The art of medical imaging: Philips and the evolution of medical X-ray technology

J.A.M. Hofman Former Marketing Director, Universal RF Systems, Philips Healthcare

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Figure 1. Gerard Philips (1858-1942).

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Figure 2. Anton Philips (1874-1951).

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Figure 3. Carl Heinrich Florenz Müller (1845-1912).

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Figure 4. Wilhelm Conrad Röntgen (1845-1923).

The history of Philips' involvement in X-ray technology begins with the history of two companies: Philips, in Eindhoven, the Netherlands, and C.H.F. Müller in Hamburg, Germany. Together, these two companies played a major role in the development of X-ray technology.

Because it would be impossible to deal with every new development within the context of a single article, we have selected a series of milestones, illustrated by typical products from each era.

Philips

In 1891 Gerard Philips, backed by his father, founded a company in Eindhoven for the manufacture of incandescent light bulbs.
In 1895, Gerard's brother Anton also joined the company to support the commercial activities.

During World War I, when it became increasingly difficult for physicians in many European countries to have their defective X-ray tubes repaired or replaced, since most of these tubes were produced by German-based companies, Dutch physicians made an urgent request to Philips, asking the company if they could repair their X-ray tubes. Because Philips had the necessary expertise in glass and vacuum technology, the company complied with the request, and so the Philips Research Laboratory (founded in 1914), took on the repair of these tubes.

While they were repairing X-ray tubes, the laboratory began acquiring knowledge of X-rays, and in 1919 the laboratory started producing small series of X-ray tubes to their own design.

C.H.F. Müller

In 1864, Carl Heinrich Florenz Müller, who was then 19 years old, began a small glass blowing facility in Hamburg, Germany, where he produced mainly artistic glass products, including wine glasses and "Venetian" goblets. Later, he decided to use his know-how and experience in glass production for other glass products, and he began to produce Geissler, Hittorf and Crookes gas discharge tubes, as well as incandescent light bulbs.

Shortly after Röntgen's announcement of the discovery of the new X-rays in January 1896, Müller began to play a prominent role in this area.

On April 17th, 1927, C.H.F. Müller became part of the Philips company, but the name would continue until 1986.

Philips and Müller played a major role in the development of X-ray technology.

1895 - 1954

1895 W.C. Röntgen discovers X-rays

The German physicist, Wilhelm Conrad Röntgen, was among many scientists experimenting with gas discharge tubes in order to investigate the nature of electricity and the mysterious cathode rays.

Figure 5. Geissler tube made by Müller.

Figure 6. Radiograph of the hand of Röntgen's wife.

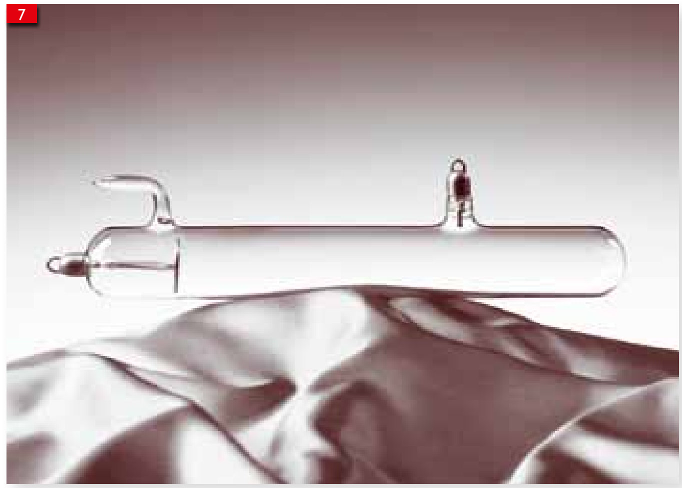

Figure 7. Early Müller X-ray tube: an ion tube with flat anode and no anticathode.

On November 8, 1895, he discovered that a screen coated with barium platinocyanide fluoresced when a nearby gas discharge tube was activated, even though the tube was fully covered with black cardboard. Because he could think of no explanation for this effect, he decided to investigate the cause of this phenomenon, and began a number of very systematic experiments. Several weeks later, on December 28, 1895, Röntgen presented an initial communication to the Physical Medical Society in Würzburg with the title, "Über eine neue Art von Strahlen" ("On a New Kind of Rays"). In the document's 17 chapters, he provided a complete explanation of the newly discovered rays.

Nearly buried among other explanations were the words, "Hält man die Hand zwischen den Entladungsapparat und den Schirm, so sieht man die dunkleren Schatten der Handknochen in dem nur wenig dunklen Schattenbild der Hand" (If one places one's hand between the discharge tube and the screen, one can see the dark shadows of the bones against the lighter shadows of the hand). This single description of an experiment with a hand would later have an incredible influence on the development of the new rays for medical applications.

Shortly after Röntgen's first publication, Professor B. Walter and J. Classen at the National Physics Laboratory in Hamburg reproduced Röntgen's experiment using a cathode ray tube which had been supplied by C.H.F. Müller.

▶ By March 1896, Müller had already manufactured an improved X-ray tube.

The sharpness of the images was far from optimal. This was due to the geometrical distortion caused by the divergent cathode rays and the movement distortion caused by the long exposure time that was necessary because of the low X-ray yield of the tube. To improve this, Walter contacted Müller very early on, and this was the beginning of a very long and fruitful collaboration between them.

1896 C.H.F. Müller's first X-ray tube

By March 1896, Müller had already manufactured an X-ray tube for Professor Walter that had a bowl-shaped aluminum cathode. The cathode rays converged into one point on the glass wall, which resulted in a much sharper image. However, the localized heat load on the glass built up tremendously, which shattered a number of tubes. The next logical step, taken shortly thereafter, was to place a platinum anticathode in the tube and focus the cathode rays on this. Because this increased the amount of radiation, it was possible to reduce the exposure time, resulting in less movement blurring. Using the anticathode also reduced the heat load on the glass, and the tube was further improved by making it spherical instead of cylindrical, and adding pipe-shaped protrusions on both of its sides for the electrodes.

1899 First patent on water-cooled anode

To meet the demand for a higher radiation intensity, Walter introduced the idea of cooling the anti-cathode with water. In 1899, this idea

Figure 8. Müller tube that received the Gold Medal in 1901.

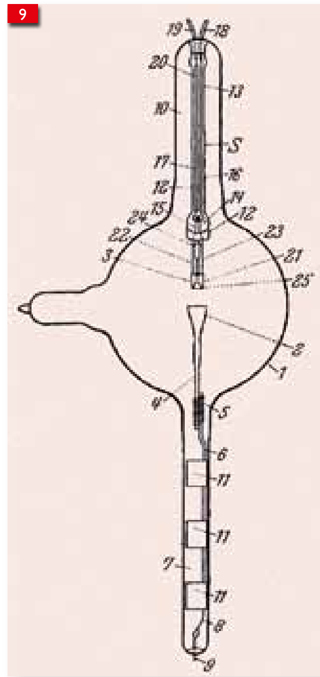

Figure 9. The Coolidge high-vacuum X-ray tube with heated cathode.

was patented by Müller and in the same year, the first water cooled X-ray tubes were manufactured that could produce about 15 to 20 mA. Because of the higher radiation output these tubes became known by the name “Müller-Rapidröhre” and they made the Müller company famous around the world.

1901 Gold medal for first X-ray tube

Müller became even more widely known when, in 1901, the British Röntgen Society awarded his tube the gold medal for the best X-ray tube (out of the 28 tubes that were tested).

Fairly soon after the discovery of X-rays, Müller decided to focus solely on manufacturing X-ray tubes. In January 1904 he ended his business activities due to poor health. Because of the many experiments he had carried out with radiation, Müller, like many others, had sustained a great deal of radiation exposure and died as a result of this on November 24, 1912. Before that, in 1909, Dr. Max Liebermann had taken over the management and ownership of the “Spezialfabrik für Röntgenröhren” (Special factory for X-ray tubes).

As X-rays became more widely used, the demand for X-ray tubes also increased. By November 1911 the company had already produced their 100,000th X-ray tube.

The early X-ray tubes were all ion tubes. A major problem with these tubes was that the intensity (current) and penetration (voltage) of these tubes could not be independently controlled. The current in the tube, which resulted from the voltage generating the gas discharge, was very dependent on the gas pressure. However, this gas pressure decreased over time because the glass wall absorbed the gas ions released by the discharge. Thus an increasingly higher voltage was needed to initiate the discharge, resulting in a hardening of the radiation.

1914 The high vacuum tube with heated anode

The solution to these drawbacks was presented by W. D. Coolidge, who worked in the United States at the General Electric research laboratory. In 1913, Coolidge made the first high-vacuum X-ray tube with a directly heated cathode. In this tube, the electron current that was necessary for generating the radiation came from thermionic emission and not from gas ionization. This made it possible to control the voltage and the tube current independently by varying the current through the filament of the cathode. By using direct heating, much higher currents could be achieved. This meant that the radiation output of the tube was about 10 times higher than that of the ion tubes.

1919 Philips begins manufacture of X-ray tubes

Drawing on the experience gained in the repair of X-ray tubes during World War I, the Philips Research Laboratory began the small-scale

In 1913, Coolidge made the first high-vacuum X-ray tube with a directly heated cathode.

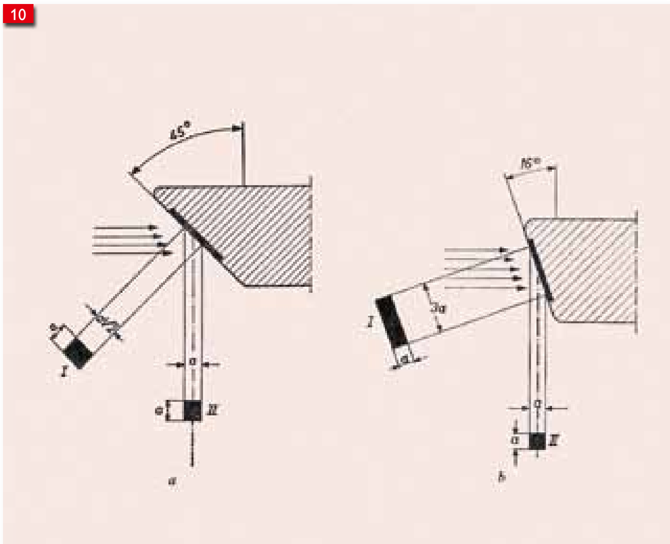

Figure 10. The line focus principle.

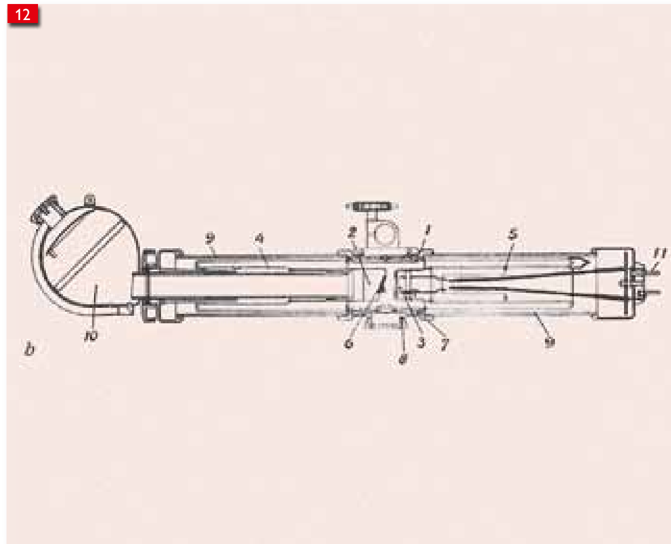

Figure 12. The Metalix tube.

Figure 11. Professor Albert Bouwers (1893-1972).

manufacture of X-ray tubes in 1919, and carried on production until 1923, after which the manufacturing activities were transferred to a new pilot factory.

1921 C.H.F. Müller's Media tube with line focus

Müller's first vacuum tube for diagnostic applications, the Media tube, appeared in 1922. This Media tube was a water-cooled tube and was also the first tube with the line focus. By applying a line focus to an angled anode, the loadability was substantially increased while maintaining the same apparent focal spot size (Figure 10). The line focus principle had been invented and patented by the German surgeon, Professor O. Goetze, in 1918. Goetze made a licensing agreement with the C.H.F. Müller Company, which gave the firm a significant advantage over its competitors.

At the first International Congress of Radiology in London, the Metalix tube was received with enthusiasm.

1925 The Philips Metalix tube

Two problems with early X-ray devices were the emission of undesired radiation in all directions and the hazard of exposed high-voltage cables. Both of these problems were solved by Professor A. Bouwers of the Philips Research Laboratory, who constructed a cylindrical X-ray tube comprising a grounded metal (a ferrochrome alloy) canister with a glass window on one side. A lead layer covering the metal canister ensured that the X-rays could only leave the tube via the special glass window. This protected the patient and physician against the hazardous radiation that was not directly used to create the image. The design also made the X-ray tube smaller than a conventional spherical tube.

In December 1923, this shielded X-ray tube was demonstrated for the first time at a meeting of the British Institute of Radiology in London. In 1925, at the first International Congress of Radiology in London, the tube was displayed under the name Metalix, and was enthusiastically received by participants. Initially, the metal canister was intended to form one pole of the high voltage system, at ground potential but, due to the lack of suitable generators, a new version was designed with symmetrical anode and cathode voltage.

The new version opened the way for a successful introduction of the Metalix. At the second International X-ray Congress in Stockholm in July 1928, participants saw devices with a Metalix tube on just about every display booth.

1927 Philips and C.H.F. Müller join forces

With the success of the Metalix tube, Philips needed a distribution network for its professional products. This problem was achieved by a cooperative agreement with C.H.F. Müller. On April 17th , 1927, C.H.F. Müller became an integral part of the Philips company. Nevertheless, until 1986, the production and sales of X-ray tubes and other X-ray products, would continue to be carried out under the name of C.H.F. Müller in Hamburg.

1928 Metalix Junior: the first portable X-ray apparatus

The next step in the development of the Metalix tube was shielding of the high tension cables. This was first applied in a small portable X-ray apparatus called the Metalix Junior. It was supplied in a suitcase that could store the X-ray

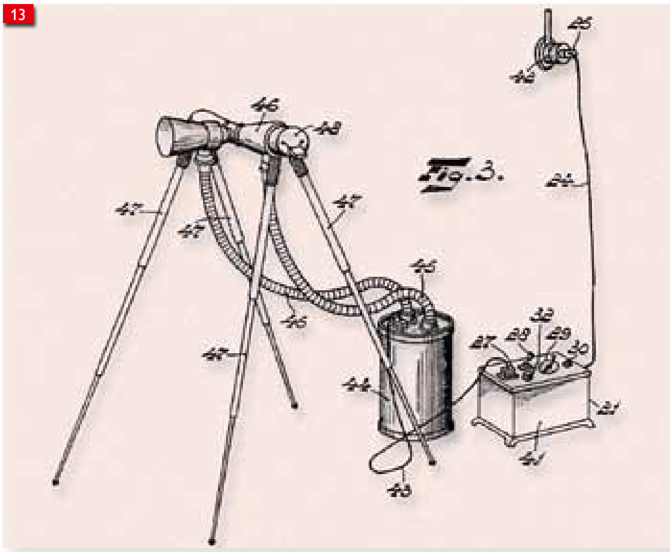

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Figure 13. The Metalix Junior.

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Figure 14. The Rotalix Metalix.

tube, cables, folding stand, switch, and film cassette, with the electrical transformer coming separately. The Metalix Junior was introduced at the second International X-ray Congress in Stockholm in June 1928 and showed that this new protection method was opening the way for more patient- and user-friendly X-ray machines.

1929 Rotalix Metalix: the first X-ray tube with a rotating anode

As a result of its shielding against unwanted radiation and its high voltage, the introduction of the Metalix tube gave an enormous boost to the development of X-ray equipment that were much more patient and user-friendly. It enabled the expansion of applications into the examination of fast-moving organs, such as the heart, lungs, and stomach. To produce images that were sufficiently sharp and rich in contrast, the focal spot had to have a high specific loadability, and this became a limiting factor.

Professor Bouwers and his team investigated the problem and realized that the specific loadability could be significantly improved by using a rotating anode in which the heat load could be spread over a larger, ring-shaped area. This resulted in the first X-ray tube with a rotating anode, the Rotalix tube, which Philips introduced in 1929.

The anode of the Rotalix was originally made of a cylindrical copper block with a disc encased with spiral-shaped tungsten. Later, this was replaced by a large anode disc of sintered tungsten, and the metal casing around the area holding the anode and cathode was replaced with a hard glass envelope. This all-glass tube, surrounded by oil, was enclosed in a metal housing. The heat of the red-hot anode could be dissipated through the hard glass envelope and then be transported via the oil and the housing to the outside. This completely improved Rotalix tube, called the Rotalix O 75 was introduced in 1946, and would become the standard type of X-ray tube for many years to come.

1931 Simplicity and safety

Professor Bouwers, the inventor of the Rotalix tube, had a clear vision of how X-ray technology should be developed. In a 1931 publication titled "New Possibilities in Radiology" in Archives d'Électricité Medical, he began by saying, "Simplicity and safety are the two principal features considered when designing the new series of X-ray apparatus which is herein described."

Simplicity of operation enables the radiologist to concentrate on his case and to deal with medical questions only, while effective radiation shielding and electrical insulation improve safety for both patient and operator.

"Simplicity and safety" continues to be the *leitmotif* of Philips Healthcare.

1934 Super D: the first generator with falling load

In the early days, the X-ray tube was powered by a Ruhmkorff induction coil, and later with the advent of mains electricity, by a transformer. However, the alternating current was potentially damaging, so it had to be converted into direct current before connecting it to the tube. At first rotating mechanical rectifiers were used, but

▶ **"Simplicity and safety" continues to be the leitmotif of Philips Healthcare.**

Figure 15. Brochure for the Super DLX generator.

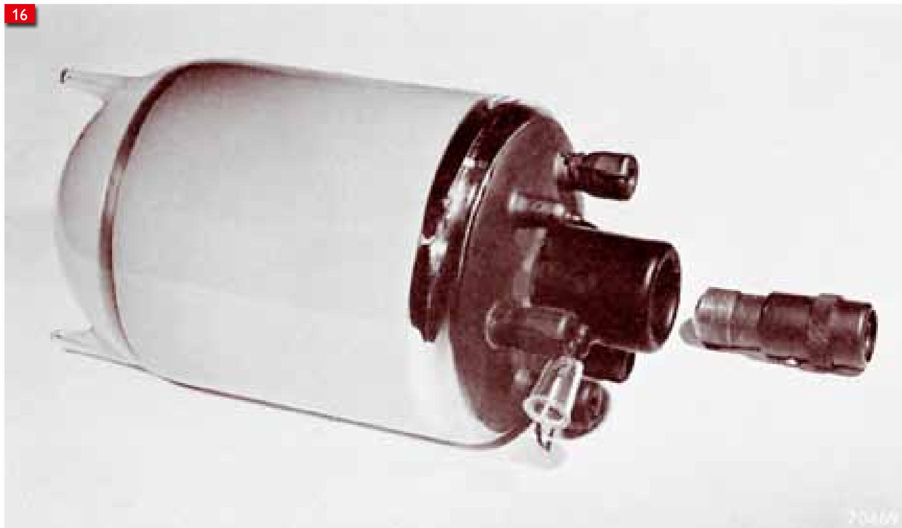

Figure 16. The 5″ image intensifier.

because of the sparks and noise they created, these were replaced during the 1920s by rectifier tubes, or valves. Because these rectifier tubes shared characteristics with X-ray tubes, Philips and C.H.F. Müller decided to develop and manufacture these to use in their own generators.

> **The Philips image intensifier increased the brightness of the image about 400 times.**

In 1934, Philips introduced a new four-valve generator called the Super D, which applied the falling load principle. This invention, for which Professor Bouwers had received a patent, shortened the exposure time significantly. This was accomplished by using the maximum amount of tube current at the beginning of an acquisition, which quickly heated the anode to its maximum end temperature. As soon as this was reached, the tube current was lowered so it maintained a consistent temperature in the anode. This meant that the acquisition time could be much shorter than by applying a fixed lower current.

This was the first of the Philips family of high-output X-ray generators.

1951 Philips demonstrates the first 5″ X-ray image intensifier

Until the 1950's, the only way to view moving images of the internal organs was via a fluorescent screen. Because of the low light intensity of the fluoroscopy screen, clinicians could only assess X-ray images in the dark. And even then, the radiologist had to let his or her eyes adjust to the dark for at least 15 minutes. Besides delaying the examination, this was also very inconvenient for the radiologist and patient. Researchers therefore explored many different possibilities to increase the brightness of the X-ray images.

In January 1951, Philips Research Laboratory presented a 5″ medical image intensifier that increased the brightness of the image about 400 times, with the expectation to improve that to about 1500 times.

1952 Philips starts deliveries of the 5″ X-ray image intensifier

In Europe, Philips introduced the 5" image intensifier in 1952, just a few months before Westinghouse introduced their own image intensifier in America. Initially, the radiologist had to look directly at the small output screen, which often meant an awkward and uncomfortable position. However, viewing became more comfortable at the end of the 1950s, when a television camera was connected to the output screen of the image intensifier. This allowed several people to look at the X-ray image on the monitor at the same time no matter how the image intensifier was positioned. This breakthrough opened the way for the development of different systems for different clinical applications – the idea that Bouwers had first talked about in 1934.

1955-1974

1955 The BV 20

By the 1950's, medical practitioners were already using X-ray technology to support surgery, in particular orthopedic procedures, with the X-ray tube attached to various kinds of stands.

▲
Figure 17. The BV 20.

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Figure 18. Image intensifier TV chain.

To improve the ease of viewing, clinicians used a fluoroscope. But because the brightness of these fluoroscopes was not very high, the X-ray intensity was increased to improve image visibility. As a result, the system exposed both the patient and the surgeon to unnecessary radiation.

These problems made the operating room the ideal application area for the image intensifier, and L. Völkel, a product manager at C.H.F. Müller, together with L. Diethelm, a professor at the University of Kiel, developed the first X-ray system optimized for surgery applications. It consisted of a movable C-arm with an X-ray tube at one end and a 5” image intensifier at the other. This was the first of the surgical C-arm systems that soon became standard equipment in the surgical suite.

The new device was referred to as the BV 20 (BV stood for Bildverstärker, the German for image intensifier, and 20 stood for 20 mA). In 1954, Philips introduced the BV 20 at the German X-ray Congress in Wiesbaden and a year later the first commercial deliveries began. The BV 20 remained the market leader until the 1960’s.

1957 First image intensifier/TV chain

In February 1957, Philips’ first X-ray television image was shown on a Closed Circuit Television (CCTV) system coupled to an image intensifier. The ELA product division of Philips marketed the CCTV system, which comprised a camera, a control unit with a video amplifier, and a monitor. Shortly afterwards, Philips started clinical application evaluation of the image intensifier-television combination. It quickly became apparent that using the television camera provided an enormous improvement for the radiologist and his staff. Because the X-ray image could now be shown on the monitor, the radiologist had much more freedom of movement with the X-ray system. An other advantage was that several people could look at the X-ray image at the same time.

1958 First remote-controlled system

The original idea for the remote-controlled systems came from Professor A. Jutras, from Hotel Dieu Hospital in Montreal, Canada. Professor Jutras felt that the efficiency of radiological examinations could be greatly improved by making optimal use of the newest technologies, including the image intensifier, television, and cineradiography. To further explore this, Jutras and his colleagues made an educational trip to Europe in 1957, and visited Philips. There they discussed whether it would be possible to adapt a new Philips tilting table, known as the Ring Stand, to create a remote-controlled system with all the features Professor Jutras envisioned.

Remote control would enable the radiologist to work behind a lead glass screen, away from the potentially damaging X-rays.

Philips rose to the challenge, and in 1958, the first adapted Ring stand was used in Montreal. It was equipped with two 5” image intensifiers, one of which was coupled to a TV camera and the other of which was coupled to a 16-mm cine film camera.

▶ **The BV 20 was the first of the surgical C-arm systems.**

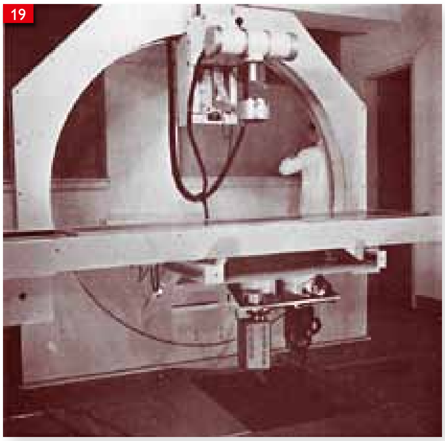

Figure 19. Jutras' Ring Stand with two 5″ image intensifiers.

Figure 20. The Diagnost 100.

Figure 21. The Diagnost 120.

Remote controlled systems offered more positioning flexibility for different applications such as linear tomography and enlargement techniques. In 1966, Philips introduced the Diagnost 100, with a height adjustable table and a tabletop that could be moved longitudinally and transversally, and was also equipped with a compression cone. The X-ray detector consisted of a 9" image intensifier with a television chain and a serial changer.

Building on the experience gained with the Diagnost 100, Philips developed a new remote-controlled system with an integrated modular control desk for both the stand and the generator. This system, known as the Diagnost 120, was introduced in 1973.

1959 The Super Rotalix (SRO) tube

▶ The Super Rotalix (SRO) tube is still one of the workhorses for universal R/F systems.

The expansion of specialized medical applications requiring lengthy imaging sessions demanded increasingly heavy tube loads. These could only be achieved by increasing the rotation speed and diameter of the rotating anode. However, the inertia of a massive tungsten anode made this difficult to achieve. Consequently, the massive tungsten anode disc was replaced by one with a composite molybdenum substrate, which has a high melting point but a low relative density, with a layer of tungsten on it. By doing this, engineers could increase the size of the anode disc to 90 mm and triple the rotational speed to 9000 rotations per minute. With the same focal spot size, the output increased by about 70%. Philips brought this new tube, called the Super Rotalix (SRO), to the market in 1959. It is still one of the workhorses currently used for universal fluoroscopy and bucky systems.

1961 The Plumbicon TV camera tube

The vidicon camera tube was compact and efficient, but was subject to comet-tail and trailing artifacts. After years of experimenting, Philips succeeded in developing a new camera tube using lead monoxide as the sensitive layer. This tube, known as the Plumbicon, was presented to the broadcast industry in 1961. The Plumbicon, which had good dynamics, a high level of sensitivity, and better contrast than the vidicon, was therefore also introduced in X-ray television cameras in 1962. It soon became the standard camera tube in image intensifier TV systems.

1969 Cesium iodide phosphors

At the World Congress in Tokyo in 1969, Philips announced a major improvement in input screen of the image intensifier. Until this time, manufacturers had used zinc cadmium sulfide as the detection material, but the new input screen used cesium iodide (CsI). The crystalline structure of CsI made it possible to construct an input screen of fine crystal rods, each of which acted as a miniature light guide, so that less light was scattered and the contrast of small details was improved significantly. Because CsI also had better X-ray absorption, the X-ray quantum noise in the image could be reduced.

1969 The 6″ image intensifier with TV and fiber optics

In addition to the improvements in the input screen and electron optics, the new image intensifiers were provided with a fiber optic output window that could be coupled directly to the camera tube, without an intervening lens system. The result was a further improvement in image quality and a lighter, more compact assembly.

1973 The Super Rotalix Metal (SRM) X-ray tube

New techniques demanded even higher output from the X-ray tube. After improvements in the

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Figure 22. The Super Rotalix (SRO) tube.

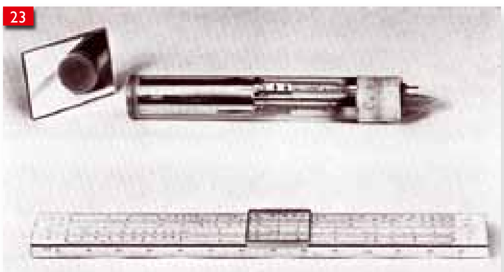

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Figure 23. The Plumbicon TV camera tube.

anode design, the limiting factor had now become the glass envelope. Constant bombardment with electrons and ions, as well as the deposition of metal particles from both electrodes, changed the insulation characteristics of the envelope and, hence, the high voltage stability of the tube.

The only option was to use another material for the tube envelope. The step that Philips took then was actually to do what Bouwers first did in 1925, using a grounded metal housing for the area around the anode and cathode. The X-rays could leave the tube via a beryllium window added to the metal housing. The Super Rotalix Metal (SRM), a tube with an envelope made of a combination of metal and glass, with a higher loadability than the existing SRO tubes, was introduced in 1973.

1973 The Angio Diagnost table
Examinations of the heart require a wide range of X-ray projections around the patient. To achieve this, the patient should, ideally, be floating in space to allow access from any angle. The nearest practical solution to this problem was the Angio Diagnost, which had a floating tabletop supported by a single narrow column at one end. This innovative design is still the standard table for cardiovascular examinations.

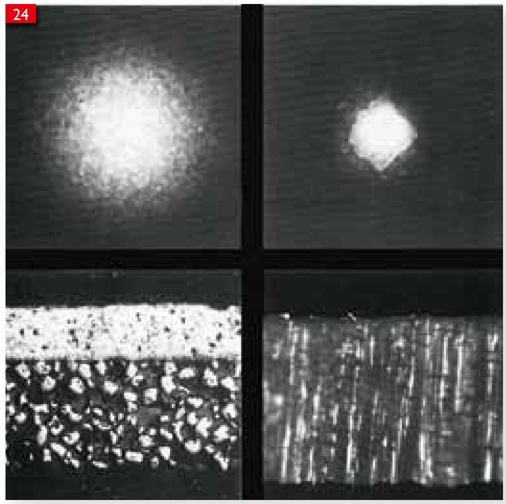

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Figure 24. Comparison of the definition of an image intensifier with a zinc cadmium sulfide input screen (left) and a cesium iodide input screen (right).

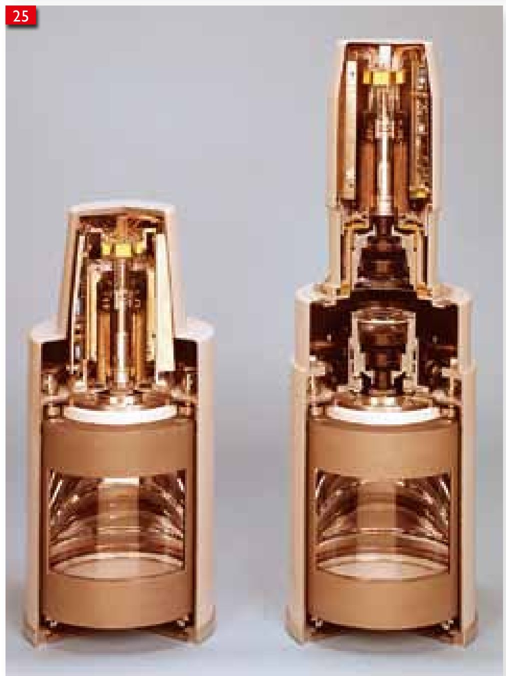

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Figure 25. 6″ image intensifier with fiber optics (left) and conventional lens optics (right).

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Figure 26. The Super Rotalix Metal (SRM) tube.

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Figure 27. The Angio Diagnost.

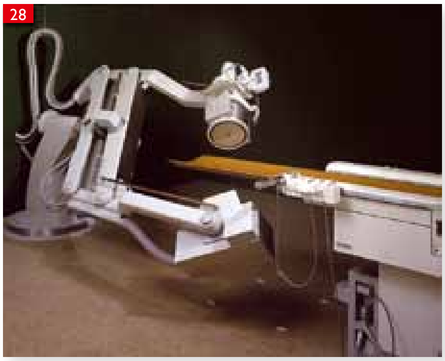


Figure 28. The Poly Diagnost C.

Figure 29. The 14" image intensifier.

Figure 30. The Super Rotalix Ceramic (SRC) X-ray tube.

1975-1990

1975 The Poly Diagnost C cardiovascular system

Because the heart is approximately an ellipsoid, standard frontal and lateral projections are not adequate for visualizing the cardiac anatomy. Ideally, cardiac examinations require an imaging system that provides a virtually unlimited choice of projections. This was achieved in 1975 with the introduction of the Poly Diagnost C, a stand that consisted of a hinged parallelogram that could rotate around a horizontal axis.

For many years the Poly Diagnost C would be the standard in X-ray systems for cardiac applications. In addition to the flexible positioning, part of its success was due to the Optimus M 200 generator that used secondary switching with tetrode tubes to produce the short exposure times that were important for cardiology.

Digital subtraction angiography (DSA) was one of the most important advances in X-ray technology.

1977 The 14" image intensifier

The image intensifier had only one drawback when compared with the fluorescent screen, and that was the smaller field size. To overcome this problem, Philips decided to develop an image intensifier with a large 14" input screen. The new image intensifier had switchable input fields of 14", 10", and 6", as well as a greatly improved electron optical system, and a fiber optic output screen. Instead of glass, which would need to have been thick and heavy, the tube envelope was made of a nickel-iron alloy with very high magnetic permeability. This also reduced the influence of the ambient magnetic field on the electron optics. The input screen consisted of a thin membrane of titanium that had very low X-ray absorption. The new image intensifier was presented at the ICR in Rio de Janeiro in 1977.

1979 The Super Rotalix Ceramic (SRC) X-ray tube

The demand for increased output from the X-ray tube continued unabated. The limited heat capacity became an increasingly serious problem, particularly in cardiac examinations, because of the long fluoroscopy times and the series of acquisitions that were made in quick succession. Even with the introduction of a metal tube envelope, the existing tube technology and dimensions allowed very little scope for increasing the maximum X-ray output, heat capacity, and lifetime of the tube.

In 1979, Philips introduced an X-ray tube with a radically different design: the Super Rotalix Ceramic (SRC). Unlike the SRM tube, which had an envelope made mostly of metal and some hard glass, the SRC tube envelope was made completely of metal, with ceramic insulators, which allowed a very compact design. The new tube had a large anode diameter of 120 mm with bearings at both sides of the anode. The SRC tube provided an X-ray source with a much higher loadability for continual use and in large series of acquisitions, which greatly reduced the long waiting times between series.

1980 DSA

Digital subtraction angiography (DSA) was one of the most important advances in X-ray technology. It enabled real-time subtraction of X-ray images and paved the way for many new interventional procedures.

Although analog subtraction techniques had been known for some time, they were difficult and cumbersome to use. The story of real-time subtraction really begins in 1976, when Dr. C. Mistretta and his colleagues at the University of Wisconsin, developed an experimental digital subtraction device. In September 1979, a refined

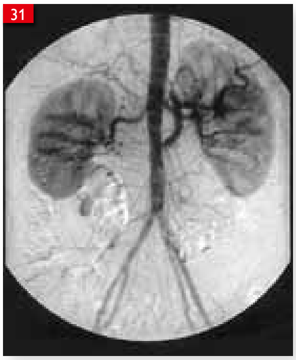


Figure 31. DSA image obtained with the DVI 2.

Figure 32. Philips Computed Radiography (PCR).

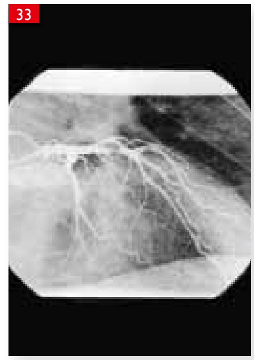


Figure 33. Early DCI image.

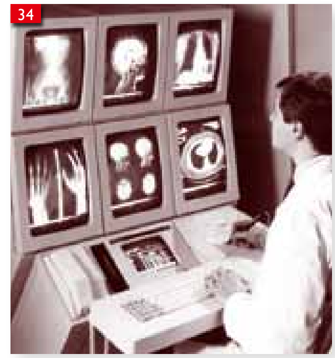


Figure 34. CommView workstation.

version of the experimental model was moved to the University of Wisconsin Hospital and Clinics, where it was connected to a standard fluoroscopy system. Clinical tests on patients, who were intravenously injected with contrast medium, began and they were so successful that physicians had already examined 100 patients by the beginning of 1980.

In January 1979, L. Verhoeven who was working in Best, visited Dr. Mistretta to gather more information about his experimental model and the future possibilities for it. After evaluating this visit, Philips decided to invest in this new technology , and in July 1980, the first prototype was installed in the St. Antonius Hospital in Nieuwegein (Utrecht) in the Netherlands.

In 1982 the first commercial, full digital DSA system, the Philips DVI 2, was introduced and launched at the RSNA.

1986 Computed radiography

In the early 1980's, CT and MRI systems had already demonstrated the advantages of digital images for storage, transportation and viewing, and efforts were made to extend these benefits to conventional radiography. Digital acquisition of X-ray images was already a reality, with the introduction of DSA, but the resolution was far less than that of film. That meant another solution had to be found for radiography. This came from the film suppliers, when the Japanese Fuji Photo Film Company introduced the first digital radiography system, the FCR 101, in 1983. This system was based on the principle of stimulated phosphors. The processed phosphor was applied to a plate that was the same size as a standard film. Because the plates could be put in cassettes similar to those used for film, there was no need to adapt existing apparatus and systems.

The advantages of such a system were clear. The development machine was replaced by an electronically controlled reader. Because the dynamic range of the phosphor plate (about 1: 40,000) was much larger than film, the X-ray exposure became much less critical, and the fast processing meant that the waiting times for patients would become much shorter.

To introduce the digital radiography system in clinical practice, Philips and Fuji entered into an agreement in which Philips would develop the workstation and the necessary hardware, while Fuji would supply the phosphor plates, the scanning system, and the read-out electronic.

Philips introduced the system under the name Philips Computed Radiography (PCR) at the RSNA in 1985, and began the first deliveries in 1986.

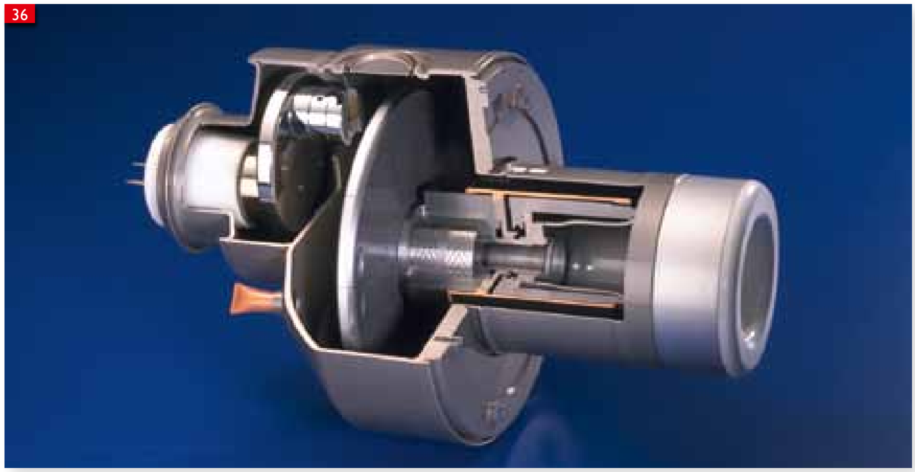
1987 DCI

With the advent of DSA, cardiologists became eager to employ the new technology in cardiac applications. However, there were problems in applying the subtraction principle to the moving heart.

To address this problem, Philips engineers began developing a system that was optimized for cardiac applications. The starting points were a 512^2 image matrix, as well as real-time acquisition, processing, and storage of 50 to 60 images per second, but no subtraction function. At first, the new system, known as the DCI (Digital Cardiac Imaging) had about the same functionality as film systems. The big difference was that cardiologists now had their images immediately available, which was of critical importance for the interventions they were performing. Cardiologists immediately saw that this was exactly what they needed, a dedicated system for their applications, that

▶ With digital cardiac imaging (DCI), cardiologists had their images immediately available.

▲ Figure 35. DSI image of the large intestine.



▲ Figure 36. Cutaway model of the Maximus Rotalix Ceramic (MRC) X-ray tube

▶ **The Maximus Rotalix Ceramic (MRC) was the first X-ray tube with spiral groove bearing and liquid metal lubricant.**

provided a great deal of ease of use and efficiency through its real-time processing. The DCI was introduced at the RSNA in 1987.

1987 CommView (PACS)

During the 1970s the American College of Radiology (ACR) and the National Electrical Manufacturer Association (NEMA) developed the ACR-NEMA standard. This standard described a format for the composition of digital images. The aim was to make it possible to exchange digital images between systems from different companies and to process these images. This ACR-NEMA standard developed into the worldwide DICOM standard that has been used since the 1980s.

This digital image standardization stimulated the development of the Picture Archiving and Communication System (PACS), a system that enabled digital images to be distributed and archived. Philips began its PACS activities around 1985, when the American government decided to implement a complete digital distribution and archiving system in two hospitals.

One of the first practical PACS was CommView, the result of a cooperation between Philips and AT&T. After the necessary adaptations and improvements, CommView was brought to market worldwide. In the Netherlands, Philips carried out an extensive application research project with the Academic Hospital at the University of Utrecht. This research, which lasted from 1987 to 1989, provided much worthwhile information for further PACS development.

1988 DSI

The advantages of digital image acquisition and processing were so clear that Philips quickly began to think about replacing the analog spot film camera with a digital equivalent in the universal fluoroscopy systems. The project started in 1987. During this project, close attention was paid to image quality to make sure that the wide variety of images routinely acquired on the universal fluoroscopy systems would have the best possible image quality. Both the technical and clinical aspects were addressed.

At the General Infirmary in Leeds, England, the clinical utility of digital spot imaging was explored and its image settings were optimized. Dr. A.R. Cowen in the Medical Physics Department at Leeds University, together with F. Clarke, carried out a wide range of comparison experiments on various test models over a long period.

In 1988, Philips introduced Digital Spot film Imaging (DSI) at RSNA, and began worldwide deliveries in 1989.

1989 Maximus Rotalix Ceramic (MRC)

In 1989, Philips became the first company to introduce an X-ray tube that replaced the existing ball bearings with a spiral groove bearing using a liquid-metal alloy as a lubricant. This design substantially reduced the noise produced by the tube, increased the lifetime and heat dissipation, and improved the current conduction.

This new bearing, combined with the technology of the SRC tube, produced the compact new MRC tube featuring a noiselessly rotating anode that could be switched on in the morning and swiched off in the evening, and that had a very long lifetime. The excellent heat dissipation of the bearings via the liquid metal lubricant gave the tube three times more cooling capacity than the SRM tube during a cine examination. The introduction of this tube would have an enormous impact on performance and ease of use, particularly for cardiology and vascular systems.

1991-2000

1991 XTV 8 X-ray TV camera

Until the beginning of the 1980s, X-ray TV chains used adapted commercial TV pick up tubes operating with a 50 or 60 Hz television standard. However, in 1986, the broadcast industry introduced the first broadcast television camera with CCD sensors, followed within a few years by the first consumer camcorders.

Because this new image sensor had many advantages compared to the existing camera pick-up tube, Philips began to research possible applications for X-ray systems early on. However, an image sensor used in medical applications had different requirements from those used in broadcast and consumer applications.

In October 1990, the first CCD camera for X-ray applications, the XTV 8, was delivered from the factory mounted on a 9″ image intensifier. The image quality was outstanding. There was no geometric distortion, the entire image had uniform sharpness, and there were no blooming effects. The XTV8 chain was first applied to the mobile surgical C-arm systems.

1992 Rotational Angiography

In conventional X-ray imaging, a three-dimensional object is represented as a two-dimensional image, which frequently limits the spatial insight for users. This could be improved by making two separate projections at right angles to each other, but is still not ideal. In 1992, Philips introduced Rotational Angiography (RA), in which a complete series of projections was acquired at a rate of at least 7.5 images per second, while the C-arm made a continuous rotation over 180°. When these images were viewed in a loop, they gave a three-dimensional impression of the object. Besides saving a great deal of time, RA also greatly reduced the usage of contrast medium and patient dose.

1993 Thoravision digital chest system

Since the 1970's researchers of the Philips Research Laboratories in Aachen, Germany, were experimenting with methods to read out a latent image stored in a selenium plate, after radiation with X-rays. At the end of the 1980's this was realized by applying a 500 µm thick layer of selenium to a rotating drum. After the exposure, a set of electrical probes was used to read out the X-ray image. This principle was incorporated in the Thoravision, the first completely digital thorax system, which was presented in September 1993 at the European Congress of Radiology in Vienna and later at the RSNA in Chicago.

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▲ Figure 37. XTV 8 camera (left) compared with vidicon camera and control unit (right).

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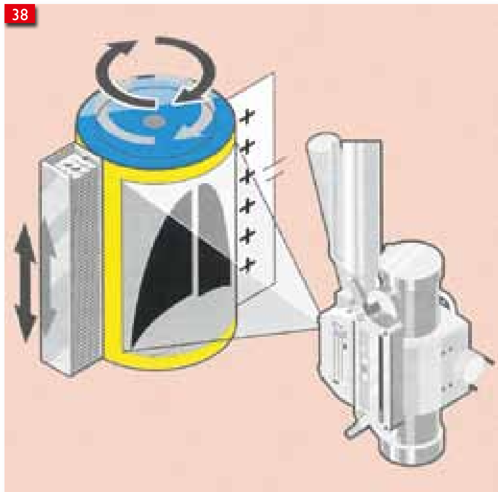

▲ Figure 38. Principle of the Thoravision.

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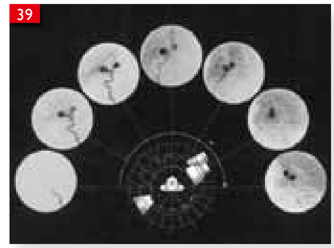

▲ Figure 39. Principle of rotational angiography.

▶ **Besides saving a great deal of time, Rotational Angiography also reduced the use of contrast medium and patient dose.**

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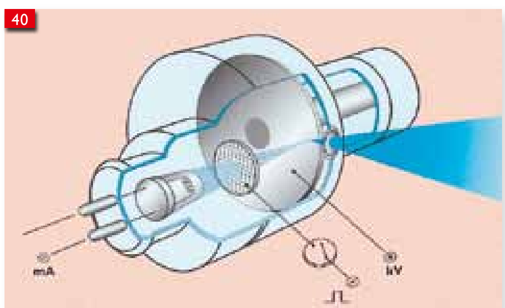


▲ Figure 40. X-ray tube with grid switching.

1995 Grid Controlled Fluoroscopy

In order to reduce the X-ray dose in universal fluoroscopy systems, pulsed fluoroscopy was introduced, based on the observation that the image content is not very dynamic for most examinations performed on fluoroscopy systems, so the temporal resolution of the image is of secondary importance. However, although the theory was correct, these pulsed fluoroscopy systems (which used kV switching), could not generate a truly rectangular pulse, due to capacitance effects in the generator and cables, so that undesirable soft radiation was produced during the rise and fall of the pulse. Moreover to achieve good stable image quality, the minimal

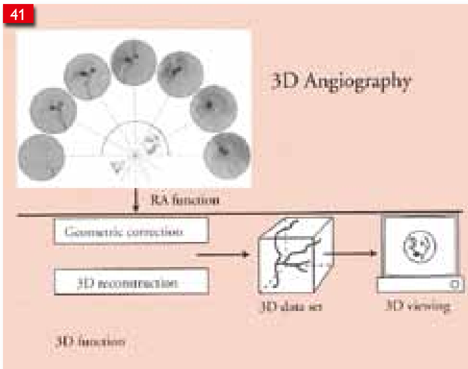


Figure 41. Principle of 3D rotational angiography.

Figure 42. 3D reconstruction

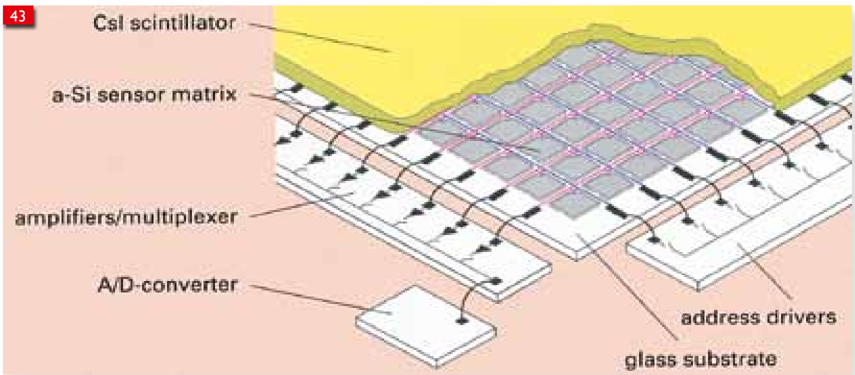


Figure 43. Flat static detector.

Figure 44. The Digital Diagnost.

A flat panel would be less bulky than the image intensifier and would offer several technical advantages.

pulse frequency was limited and would not reduce X-ray dose significantly.

This problem was solved by using a grid-controlled X-ray tube that could create a rectangular X-ray pulse. A new regulator controlled the high-voltage, current, and time during the pulse, rather than after the pulse as was normal. This made it possible to use very low pulse frequencies, even with dynamic images. The combination of short pulse length and a higher dose per pulse produced much better fluoroscopy images with an integral lower dose, depending on the chosen pulse frequency. This new technique, referred to as Grid Controlled Fluoroscopy, was demonstrated for the first time at the RSNA in 1995.

1998 3D Rotational Angiography

Rotational angiography, in which a complete series of projections was acquired on a conventional angiography system while the C-arm made a continuous rotation over 180° around the patient, had the potential to create a 3D data set. However, this potential could not be realized because it was not possible to perform the scan during the few seconds of the contrast injection, while longer injection times were regarded as impractical because the arterial and venous phases would then be superimposed.

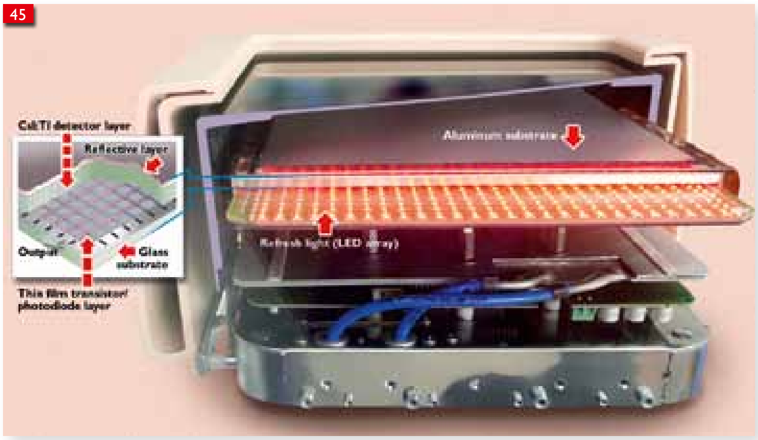
However, phantom studies in which contrast agent was applied over the whole seven-second rotation period produced superb results, and clinicians were persuaded to inject contrast medium during the entire rotation period. By using a large viewing window, because of the high contrast, the overlap of the arterial and venous phase disappeared.

3D-RA was introduced at the RSNA in 1998 and the first deliveries took place in the second half of 1999. Some 60 systems were supplied in the first six months. The research into 3D imaging now began in earnest and would lead to more interesting technological and clinical results.

1999 The static flat panel detector

In the early 1990's, work began on the development of a flat panel detector to replace the image intensifier. A flat panel would be less bulky than the image intensifier, and would offer several technical advantages. For example, it would have a higher dynamic range, able to differentiate a larger range of grayscale values to provide clearer images with better contrast. In addition, there would no distortion due to ambient magnetic fields, and no pincushion distortion, because the convex image intensifier input screen would be replaced by a truly flat detector panel.

Research at Philips Research Laboratories and at the X-ray predevelopment group of Philips in Best resulted in several successful prototypes, but it soon became clear that the investment required to develop a commercial product was far beyond what one company could afford. Accordingly, Philips became stakeholder in a joint venture with Thomson and Siemens under the name "Trixell". This company would not only deliver detectors to Philips, Siemens, and Thomson, but would also sell detectors to third-party X-ray companies. By selling to third parties, the output of the factory could be increased, and as with semiconductors, the yield of the production process could be more



▲
Figure 45. Cut-away model of the FD 10 flat dynamic detector. A 550 μm thick layer of CsI is superimposed on the photosensitive layer of the amorphous silicon, which is divided into 1000 x 1000 pixels. The light below the detector is used to refresh the image after each frame to eliminate ghosting.

▲
Figure 46. Allura Xper angio system with FD 20 large flat panel detector.

Figure 47. 3D-RA scan (left) showing aneurysm at the bifurcation and corresponding XperCT axial view (right).
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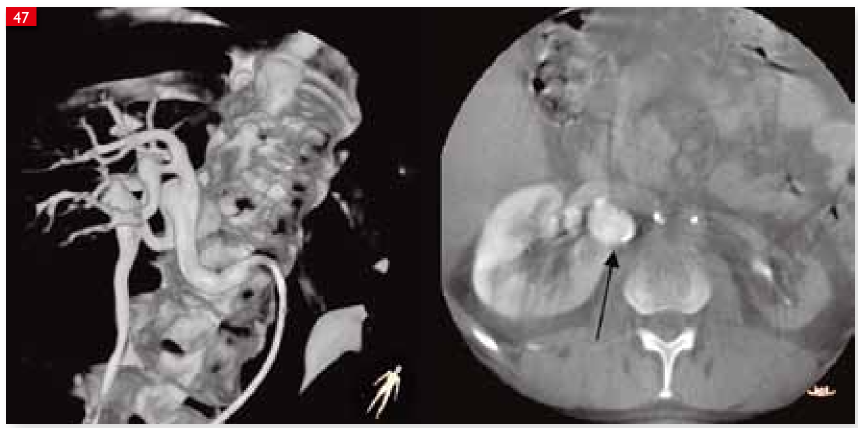

quickly increased, which would reduce the cost price of the product.

For technical reasons, the first detector was a flat static detector (FSXD) for radiography with an image matrix of 3000 x 3000 pixels and a spatial resolution of 3 lp/mm.

Philips used this detector for the first time in the Digital Diagnost, a high-end bucky system that was brought to market in 1999.

2001-2010

2002 The dynamic flat panel detector

After the succesful introduction of the static flat panel detector at the turn of the century, small flat dynamic detectors for cardiac applications were introduced and, later, large flat detectors for vascular and multifunctional fluoroscopy systems. Combining 3D RA with a flat dynamic detector made it easier to perform simple CT-like scans with a conventional X-ray system. These developments are expected to play a major role in the future.

2005 The XperCT

Interventional radiologists had long been confronted with the problem of obtaining a three-dimensional view of the internal structures. 3D-RA made this possible for high-contrast structures, but these views do not show any soft tissue. These could be obtained via a CT system or MRI system, but this meant moving the patient back and forth between the angio system and the other imaging modality, which was time-consuming, often impractical, and not real time. Integrating an X-ray system with a CT system or MRI system was realized, but was not an optimal economic solution. Eventually,

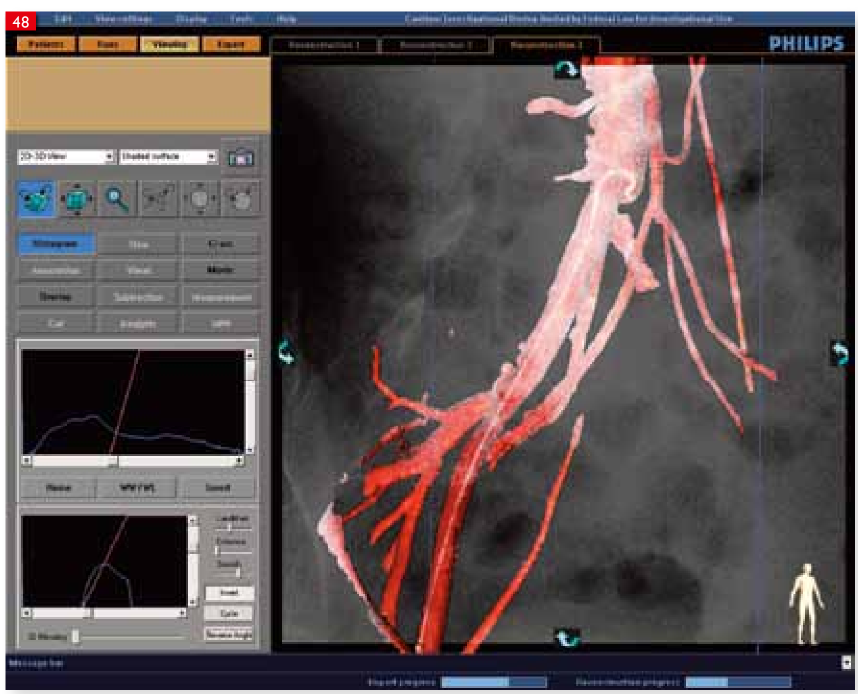

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Figure 48. 3D roadmapping for accurate navigation: the live 2D image is superimposed on the 3D image.

Figure 49. Conventional EP room (left) and EP room with EP Cockpit (right).

The EP cockpit was a total solution to the needs of electrophysiology.

Philips decided not to integrate the CT scanner with the X-ray system, but to design an X-ray system that would use 3D-RA technology to generate CT-like images itself.

Philips brought this new feature to the market in 2005 as XperCT.

In addition to XperCT, the company also developed Dynamic 3D Roadmapping to further improve interventions. During navigation, the orientation of the three-dimensional image is automatically changed to match the projection direction, which provides tremendous support in real-time catheter navigation or when placing a coil.

In 2007, Philips introduced XperGuide to support percutaneous interventions. Based on XperCT images, XperGuide plans a trajectory that the needle must follow to reach the correct position.

2007 EP Cockpit

Because of the increasing number of older people in the population, the number of heart attacks as a result of irregular heart rhythms in the heart's electrical system is also rising. This trend, as well as new technologies and treatment methods, has also led to an increase in the number of diagnostic and therapeutic electrophysiology procedures.

During these procedures, an electrophysiologist uses X-ray and many other medical devices, including monitors, electrophysiology recorders, ultrasound scanners, and ablation and navigation equipment.

To meet the increasing demand for EP procedures, and to provide an integrated package of equipment, Philips began the Electrophysiology Business Program as part of its Cardiovascular Business Unit.

The first step in this direction was made with EP Cockpit, a total solution that became available in 2007. It consisted of a ceiling-suspended equipment rack that could hold all bedside equipment used during the EP procedure, displays to show the information from all of the EP imaging and information sources, and two keyboards to control the system. Connecting the system to an Xcelera PACS made it was possible to grab images and archive them. EP cockpit was delivered for the examination room and the control room, and significantly improved the EP working environment.

During an EP procedure, the electrophysiologist has to apply ablation to very specific electrical connections in the heart. The procedure requires very accurate navigation to be carried out successfully. For this reason, the second EP product that Philips made available was EP Navigator: a navigational tool that used automatic segmentation software to make the left atrium visible in a previously acquired 3D image. This image then serves as a map to navigate the catheter in the patient's heart using the overlaid live fluoroscopy image.

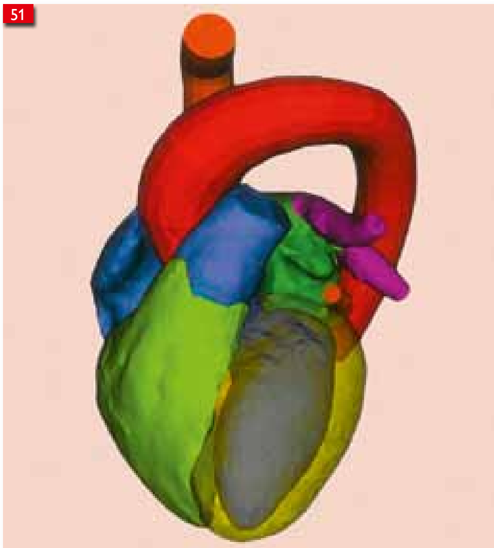

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Figure 50. Generic heart model used for heart segmentation in the EP navigator.

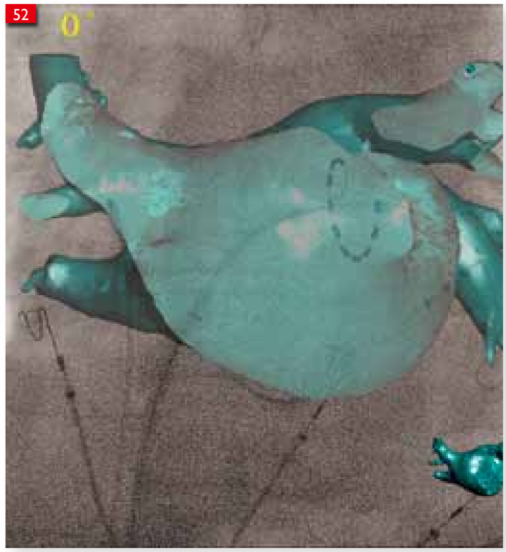

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Figure 51. Fluoroscopy image of EP procedure with EP navigator.

Quo vadis?

In 2010, 115 years after their discovery, X-rays are still the most frequently applied technology for medical imaging. As we have seen, a great deal has changed over the years – in technology as well as in applications. For a long time, the X-ray system was a very technical device that was made up of separate components. Today, these are well-designed systems with the newest technologies, largely automated functionality, and very intuitive and user-friendly controls. Sense and Simplicity, as Albert Bouwers already saw it in 1934, is now a reality.

Over the years, diagnostic examinations, which were once very diverse, have become increasingly limited to the most basic ones. At the same time, the number and diversity of interventions have increased significantly. This trend will continue in the coming years. If we look at the way in which X-ray technology has adapted itself to both threats and opportunities in the past, we can be confident that there are still many exciting developments to come.

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► **115 years after their discovery, X-rays are still the most frequently applied technology for medical imaging.**