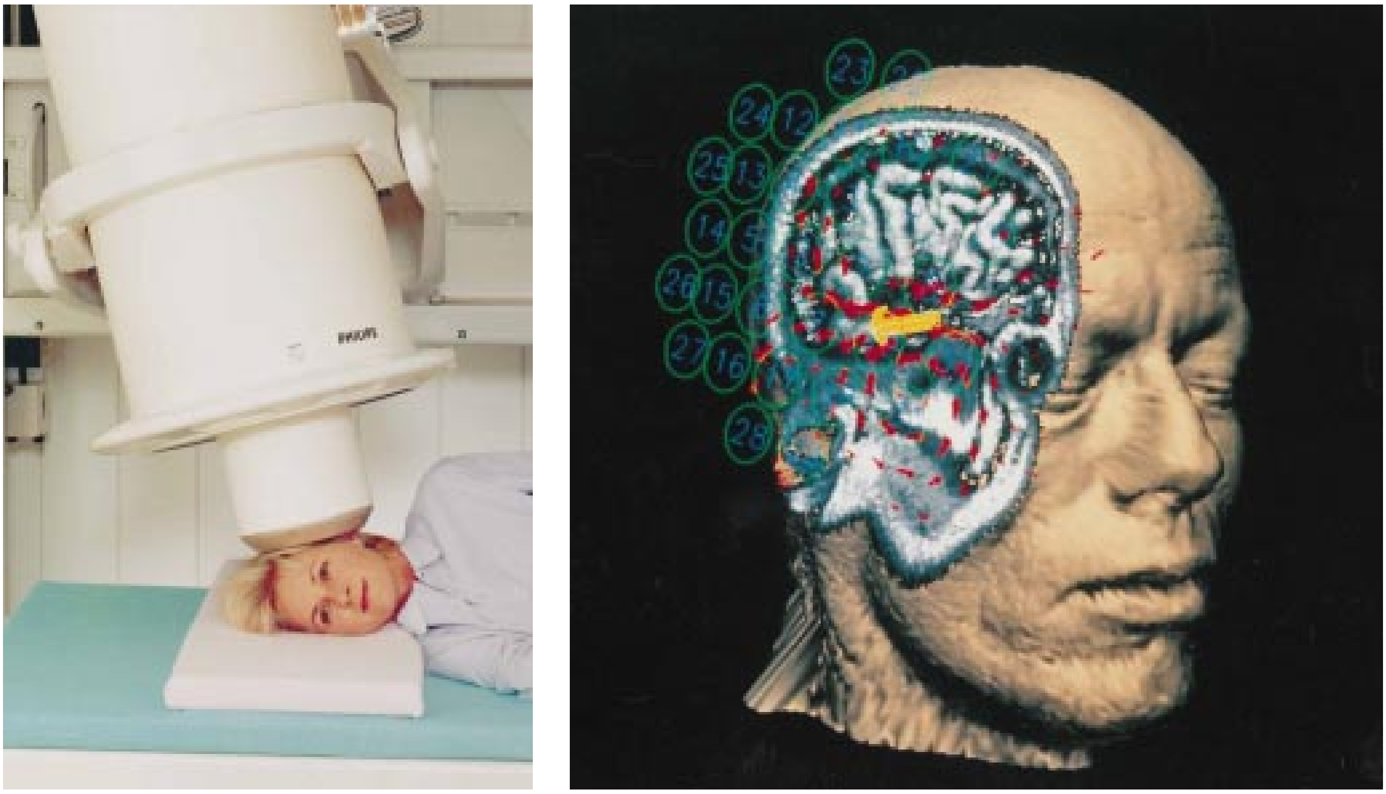

Fig. 14. Magneto-encephalograpy using superconducting quantum interference devices (SQUIDs).
a. *Acquisition.*
b. *Reconstructed image showing the electrical current dipoles in the brain.*

projections, representations of organs ‘dissected’ free from their surroundings, and superimposition and synthesis of information from various sources (matching) have all become possible.

Radiology, which once broke away from surgery to become a separate specialty, now offers the possibility of image-guided interventions, opening the door to noninvasive or minimally invasive techniques from which much can be expected in the future.

All of this began with W.C. Roentgen’s ‘accidental’ discovery, more than one hundred years ago, and has been kept going by the high-level technology which it stimulated, leading to a series of successful developments in which the Philips company has made a very significant contribution, from the very beginning right up to the present day.