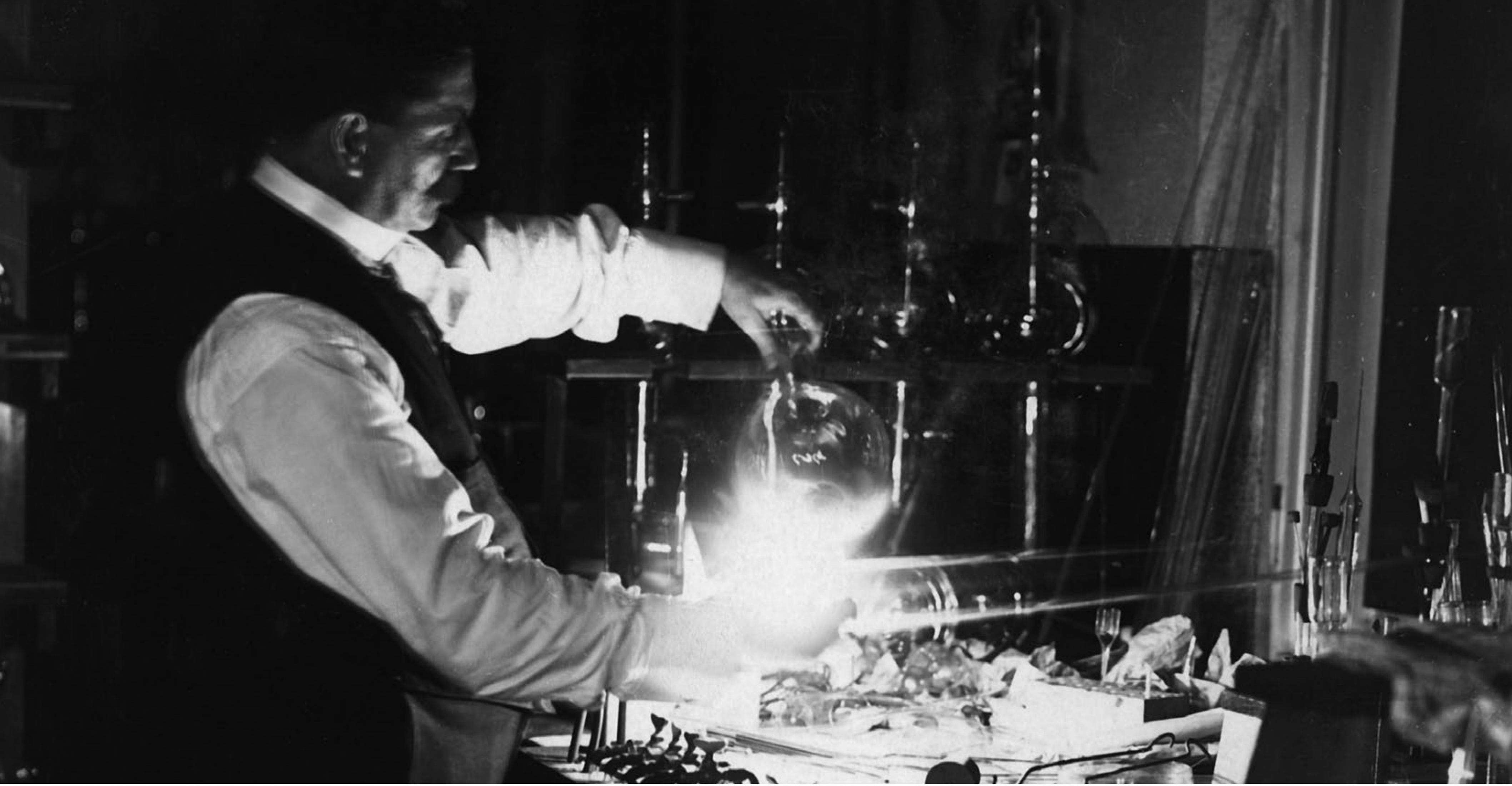

Siemens Healthineers Historical Institute

The history of X-ray technology at Siemens Healthineers

SIEMENS Healthineers

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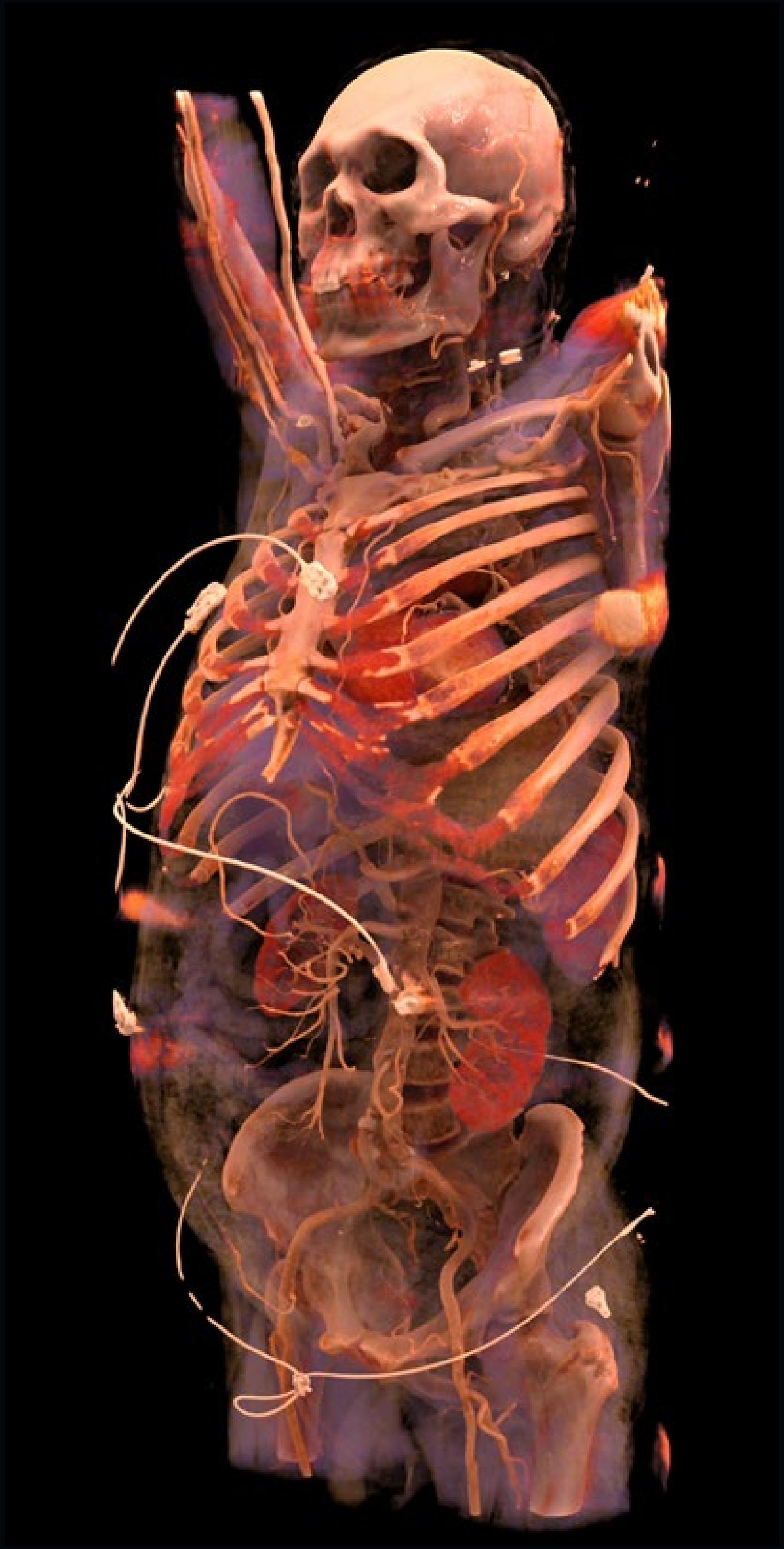


Introduction

The future often arrives sooner than one thinks. When the German science fiction author Kurd Lasswitz dreamed of using technology to make living people transparent in a utopian novel in 1874, he didn't expect the technique to be invented until the 39th century. Likewise, the Swabian physician Ludwig Hopf set his 1892 medical fairy tale *Elektra* at the end of the 20th century, which seemed like the distant future in those days. The hero of the tale was a young country doctor who was thinking of new ways to diagnose diseases. While on a nighttime stroll, he sighed to himself:

"Oh, if only there was a way of making people as transparent as a jellyfish!"

This fairy-tale wish ultimately came true with the help of a "magic light" from a "glowing device," allowing the astonished doctor to see inside his patients. News of the magic light quickly spread "across the country and soon, through reports in newspapers and telegrams, around the world." Some three years after the fairy tale was published, it began to come true – and some aspects turned out to be surprisingly accurate: On the evening of November 8, 1895, the Würzburg-based professor of physics Wilhelm Conrad Röntgen discovered "a new kind of rays," triggering a sense of euphoria around the world. Many saw the discovery as the dawn of a new era.

One of the first books on the medical use of X-rays alluded to the transparent patients in *Elektra* and ended with the words: "If the technology becomes so advanced as to allow improvements to existing tools, then we will not be far from the jellyfish-like state described in the medical fairy tale, and this figment of the author's imagination will become a reality." It is unlikely, however, that any of the pioneering radiologists foresaw the extent to which the technology would develop over the next 125 years. Today, X-ray technology is far more than just a tool for making humans as "transparent as a jellyfish."

Over the years, its development has given rise to countless helpful – and often fascinating – new ways of diagnosing and treating diseases and injuries. This book tells the story of many remarkable people who contributed to the process of development with their inventions, which were the result of ingenious brainwaves, astonishing discoveries, and even the occasional "crazy idea." At the heart of it are the milestones with which Siemens Healthineers helped to drive forward and shape the history of X-ray technology.

Strictly speaking, the pioneering era of X-ray technology has never come to an end. To this day, our engineers continue to work on improving the technology in collaboration with physicians and scientists around the globe, and with the same drive as the pioneering radiologists of 1896. History is still being written – and, as you are about to discover over the next 12 chapters, we are once again standing on the threshold of a new era of medical technology.

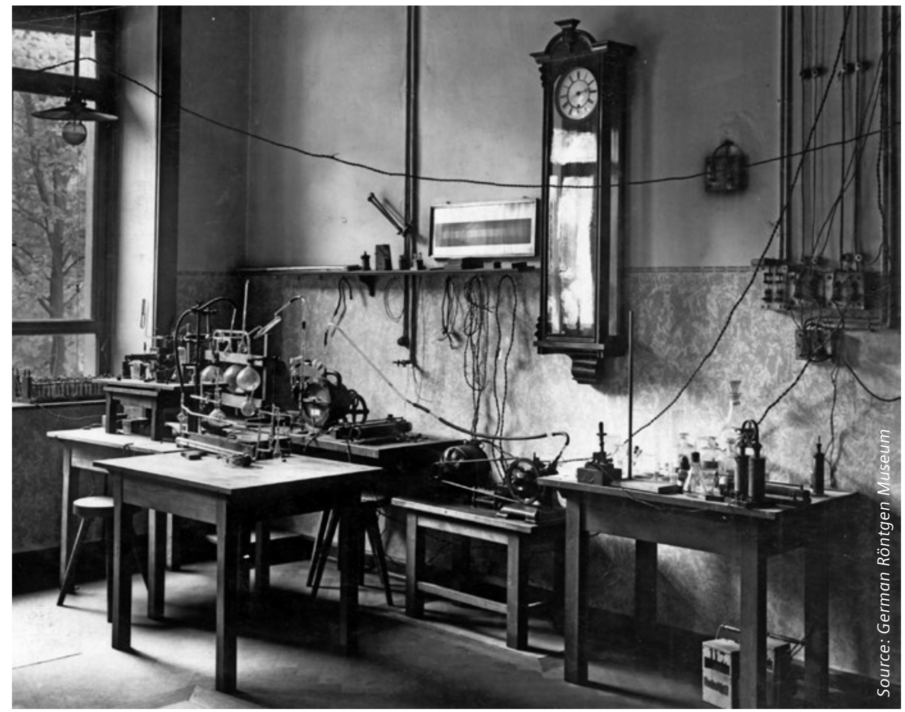
We hope you enjoy this book!
Siemens Healthineers Historical Institute

Röntgen poses for a statue – in his hand is one of the smaller versions of the first medical X-ray tubes in the history of Siemens Healthineers

Source: German Röntgen Museum

“So, now all hell will break loose!”

How the discovery of X-rays changed the world



Source: German Röntgen Museum

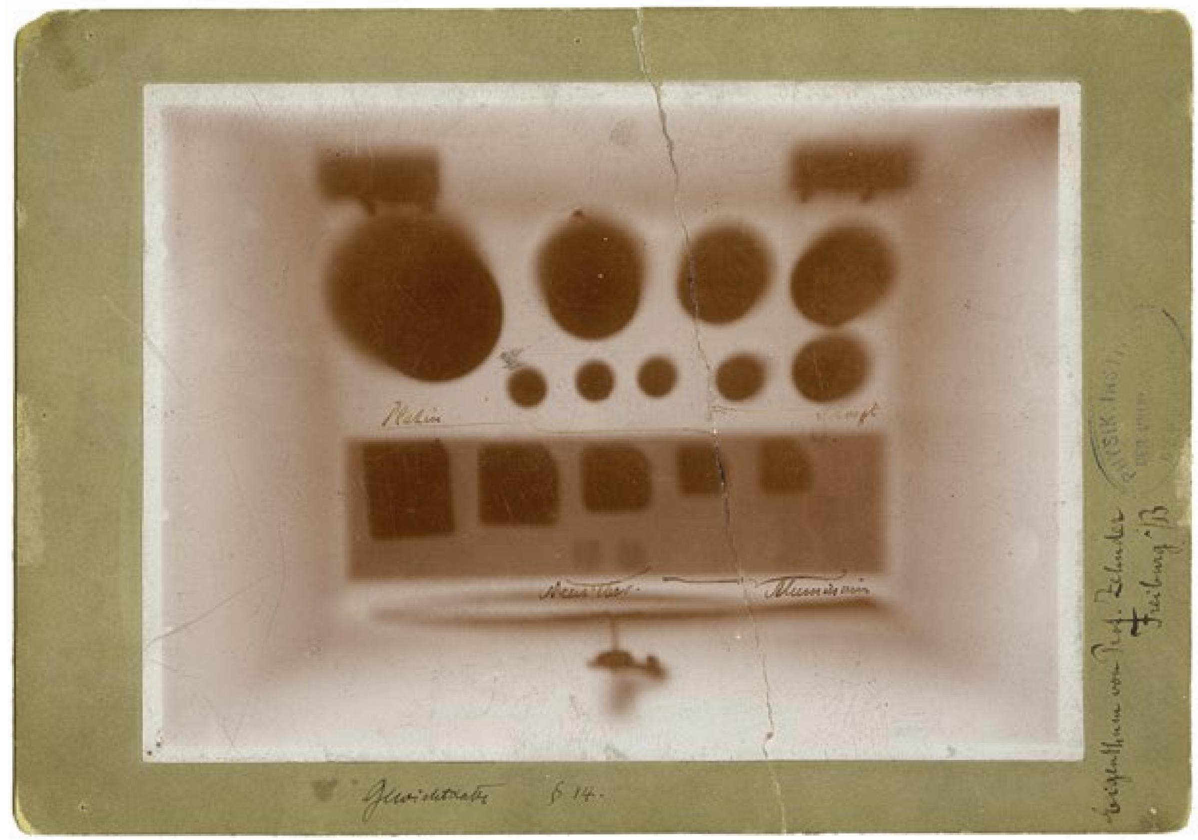
Where the X-ray was discovered: Röntgen’s lab at the University of Würzburg

The 19th century was a golden era for sensational scientific discoveries. Never before in history had so much been discovered, invented, measured, and mapped – and newspapers were reporting astonishing findings and innovative electrical devices on an almost daily basis. Scientists were researching electricity and magnetism, while engineers were building the first bicycles, typewriters, and airships. Toward the end of the century, the first motorized streetcars were operating in cities; streets and alleyways were lit with electric lamps; and people were sending telegrams, having their photos taken, and going to the movie theater. In an era such as this, you would be forgiven for thinking that new discoveries ought not to come as a great surprise. But in 1895, the year in which the first movie was shown, the Würzburg physics professor Wilhelm Conrad Röntgen discovered a phenomenon so peculiar that, at first, no one could quite believe it. The London *Standard* printed one of the first reports of Röntgen’s discovery and ended its article with the following words: “The *Presse* assures its readers that there is no joke or humbug in the matter. It is a serious discovery by a serious German Professor.”

News of Röntgen’s discovery spread around the world from January 5, 1896, and must have been hard to believe back in those days. Newspapers reported that the professor in Würzburg had successfully used a new type of “light” to take “ a photograph of a set of weights without opening the wooden box in which the weights were kept” and of a human hand, showing the bones “without the flesh.” This was an absurd claim according to the understanding of physics in those days. Many scientists responded with bewilderment, while others dismissed the reports as the trick of a practical joker. Even Röntgen’s good friend, the Berlin-based physics professor Otto Lummer, appeared doubtful of his colleague at first: “Röntgen has otherwise always been a sensible fellow, and it’s not carnival season yet.” The origin of many scientists’ doubts is clear, as initial reports centered around the ability of this “unknown radiation” to “penetrate dense objects as easily as sunlight penetrates a piece of glass.” What was not clear, however, was how light of this kind could actually be produced. How was it possible to photograph the insides of objects? What exactly had Wilhelm Conrad Röntgen discovered in his Würzburg laboratory?

A seemingly trivial phenomenon

On November 8, 1895, "at a late hour when assistants were no longer to be found in the laboratory," Wilhelm Conrad Röntgen was preparing for one of his experiments. Like many physicists of his day, Röntgen was interested in a relatively unspectacular but extremely popular subject of research: Gases begin to glow when they come into contact with electrical current. The conductivity of various gases could be analyzed using a comparatively simple experimental setup: A gas discharge is produced inside a sealed glass tube containing two electrodes. When a voltage is applied to the electrodes, they produce a beam of electrons known as a "cathode ray" that moves from one electrode to the other at high speed. The required voltage is generated by an induction coil, which is essentially a larger and heavier predecessor of the spark plugs found in today's internal combustion engines. The cathode rays could then be observed using a fluorescent screen, which in those days was made of barium platinocyanide crystals spread as evenly as possible across a piece of cardboard. Röntgen darkened his laboratory and wrapped the glass tube in black paper in order to observe the effect of the cathode rays on the fluorescent screen without interference from the light produced in the tube. When he switched on the induction coil and current began to flow through the tube, his eye was drawn to an incidental and seemingly trivial phenomenon: In the darkened laboratory, a green glow began to emanate from a fluorescent screen – or, rather, from a piece of paper coated with fluorescent crystals – that happened to be lying on a table next to the tube. Röntgen checked for cracks in the lightproof black paper that covered the tube and passed a current through it again. Once again, the sheet of paper glowed light green. Röntgen would later summarize what happened next with his now famous words: "I did not think; I investigated." First, he increased the distance between the tube and the sheet with crystals, but the effect of this unknown, invisible radiation remained unchanged even at a distance of several meters. Not even wood, paper notebooks, or a book of around 1,000 pages could stop the mysterious rays in their tracks – but platinum and lead could. This observation gave Röntgen an idea: He held his hand in the path of the rays and made probably the most exciting discovery of his lifetime: On the screen, he could see the shadows of the bones in his hand!



Source: Röntgen Memorial, Würzburg

The "shadow-image" of a set of weights inside a box

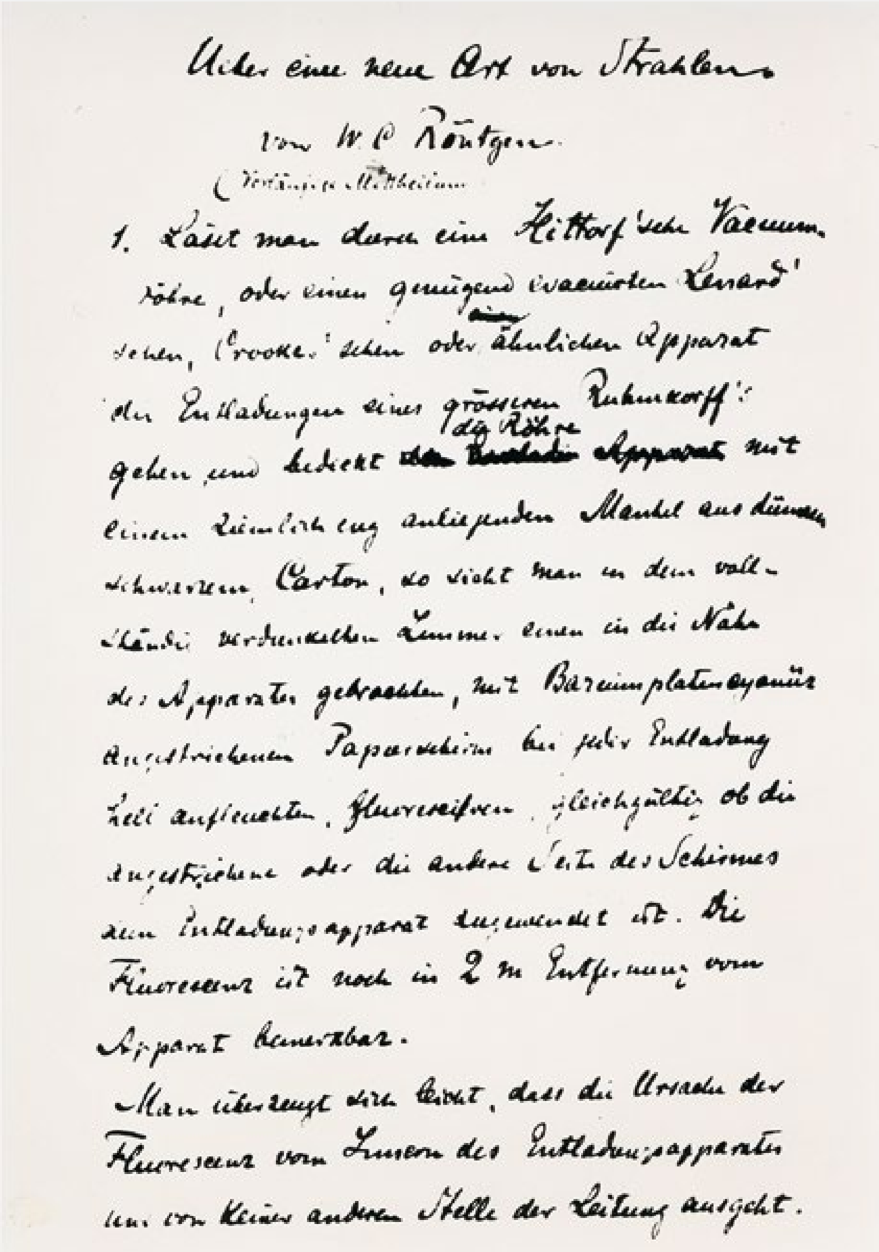
“Röntgen must have gone mad”

Wilhelm Conrad Röntgen believed he was a “victim of deception” and checked his observations over and over again until he eventually “used photography and the experiment was successfully culminated.” Now convinced that his “startling” discovery was a reality, he withdrew into his work and was barely seen for the next seven weeks. No one knew what was going on in the professor’s laboratory – his assistants found the doors locked, and his wife, Bertha, went through what she would later describe as a “dreadful time.” Röntgen came home late and in a foul mood, barely spoke as he ate, and raced back to his lab immediately afterwards. Soon, he even had his bed taken into his laboratory, and his wife sometimes didn’t see him for days on end. When Bertha asked what the matter was, she initially received no answer. It was only when she pressed him that Röntgen said if people knew what he was doing, “they would say ‘Röntgen must have gone mad.’”

It must have been difficult for Röntgen to convince his contemporaries of what had been going on behind the closed laboratory doors for all those weeks: As well as “X-raying” a wooden spool to produce a photograph of the wire inside it, Röntgen was able to read the direction on a compass enclosed in a metal case and – in one particularly noteworthy example of his many experiments – to look through a closed door by setting up a fluorescent screen in the room next to his lab. Wilhelm Conrad Röntgen painstakingly studied the properties of the unknown rays and tested the permeability of rock powder, zinc, aluminum, and a whole variety of other substances. In addition, he searched for metals that could deflect or stop the rays and observed their speed as they travelled the various substances.

Wilhelm Conrad Röntgen in 1900

Source: German Röntgen Museum


Ueber eine neue Art von Strahlen
von W. C. Röntgen.
(Vorläufige Mittheilung.)
1. Lässt man durch eine Hittorf'sche Vacuumröhre, oder einen genügend evacuirten Lenard'schen, Crookes'schen oder ähnlichen Apparat die Entladungen eines grösseren Ruhmkorff's gehen und bedeckt die Röhre mit einem ziemlich eng anliegenden Mantel aus dünnem schwarzem Carton, so sieht man in dem vollständig verdunkelten Zimmer einen in die Nähe des Apparates gebrachten, mit Baryumplatincyanür angestrichenen Papierschirm bei jeder Entladung hell aufleuchten, fluoresciren, gleichgültig ob die angestrichene oder die andere Seite des Schirmes dem Entladungsapparat zugewendet ist. Die Fluorescenz ist noch in 2 m Entfernung vom Apparat bemerkbar.
Man überzeugt sich leicht, dass die Ursache der Fluorescenz vom Innern des Entladungsapparates und von keiner anderen Stelle der Leitung ausgeht.

First page of Röntgen's handwritten manuscript *On a New Kind of Rays*

Source: German Röntgen Museum

Röntgen recorded the results of his experiments in a ten-page paper entitled *On a New Kind of Rays*, which was written in clear language that was comprehensible even to the general public. He wanted to call the new kind of rays X-rays "for brevity's sake and to differentiate them from others of this name."

Source: German Röntgen Museum

The most sensational example of the early X-ray images: the bones of Bertha Röntgen's hand with wedding ring

In science, the letter X stands for the unknown, for although Röntgen gave a detailed description of the effects of X-rays in this first paper, their underlying nature remained a mystery. Were they electromagnetic waves such as those first demonstrated by the physicist Heinrich Hertz a few years earlier? Were X-rays actually related to visible light? Or were they made up of a stream of electrons like the cathode rays inside the tube? These questions would remain unanswered for a number of years.

In late 1895, after seven weeks of tireless work and without telling another soul about the X-rays, Wilhelm Conrad Röntgen decided to make his discovery public. He included a number of X-ray images with his paper to provide visible proof of the text's revolutionary content. The most sensational of these "shadow-pictures" – as Röntgen called them, taking his inspiration from the world of photography – was taken on December 22, 1895. By asking Bertha to place her hand on a photographic plate and "X-raying" it for 15 minutes, Röntgen took one of the most famous photos in the world: the bones of Bertha Röntgen's hand, showing a wedding ring that appeared to be floating around her finger. Wilhelm Conrad Röntgen was well aware of the storm that his paper and the shadow-pictures would unleash. When he submitted the manuscript for publication to the secretary of the Physical Medical Society of the University of Würzburg on December 28, he said to his proud and happy wife: "So, now all hell will break loose."

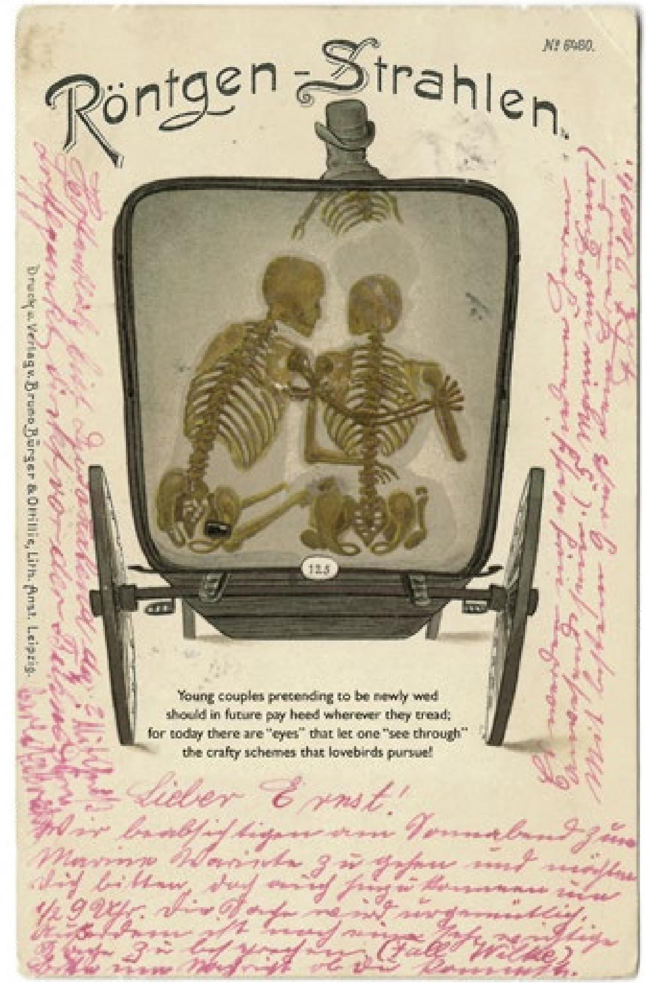
All hell breaks loose

The months following the announcement were unprecedented in the history of science. Never before had a message spread around the world so quickly. The first article on the discovery of X-rays appeared on January 5, 1896, in the Austrian newspaper *Die Presse*. A day later, the news reached London, from where it was transmitted to North America by telegram. Within a few days, newspapers around the world were full with reports of these incredible magic rays. Years later, Röntgen would write: "I didn't even recognize my own work from the reports." Nevertheless, this veritable storm of publicity all stemmed from the first article in Austria.

The scientific community's initial skepticism quickly subsided – for one simple reason: In those days, virtually every physics laboratory was equipped with induction coils, cathode ray tubes, and fluorescent screens, and Röntgen's experiments could therefore be reproduced and confirmed with little effort. By mid-January 1896, the world was in the grips of "X-ray fever" or, as the commotion was known in America, "X-ray mania." Everything imaginable was X-rayed: purses, mummies, furniture – and above all the human body. At first, physicians began taking their patients to physics labs in order to use X-rays as a diagnostic tool. Before long, however, shadow-pictures had become a public spectacle, with innumerable images of living hands produced at fairs and private parties. Well-known toy manufacturers even offered very simple X-ray devices specifically aimed at classrooms and nurseries.

Opera glasses without X-rays

The commotion surrounding X-rays led to some bizarre concerns and comical situations, especially because they were initially mistaken for a new form of photography. A few weeks after the discovery was announced, a firm in London advertised the sale of "X-ray-proof underclothing" to protect people's privacy from these "all-penetrating" rays.



Some people had bizarre ideas about X-rays – as this postcard from 1901 demonstrates

On February 19, 1896, an American congressman in the state of New Jersey introduced a bill "prohibiting the use of X-rays in opera glasses in theaters." And a New York newspaper reported – in all seriousness – "that at the College of Physicians and Surgeons the X-rays were used to reflect anatomic diagrams directly into the brains of the students." This, the report said, gave a much more enduring impression of the anatomical details than conventional teaching methods.

Physicians and physicists of the day also recounted a number of peculiar anecdotes. For example, one reported that "two elderly ladies walked into a room" containing X-ray apparatus "and solemnly seating themselves requested me to close and fasten the door. Upon my complying, they said they wished 'to see each other's bones.'" In another example, a "young girl, of the domestic servant class asked me in confidence" whether it would be possible to look through her fiancé "unbeknown to him to see if he was quite healthy in his interiors." The excitement triggered by X-rays would go on like this for several months – but the man responsible for their discovery showed little such enthusiasm.

A man of few words

In an interview with a Munich daily newspaper on January 19, 1896, Wilhelm Conrad Röntgen was already expressing his desire for the furor around his discovery to subside. This "man of few words," as one of his biographers described him, didn't like to be the center of attention and preferred to work quietly. Indeed, Röntgen only spoke about his discovery twice in public: At the invitation of Kaiser Wilhelm II, he gave a first talk on January 13, 1896, in the "star chamber of the royal palace, hastily and temporarily converted into a laboratory." One newspaper reported that he "was richly rewarded simply by the insightful interest of his illustrious listener." Moreover, he "gained public approval, among other things, when His Majesty himself presented him with the Order of the Crown, 2nd Class." This was just the first of many honors that Röntgen would receive over the coming years. The second was of a linguistic nature, and he received it – somewhat reluctantly, by all accounts – at his second and last talk, which was also the only one he gave before a large audience.

On January 23, 1896, Röntgen walked into the lecture room of the Institute of Physics at the University of Würzburg to thunderous applause. Every last seat was filled, and those in attendance waited, as a contemporary witness later recalled, "with great excitement and enthusiasm" for this "extraordinary demonstration" to get underway. Röntgen began by saying a few modest words of thanks for the audience's interest in his discovery, before remarking that he thought it his duty to speak publicly about his work. He mentioned his experiments with cathode ray tubes on the evening of November 8, 1895, during which he made his discovery "by accident." Röntgen performed a series of experiments, X-raying wood, paper, a sheet of metal, and his own hand, before exhibiting a number of X-ray images. At the end of his talk, he asked his friend – the famous anatomist and privy councilor Albrecht von Kölliker – for permission to photograph his hand with X-rays. "As the successful photograph was passed around, tremendous applause broke out," one of those present would later recall. "An excited von Kölliker gave a rousing speech" in which he proposed that X-rays henceforth be called Röntgen's rays. "This suggestion was adopted amid renewed applause for Röntgen." Wilhelm Conrad Röntgen preferred – and continued to use – the term "X-rays," but the expression "Röntgen's rays" gained temporary currency, even at the international level, and remains the common term in German-speaking countries today.

Mockery and a trip to Sweden

Wilhelm Conrad Röntgen genuinely seemed to attach little value to the numerous honors and awards he received over subsequent years. For example, it took some cunning to persuade him to pose for a monument on the Potsdam Bridge in Berlin. Röntgen steadfastly refused to do so until a close friend said to him: "You're going on the bridge anyway, but if you don't do us the favor of granting the artist a sitting, the monument will prove to be very unsatisfactory. Surely you wouldn't want that." As was customary at the time, he wore his Order of the Crown on his chest for festive occasions – but he often attached it incorrectly, as his housekeeper, Käthe Fuchs, later recalled: "This led to much mockery from the other Knights – after all, the requirements were very precise."

With Röntgen set to receive the Nobel Prize in Physics in 1901, he sent a telegram to Sweden asking whether anyone would mind if he didn't attend. The Nobel Committee informed Röntgen that it would probably be better to come. On December 7, 1901, Röntgen embarked on what was then a long and arduous journey to Stockholm. The first stage – a train from Munich to Berlin – took around 12 hours, as trains ran at an average speed of some 40 kilometers an hour in those days. After another train journey to the island of Rügen, Röntgen boarded a ship bound for Malmö – or rather, as he wrote in a letter to Bertha, a "nutshell" that was tossed up and down on the waves. In Stockholm on December 10, the anniversary of Alfred Nobel's death, Wilhelm Conrad Röntgen received the first ever Nobel Prize in Physics. After the ceremony, he was nowhere to be seen – and he even managed to escape giving an acceptance speech, which is actually stipulated in the foundation's statutes.

On December 10, 1901, Röntgen received the first ever Nobel Prize in Physics

Source: German Röntgen Museum

Like a magical cure from another world

Alfred Nobel, the Swedish inventor and industrialist, wrote in his will that the Nobel Prize was to be awarded "to those who, during the preceding year, have conferred the greatest benefit to humankind." It was only in subsequent decades that it became clear how immeasurably useful X-rays would be in the natural sciences. In numerous disciplines – such as physics, chemistry, biology, and astronomy – we now use X-rays to visualize things that would have remained invisible to us without the help of this tool: the structure of atoms and genes, the environment surrounding black holes in the center of the galaxy – and new discoveries are constantly being made.
In medicine, on the other hand, the value of X-rays was clear right from the beginning: In January 1896, the first physicians had already begun using them in certain examinations. For many practitioners, these previously unimaginable insights into patients' bodies triggered nothing less than euphoria. The military surgeon Ernst Sehrwald wrote: "X-rays almost have the aura of a magical cure given to us by a helping hand from a totally alien world."

With X-rays, the age-old dream of the "glass patient" had finally come true. Almost from one day to the next, many diagnostic procedures were utterly transformed. For example, the examination of a gunshot wound could cause the patient additional pain, as it required the physician to stick their finger – or a probe – into the wound to determine where the bullet was lodged. The diagnosis of a broken bone must have been equally unpleasant for patients, for physicians had no choice but to apply pressure to and mobilize the affected part of the body in order to determine the approximate type and location of the fracture. In the ideal scenario, other medical issues could be investigated by inserting mirrors and lights into body orifices to get as close as possible to the target location. But many cases would probably never have been solved were it not for X-rays, as illustrated by the following example of a child who – shortly after Röntgen's discovery – was taken to the hospital suffering from prolonged fits of coughing over several hours.

In October 1896, an Austrian medical journal cited the child's examination as an example of the significance of X-rays in the field of internal medicine: A ten-year-old boy swallowed a carpet tack and immediately began suffering from shortness of breath. The physician conducting the examination probed the boy's esophagus with a tube but encountered no resistance. As the tack seemed to have already slipped down into the stomach, the physician recommended that the child consume large quantities of mashed potatoes. The boy was in good health for several days before ultimately being taken to the hospital with a very bad cough. During his fits of coughing, which lasted up to an hour and a half at a time, a wheezing noise could occasionally be heard. The sound seemed to be coming from somewhere in the boy's chest, but investigations revealed nothing wrong with his lungs. "The patient was then X-rayed," first from the front and then from right to left, "revealing that the foreign body was located between the sixth and seventh rib near the spinal column."
In a subsequent X-ray examination during one of the child's fits of coughing the physician could even observe that "the tack was jumping up and down with its head pointing downward and tip pointing upward." Nevertheless, this jumping carpet tack is a relatively unspectacular example compared with other cases – over the years, X-rays have revealed a whole host of swallowed items, including frogs, toothbrushes, and even forks.

By spring 1896, reports were emerging on a daily basis of important diagnoses, new research, and ideas for future developments. Pioneering radiologists were studying the use of X-rays to image the stomach and intestines, sometimes with seemingly far-fetched suggestions, such as guiding a fine metal wire through the esophagus and around the outline of the stomach as a sort of X-ray plate to depict the size of the organ. But the "physicians of phototherapy" – as the radiologists soon came to be known – faced a series of technical obstacles: "For beginners, the correct handling of the tubes can prove quite a challenge," wrote the pioneering radiologist Heinrich Albers-Schönberg. "Many tubes were damaged by unwanted sparkover – in other words, disruptive discharge." Occasionally, the tubes shattered "with a loud bang, spreading tiny fragments of glass in all directions." Albers-Schönberg therefore suggested covering the patient's face with a cloth "to protect their eyes in the event that the tube should smash." This problem was compounded by the fact that cathode ray tubes were originally designed for studying gases and either couldn't produce X-rays or required great dexterity, a sufficient knowledge of physics, or sheer luck on the part of the user. However, researchers in Berlin and Erlangen were already working on a solution in January 1896.

Whispers, awe, and quiet disbelief

Siemens & Halske and Reiniger, Gebbert & Schall (RGS) – the two oldest ancestors of Siemens Healthineers – were competitors in those days. Since Siemens & Halske was founded in 1847, it had been manufacturing electromedical apparatus for the treatment of pain, for example. Meanwhile, 450 kilometers away in Erlangen, RGS, founded in 1886, was dedicated to medical technology and the construction


Source: Medical University of Vienna

X-ray of a swallowed fork

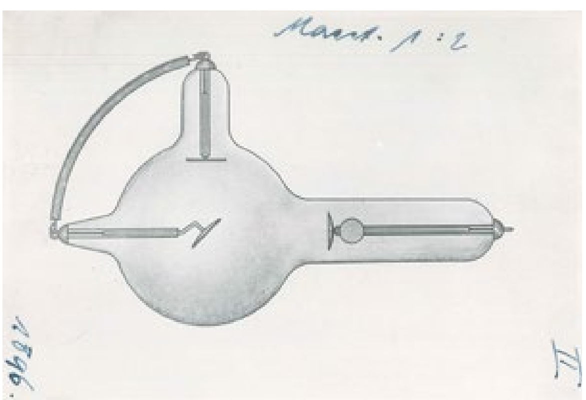
of electrotherapy devices, light baths, and electric dental drills, among other things. Before RGS merged with the medical technology division of Siemens in 1925, the two companies were locked in a fierce competition to supply the most advanced technology – and, from 1896 onward, this competition centered around the development of X-ray technology.

Three days after the discovery was announced, Max Gebbert, the owner of Reiniger, Gebbert & Schall, dispatched one of his employees, an engineer by the name of Robert Fischer, to Würzburg. Fischer had instructions to visit Wilhelm Conrad Röntgen and discuss his findings. However, a file in the Siemens Healthineers MedArchiv reveals that "Röntgen did not receive Mr. Fischer, as he was refusing visits altogether." Instead, he referred Robert Fischer to one of his assistants, who "demonstrated the very modest apparatus to Mr. Fischer in operation." Following Fischer's report, Max Gebbert enlisted the help of privy councilor Eilhard Wiedemann, a physicist at the University of Erlangen who already had some experience with cathode ray tubes. Wiedemann recommended several experimental setups and proposed to Gebbert that RGS take on his young assistant, the electrical engineer Josef Rosenthal.

In this pioneering era of medical X-ray technology at Reiniger, Gebbert & Schall, "whispers of amazement spread through the ranks," according to the memoirs of the mechanist Alexander Erdmann of his time at RGS. "The company immediately seized upon this area with a view to producing ready-to-use apparatus and equipment." Money was no object. "Sometimes I watched in quiet disbelief as copper coils costing many hundreds of marks went to scrap because they didn't meet the stipulated requirements." The man at the heart of this intensive research work was

Josef Rosenthal, who worked on the basic design of the X-ray apparatus. "I conducted my first experiments with the cathode ray tubes used in physics laboratories," Rosenthal later recalled. "As no one had any concept of the true nature of X-rays at that time, we tested every possibility, including whether the mysterious rays could be produced by overloading the filament of an ordinary light bulb. A number of light bulbs were burned out in the process – naturally, to no avail." Soon, Rosenthal realized that "the key to producing good X-rays was a particularly well-suited tube, and I succeeded in producing some outstandingly beautiful X-rays using such tubes in 1896." Josef Rosenthal used this type of X-ray tube, which was designed specifically for medical use, to create an image of a living 16-year-old girl's head – and sent the resulting radiograph to Wilhelm Conrad Röntgen in Würzburg. A few days later, RGS received what was probably the most pleasing correspondence in the company's history.

Josef Rosenthal sent this image of a 16-year-old girl's head to Wilhelm Conrad Röntgen in October 1896



Original sketch from 1896 of the first X-ray tube from RGS. Röntgen found this tube "really very good."

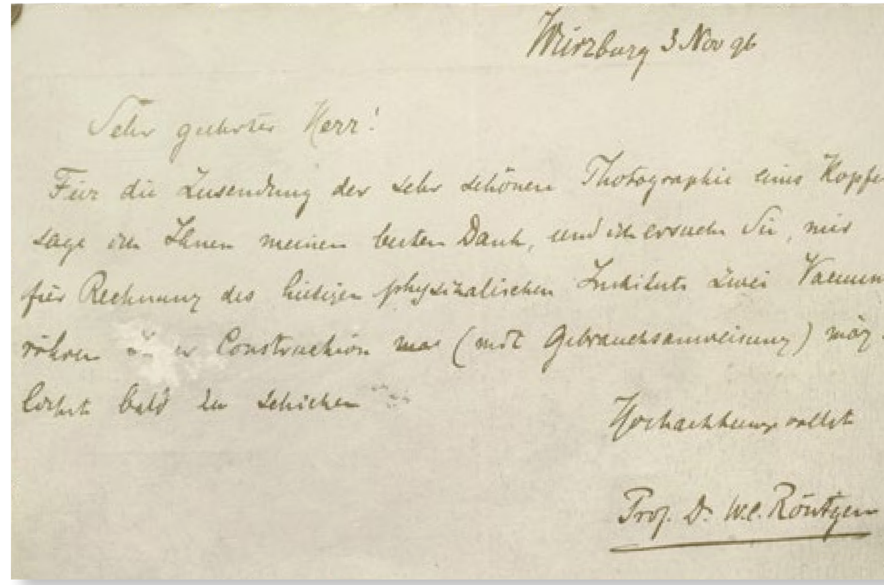
Königreich Bayern.

Postkarte.

An

Herren Reiniger, Gebbert & Schall

in Erlangen



Würzburg 3 Nov 96

Sehr geehrter Herr!

Für die Zusendung der sehr schönen Photographie eines Kopfes sage ich Ihnen meinen besten Dank, und ich ersuche Sie, mir für Rechnung des hiesigen physikalischen Instituts zwei Vacuumröhren Ihrer Construction mit (mit Gebrauchsanweisung) möglichst bald zu schicken.

Hochachtungsvollst

Prof. Dr. W.C. Röntgen

Probably the most pleasing correspondence in company history

“Your tubes are really very good”

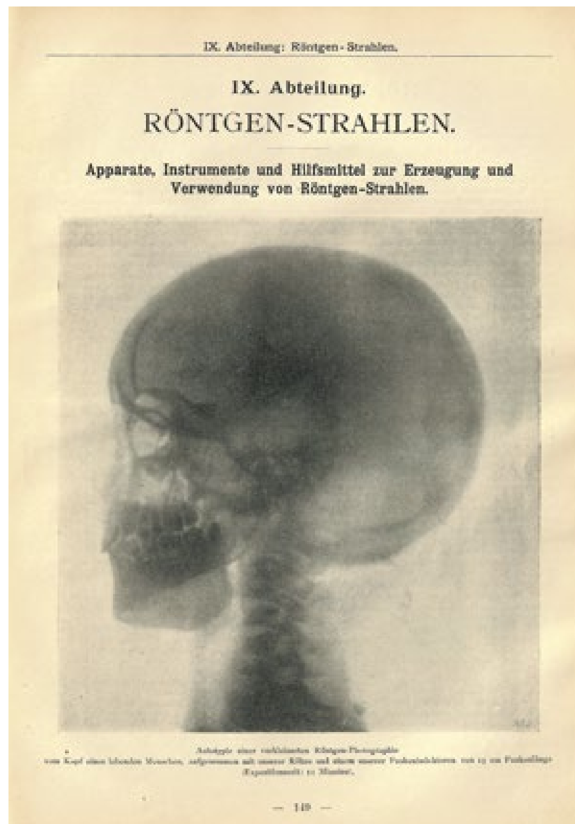
“Esteemed Sir,” Röntgen wrote on November 3, 1896. “My sincerest thanks for the very pleasing photograph of a head you dispatched to me. Pray send me, at your earliest possible convenience and for the account of the local physical institute, two vacuum tubes of your construction (together with instructions for use). Very respectfully yours Prof. Dr. W.C. Röntgen.” Rosenthal immediately dispatched two tubes and, some three weeks later, heard from Röntgen again – this time by letter and in rather more detail: “Your tubes are really very good,” Röntgen began his letter. But they were too expensive for his limited budget at the time. “I would like to ask whether you are able to let me have the tubes for twenty instead of thirty marks.” He believed this suggestion may be acceptable to RGS, as it was a special case “and you may be interested in having more orders from me. In case you should agree to this proposition, I should like to ask you to send four tubes of the same quality as the ones which I have used, two of the smaller and two of the larger size.” The suggestion must indeed have been acceptable to Reiniger, Gebbert & Schall – although this can no longer be confirmed from the archives – for Wilhelm Conrad Röntgen was holding one of the smaller RGS tubes in his hand when he posed as a model for the monument on the Potsdam Bridge.

From 1897 onward, RGS was the first company in the world to advertise “complete sets of X-ray equipment” with all that they entailed in those days: an induction coil, a battery to supply the power, a sturdy 1.75-meter stand mounted on wheels, and a solidly constructed iron table, as well as the

Source: German Röntgen Museum

Röntgen’s statue on the Potsdam Bridge. The statue was melted down during the Second World War. The head can now be found as a bust in Berlin’s Charité hospital "excellent, tried-and-tested vacuum tube to go with the inductor." Sales of this X-ray equipment rapidly became a huge success. In 1898, RGS was employing three times as many people as it did before the discovery of the X-ray – and had to expand its factory, which was still just a few years old, in order to keep pace with the huge demand. At that time, however, the company lacked a glass-blowing workshop of its own. The tubes were being produced – according to the designs of RGS – by the company Emil Gundelach in Gehlberg, close to the present-day Siemens Healthineers X-ray factory in in the German federal state of Thuringia, where there is glassblowing tradition stretching back for centuries.

Company catalog from Reiniger, Gebbert & Schall from the year 1897


IX. Abteilung: Röntgen-Strahlen.

IX. Abteilung.

RÖNTGEN-STRAHLEN.

Apparate, Instrumente und Hilfsmittel zur Erzeugung und Verwendung von Röntgen-Strahlen.

— 149 —


IX. Abteilung. Röntgen-Strahlen. Komplette Einrichtungen.

Preis-Liste über komplette Einrichtungen von Röntgen-Instrumentarien.

— 153 —

Our first medical X-ray tube is inspected by RGS employees Siff, Immelen, Horn, and Schnitzler in a photo probably taken toward the end of 1896 or at the beginning of 1897

No end of new discoveries

Much less is known about the development of the first X-ray tubes from Siemens & Halske. Historical sources indicate that basic research began at the laboratory in Berlin just three weeks after the discovery was announced. These initial experiments were plagued by the same problems as probably occurred in all physics labs in those days: First, the tubes lost their power very quickly if there was a change in the vacuum they contained; second, "it was unfortunately all too often the case that the tubes were punctured by sparks and therefore became unusable." However, the experiments showed "that there is still no end of new discoveries to be made in this area, and that the procedure can be made far simpler." By all accounts, the engineers from Siemens & Halske focused on rectifying these technical deficiencies during the development of their first X-ray system. By February 5, 1896, they had identified "a completely new setup that, with surprisingly good results, almost completely eliminated the risk of disruptive discharge."

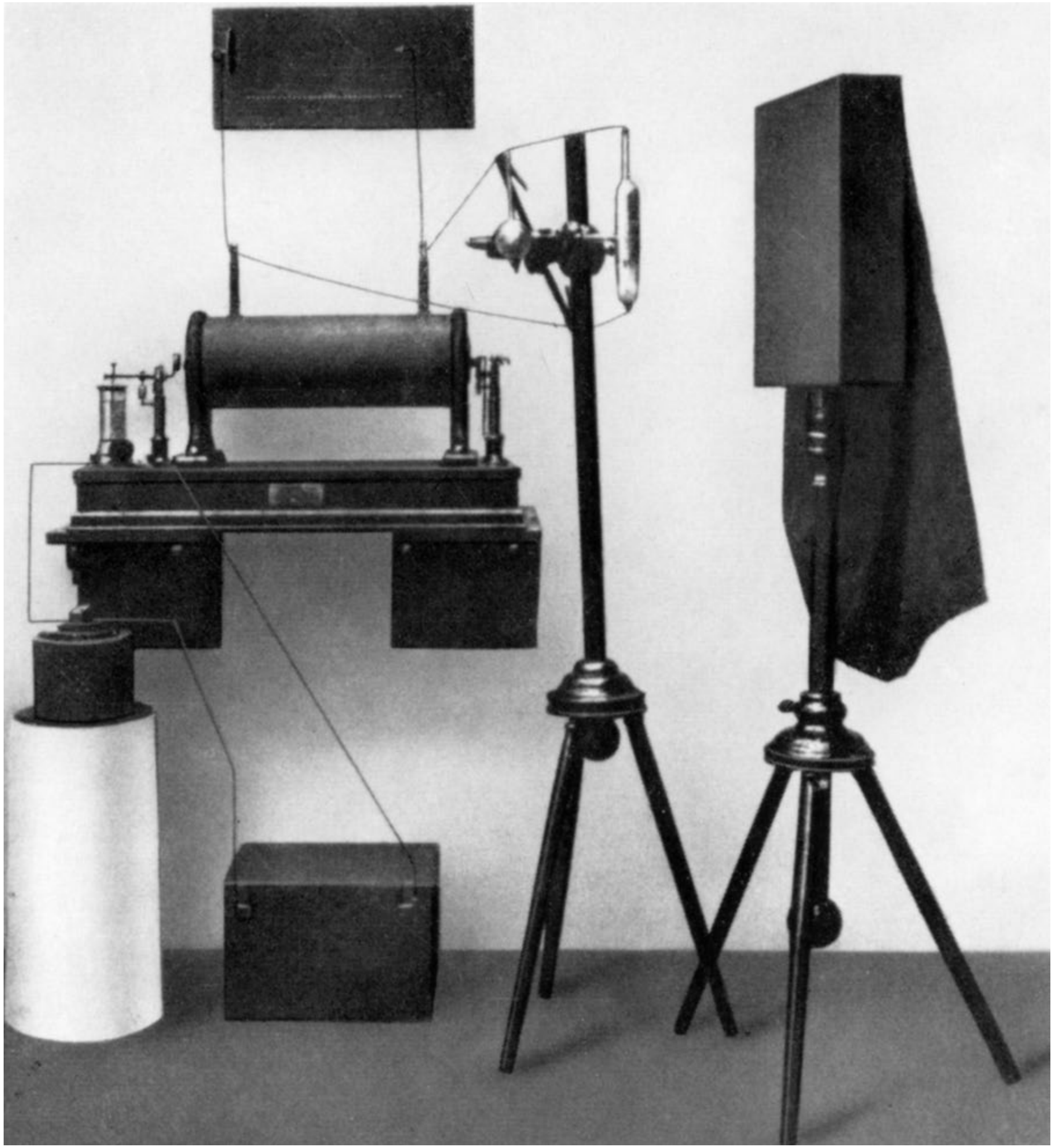
Some six weeks later, on March 24, 1896, Siemens & Halske also registered a patent for an unusual-looking tube. This "X-ray lamp," as it was advertised when it went on sale, was a tube with an adjustable vacuum. In other words, the X-ray lamp could be configured so that "the most favorable air pressure for the generation of X-rays" was always present during its operation. While this fundamental work was underway, editors from the *Elektrotechnische Zeitschrift*, a journal in the field of electrical engineering, "had the opportunity to see the setup in operation for themselves at Siemens & Halske's laboratory, where it was connected to the cable network of the electrical power station." To them, it seemed likely that, "on further development, the chosen approach would produce a practical solution to the problem of creating a suitable setup for hospitals and physicians." Continuing in this vein, the company first launched the X-ray lamp in January 1897, followed by the first full X-ray system from Siemens & Halske four months later – a few weeks after the development by their future colleagues in Erlangen.

The unusual-looking "Röntgen lamp" from Siemens & Halske in an advertising leaflet from January 1897

Joy and admiration

Röntgen's discovery transformed the world within a short space of time. In 1896 alone, there were 1,044 scientific publications on X-rays and their potential applications in science and medicine. Countless further discoveries emerged as a direct result of research into X-rays, such as the findings of Henri Becquerel and Marie Curie in relation to radioactivity. By the time of his death in 1923, Wilhelm Conrad Röntgen had received over 80 awards of one kind or another. Yet it is worth noting that, even during his lifetime, some claimed that Röntgen was not actually responsible for the discovery of the X-ray – and some people echo this claim today. In fact, it emerged shortly after Röntgen's publication that several scientists before him had already observed the phenomenon of these mysterious rays. None of them, however, had realized how remarkable the rays were or studied them in greater depth. Röntgen's undeniable contribution is to have done precisely that.

By 1905, the delegates at the first German Radiology Congress remarked that X-ray technology was "an indispensable tool in all specialties of human medicine." Even Wilhelm Conrad Röntgen was excited about the developments of the previous few years. In a telegram, he told those attending the Radiology Congress: "I am filled with joy and admiration for what the work of others has made of the discovery of the X-ray." The wealth of advances and potential applications of the first ten years had indeed been astonishing – but the technology's development was just getting started ...



The first series-produced X-ray system
from Siemens & Halske

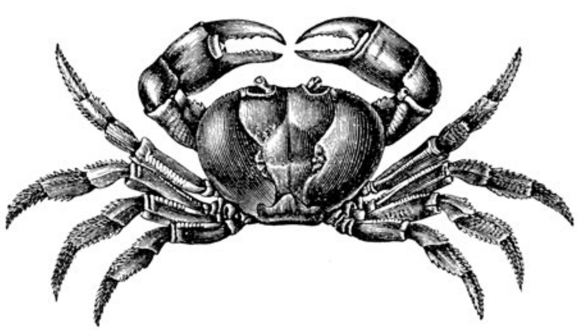
Operation to remove a patient's breast, overseen by the American surgeon David Hayes Agnew before students and colleagues. Painting "The Agnew Clinic" by Thomas Eakins, 1889

Source: Getty images

The battle against cancer

How X-rays became a form of treatment

In the year 1930, a papyrus from the 16th century BC was deciphered. In it, the renowned ancient Egyptian physician Imhotep describes medical case studies, diagnoses and treatments. Case no. 45 reads as follows: "bulging lumps in the breast, hard, without excessive warming, which progressively spread under the skin". It is the first known description of cancer. Under potential treatments for the disease, Imhotep simply remarks "none" . The famous physician Hippocrates also examined various growths in human organs. He found these tumors to be reminiscent of crabs burrowed in the sand, inspiring him to name the notorious disease 'Karkinos' – the Greek word for crab. Later, the more common term was the Latin translation of the word: cancer.



Black land crab, Gecarcinus ruricola

Source: Getty images

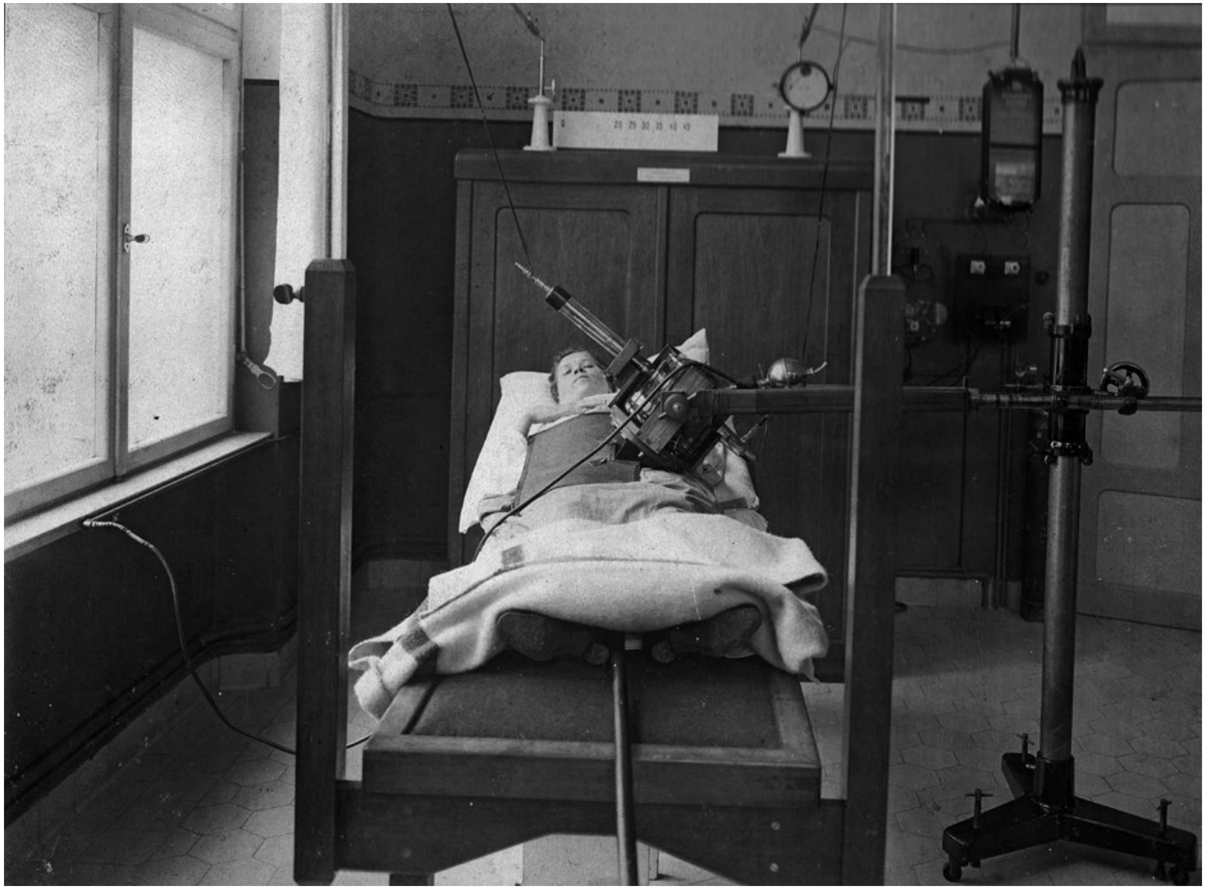
But what is cancer, and how does it develop? This question was first answered by Rudolf Virchow in the mid-19th century: Cancer is a disease that occurs when pathologically altered cells multiply in an uncontrolled manner. Given that all cells arise from other cells, its origin ultimately lies in a single cell. The uncontrolled and rapid multiplication of these cells leads to the formation of a tumor – what we now call cancer. Of course, Virchow knew nothing of the crucial inner life of cells – DNA. DNA is responsible for the specialization of individual cells and their role in the organism as a whole, and is replicated with each cell division. In this process, errors inevitably creep in; these errors are what we refer to as mutations. For the most part, mutations are either repaired, or lead to premature cell death, with no further repercussions. However, if the mutation affects a cell's growth mechanism, conferring growth advantages on it, the cell begins to divide and multiply without regard for the organism as a whole. In this sense, cancers are diseases caused by the mutation of critical genes. It is remarkable that mutations do not occur more often during the many trillions of times DNA is replicated within the body over the course of a lifetime, but in fact the error rate is only around one in a billion. Nevertheless, again and again mutations succeed in bypassing the body's defenses. This shows that cancer can arise in the body with no external influence whatsoever. However, in the presence of known risk factors such as certain toxins, viruses, radiation, or hereditary predisposition, the likelihood of cancer occurring is significantly increased. For instance, heavy smokers are ten times more likely to develop lung cancer than non-smokers. Yet, exposure to one or even all of these risks is still not guaranteed to cause cancer.

With the exception of leukemia, cancer generally begins as a local disease, and only later spreads to the rest of the body, becoming systemic. Between these two phases is a window of opportunity during which the cancer can still be treated locally. For a long time, surgery was the only available option to this end. With the rise of modern medicine in the mid-19th century, more and more doctors ventured to remove tumors by surgical means. Healthy and diseased tissue, however, cannot be reliably distinguished with the naked eye. As a result, the 19th century saw a trend toward increasingly radical operations in which large amounts of healthy tissue were removed in order to ensure that the cancer was fully excised. Unfortunately, this approach only led to lasting recovery in a minority of cases, while often leaving patients disfigured.

Experimental successes

The discovery of X-rays in 1895 revolutionized the field of medicine. To begin with, the ability to look inside the human body promised previously unimagined diagnostic possibilities. But just three weeks after Röntgen's discovery, the Hungarian pathologist Endre Högyes wrote: "There is no doubt that in addition to their chemical effect, the rays are also biologically active, and will one day play a therapeutic role in medicine." And so, researchers fascinated by the new technology set about exploring its therapeutic potential. One of the first was the physician Leopold Freund. In 1896, he treated a girl suffering from abnormal back hair growth with X-rays at the Vienna General Hospital. Of even greater significance are the trials conducted by 21-year-old medical student Emil Grubbe from Chicago. Grubbe, who worked in a factory that made X-ray tubes, observed that the factory workers exposed to X-rays lost fingernails and developed sores on their skin. In the course of his experiments, he also observed the same symptoms in himself. He decided to apply his observations of the destructive effect of X-rays on biological tissue to tumors: In 1898, Grubbe treated an older lady with breast cancer in what with hindsight can only be described as a reckless manner, shielding the healthy tissue with tin foil for protection. After 18 days of treatment, the effect was increasingly apparent: The tumor was shrinking. It was "the first documented local response in the history of X-ray cancer therapy." Reports of these early attempts at treatment were enthusiastically received by the medical community, sparking great optimism, although in many respects practitioners were still groping in the dark. For instance, no one knew how much radiation an X-ray tube emitted, or how to accurately measure radiation at all. In other words, the concept of dose was still foreign. Above all, however, no one fully understood the effect radiation had on cells, or how much radiation was needed to eliminate tumors. Yet, this is the decisive factor. Today, we know that X-rays or other forms of ionizing radiation can change the DNA contained within cells, and that exposure to radiation at sufficiently high levels causes irreversible damage, resulting in cell death. This effect is what makes X-rays a suitable tool for fighting cancer. At the same time, however, they also remain a threat given their ability both to destroy healthy tissue, and to provoke cancer.

Irradiation of a cervical carcinoma using the Symmetrie-Apparat, 1918

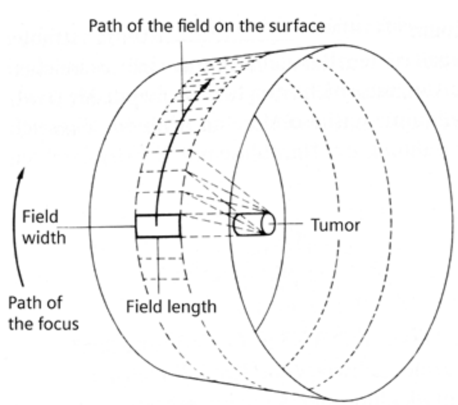


By modern standards, early X-ray tubes and equipment were quite unsuitable for therapeutic applications: "Above all, X-rays for cancer treatment must meet three requirements: they must allow precise focusing, have a high level of medium-energy radiation and as little low-energy radiation as possible." In those days, the available technology could not satisfy these criteria. Accordingly, physicians and engineers increasingly collaborated to build devices better suited for therapeutic purposes. The first major step in this direction was the X-ray tube developed by William Coolidge in 1913, which generated harder radiation able to penetrate further into the body. Friedrich Dessauer, a pioneer of radiation therapy, cites this development as the "crucial first step" in his memoirs. By 1913, the "Reformapparat" (Reform Apparatus) developed by Dessauer for deep therapy was in use in six German women's hospitals. Meanwhile, Reiniger, Gebbert & Schall (RGS) in Erlangen also created a successful X-ray device designed specifically for deep therapy, the "Symmetrie-Apparat" (Symmetry Apparatus). "The levels of hard radiation it yields exceed those of any other device," a senior doctor at the Munich women's hospital enthusiastically wrote in 1918.

As radiotherapy sessions often lasted for hours at a time, radiation protection became a key focus – even more so than in diagnostic X-ray procedures. In 1922, the "Siemens Bestrahlungskasten" (irradiation box) became the first Siemens device to reliably protect operators and patients from the harmful effects of deep X-ray therapy, such as radiation, but also high electric voltage. The development simplified treatment, while reducing the discomfort involved. It did, however, also require powerful and robust tubes and apparatus. Key components of the "Siemens Bestrahlungskasten" were the Stabilivolt and Multivolt systems, which provided a steady current and an effective radiation spectrum with less soft radiation, which is harmful to the skin. They were designed for continuous

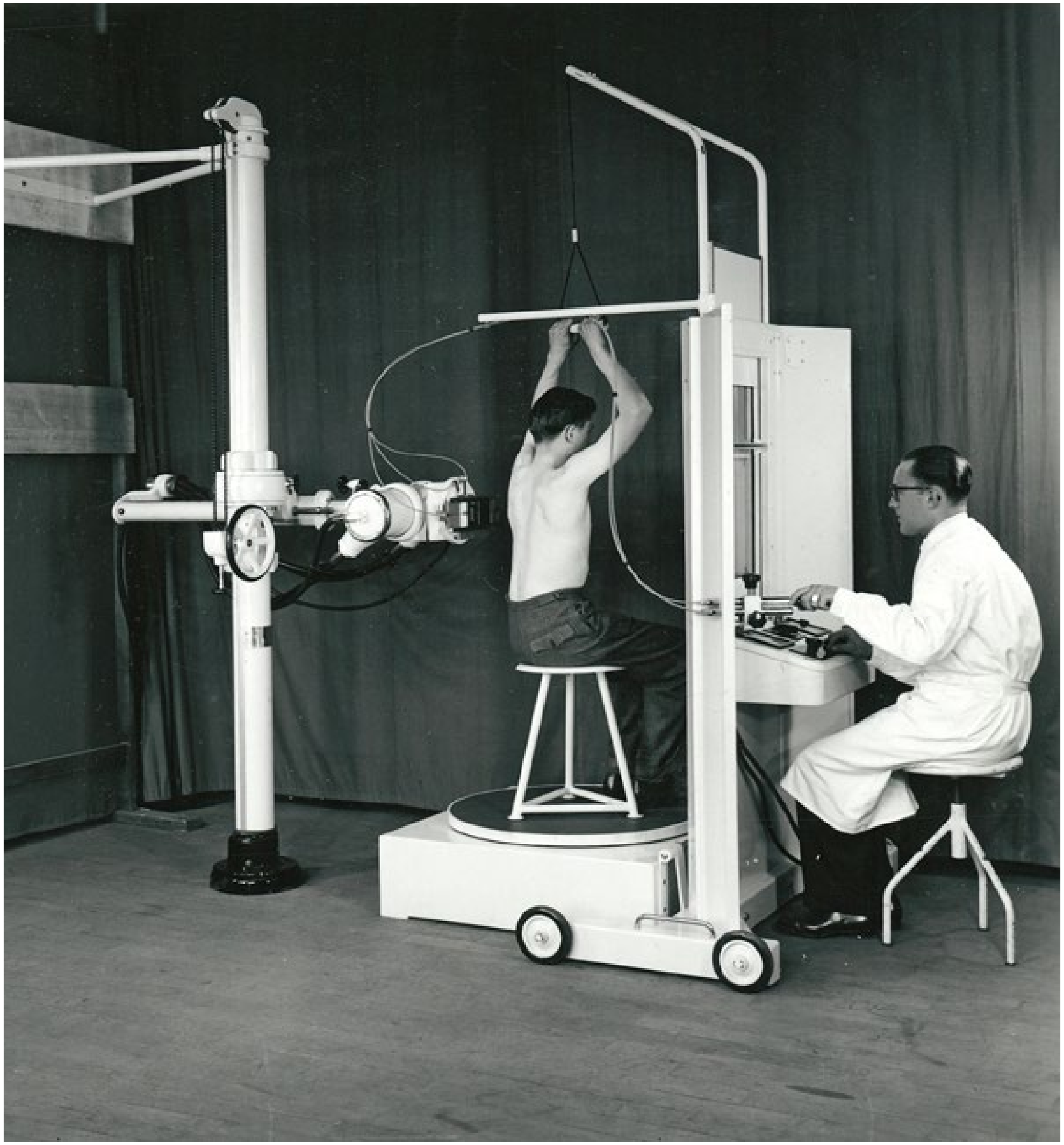
Siemens Bestrahlungskasten operated with a Multivolt apparatus, 1920 operation, and allowed shorter exposure times. The new system meant that besides university hospitals, smaller institutions could also afford to set up radiotherapy departments, making this form of treatment accessible to more patients.

In the 1920s, mounting evidence emerged in support of a theory that had already been held for some time: that rapidly dividing cells are considerably more prone to the effects of radiation. As this distinction was particularly true of cancer cells, it provided a way to differentiate between healthy and diseased tissue. The result was a transition away from high individual doses to regimes in which patients were exposed to smaller doses over the course of several sessions (an approach known as fractionation), giving healthy tissue a chance to regenerate. This was also the idea behind the multiple field technique, developed in the early 20th century, whereby the tumor is irradiated from different angles so as to concentrate the dose in the tumor and spare the surrounding tissue.



Source: Scherer, E. (Hrsg): Strahlentherapie 1978, p. 92

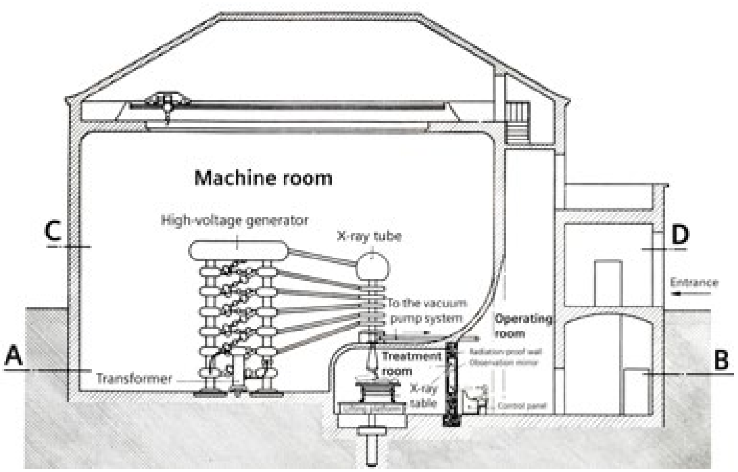
Principle of rotation therapy



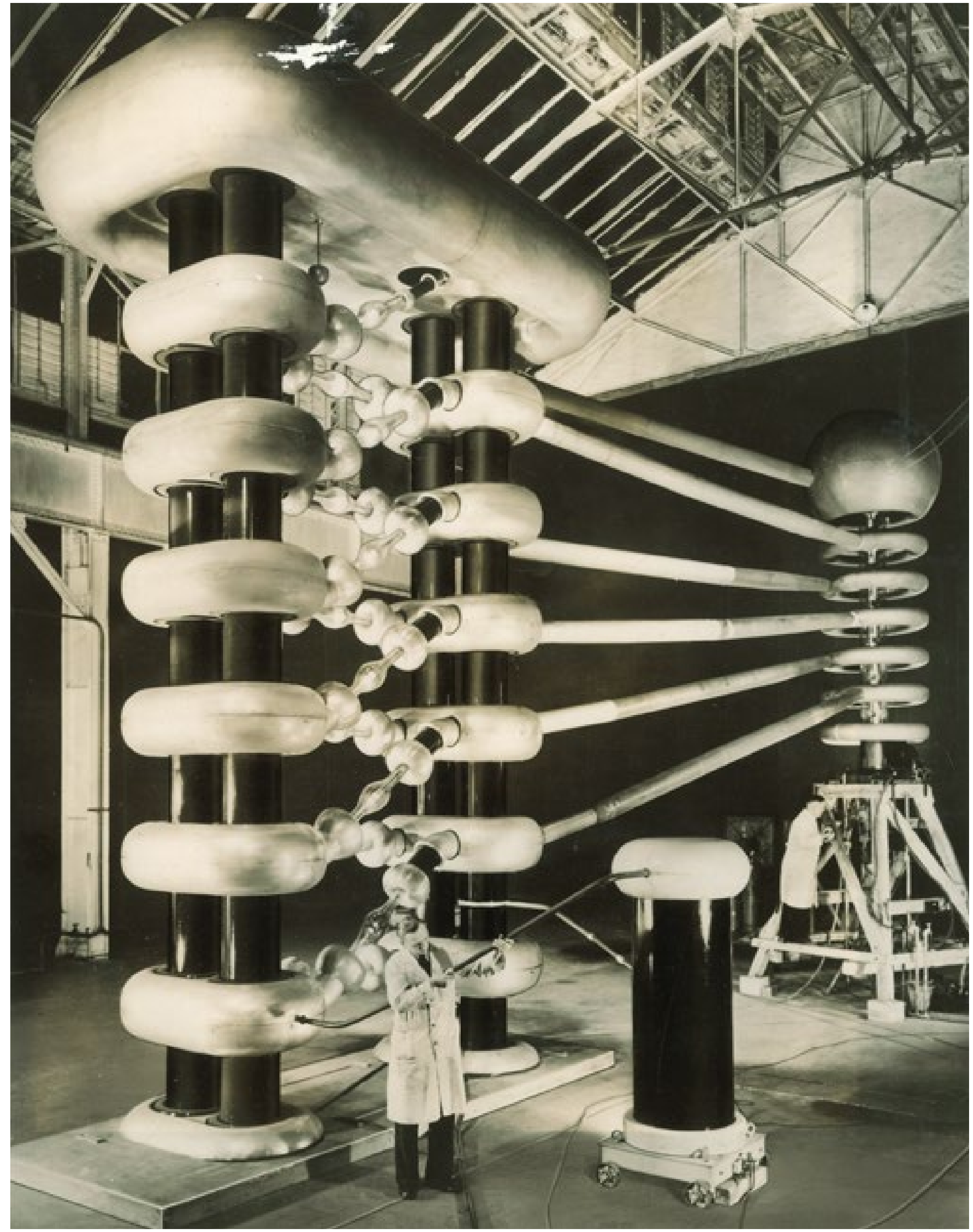
Rotation therapy, 1952

Beyond the surface

Despite these major breakthroughs in the field of radiotherapy, by the mid-1930s the limits of conventional X-ray devices had been reached. It was still not possible to generate X-rays hard enough to successfully treat deep-seated tumors, for which ultra-hard X-rays were necessary. Besides requiring high-performance tubes, this also called for very high voltages to power them. The plants needed to generate voltages on this scale were enormous. In the late 1930s, a plant with a capacity of 1 million volts was built for the Hamburg-Barmbek hospital. The colossal machine had to be housed in a building of its own, but was never actually put to use due to the war. In the end, a different approach turned out to hold greater promise.



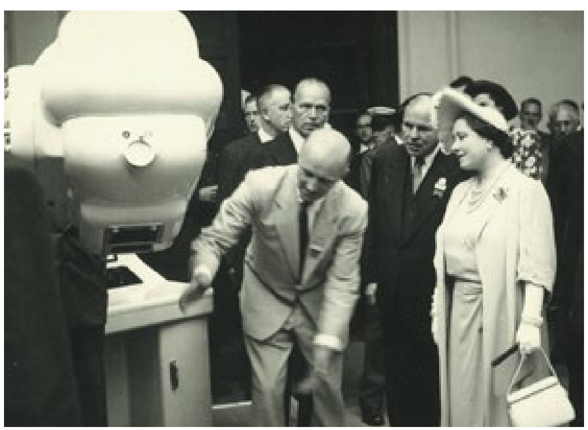
Cross-section of the 1-million-volt plant for Hamburg-Barmbek, 1939



Technicians working in the 1-million-volt plant for Hamburg-Barmbek, 1939

Since the 1930s, researchers in the USA and Germany had been experimenting with electron accelerators, which used electromagnetic fields to direct electrons along a circular path and accelerate them. This appeared to be an ideal method of generating very hard X-rays: when these high-energy particles were abruptly decelerated, the energy they released could be used in the form of ultra-hard X-rays. At the same time, the accelerated electrons themselves could also be used to irradiate the patient. Work on this technology at Siemens-Reiniger-Werke in Erlangen was led by the engineer Konrad Gund, beginning in the early forties, but had to be postponed due to the war. It was therefore not until 1950 that the Betatron circular accelerator was unveiled at the International Congress of Radiology in London. With this electron accelerator and subsequent models boasting even greater capacity, it became possible to sufficiently irradiate virtually any tumor anywhere in the body.

At the same time in California, the American company Varian – founded in 1948 – was researching the implementation of a concept that proved to be the ideal technology for radiotherapy: the generation of precise and energy-rich beams by linear accelerators (linacs). In the early 1950s, Varian and Stanford University worked together on a linear accelerator measuring almost 70 meters in length for use in studying atoms in the field of particle physics. This linac inspired Stanford professor and radiologist Henry Kaplan to make a suggestion that led to the invention of modern radiotherapy: He wanted to develop a medical linear accelerator specifically for treating cancer. In 1960, after a total of some nine years of development and clinical testing, Varian delivered the first "Clinac 6" models to UCLA (University of California Los Angeles) Medical Center in Los Angeles and to Henry Kaplan at Stanford University. With this medical linear accelerator, the treatment beam generated by a klystron could reach tumors deep inside the body with an energy of 6 million volts – and the Clinac 6 was the first system in the history of radiotherapy in which the radiation source could be rotated through 360 degrees around the patient.



Queen Elizabeth (known later as the Queen Mum) observes the Betatron at the International Congress of Radiology in London in 1950

Source: Varian

Varian revolutionized radiotherapy with the Clinac 6, about 1960

In 1975, Siemens also brought its first linear accelerator, known as the Mevatron, to market. Over the next two decades, in view of their growing operating safety combined with superior output and X-ray quality , linear accelerators ended up replacing circular models and other forms of radiation in the field of medical radiotherapy. Radiotherapy subsequently became established as the second pillar of cancer treatment alongside surgery.

In the 1950s, a third pillar of cancer treatment emerged in the form of chemotherapy, the foundations of which were laid in 1948 by Sidney Farber, a professor for pathology at the Boston Children's Hospital. Early trials of a drug to treat leukemia showed great promise, although it caused severe side effects, and the cancer returned after a short time. Nevertheless, research into new chemotherapy agents and their proper dosage and combination continued over the following decades.

The quest for precision

With the linear accelerator, any tumor could be reached – no matter how deeply it was situated in the patient's body. Using model measurements and calculations, clinicians were able to estimate roughly the amount of radiation reaching its target. However, determining the tumor's exact size and position was more difficult. On the basis of two-dimensional X-ray images alone, the task was virtually impossible. Planning of the radiation fields was guided by knowledge from anatomy textbooks and the bones in the vicinity of the tumor. Accordingly, the emergence of computed tomography revolutionized diagnostics, opening up entirely new avenues for radiotherapy. Besides more precise information on tumor size and position, radiation planning could also benefit from

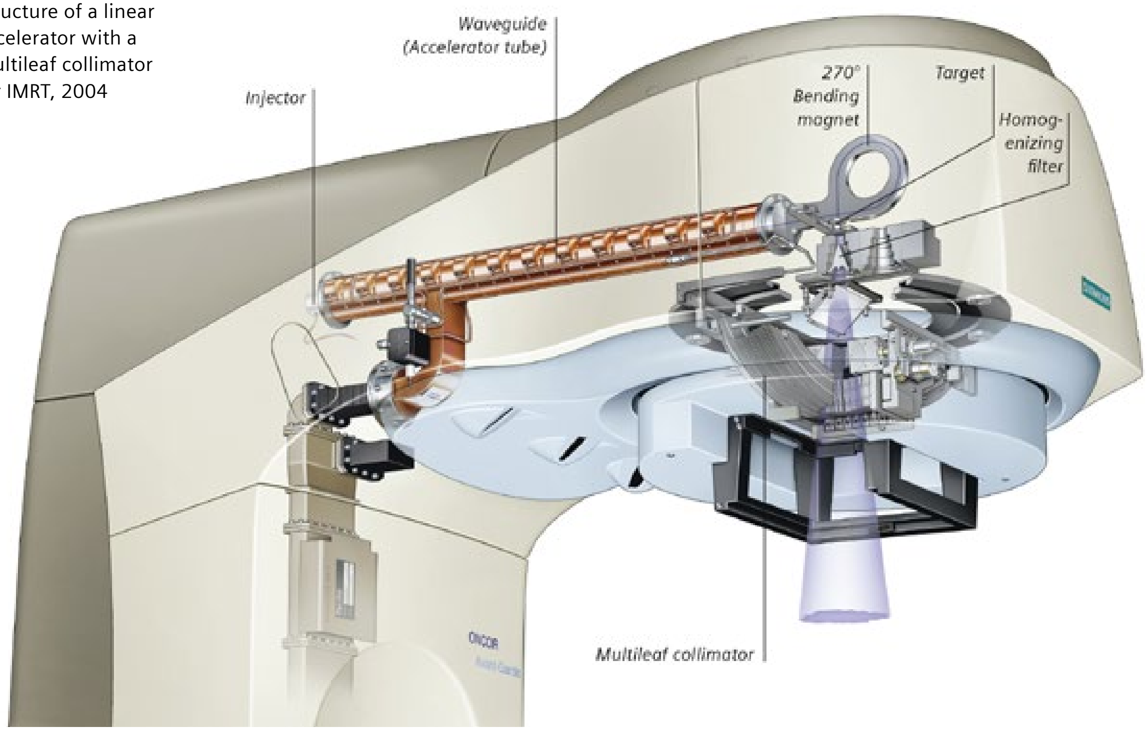
MEVATRON 6 , 1975

CT imaging data – although this required the patient to undergo irradiation in exactly the same position as when the images were captured. Various approaches were employed to this end, such as markings on the skin or special radiation masks. As a result, the radiation dose could, for the first time, be adjusted and calculated according to the target volume – the tumor – allowing even more accurate differentiation between diseased and healthy tissue, with a view to protecting the latter as effectively as possible. Moreover, CT scans made it possible to observe exactly how the radiation behaved in the body of each individual patient, further enhancing the precision of radiation fields and dose distribution. These calculations were aided by modern computers and special software for linear accelerators. Refinements in computed tomography (CT), combined with the development of magnetic resonance imaging (MRI), and above all positron emission tomography (PET) meant that tumors could be viewed in unprecedented detail, with all their ramifications, bulges, and indentations. Exploiting these complex images required increasingly sophisticated tools, leading to the development in the 1990s of intensity modulated radiation therapy (IMRT), in which special software and a multileaf collimator (MLC) – a device that shapes the X-ray beam – were used to almost exactly recreate the contours of the tumor with X-rays. The result was a sculpture consisting of a large number of individual X-ray beam segments with different dose distributions that very closely approximates the shape of the actual tumor, allowing the radiation to be targeted with a very high degree of precision.

Multileaf collimators were increasingly used in radiotherapy from the 1990s onward. While MLCs were initially available to buy as an add-on to linear accelerators, the MLC was incorporated as a fixed system component in the Clinac® EX product series, which was launched by Varian in 1997. Siemens also used IMRT technology and launched the PRIMUS linear accelerator in the same year, selling over 100 units in the first 12 months alone.

The growing precision of imaging techniques led to increasingly accurate focusing of X-rays on tumors, although this meant it was all the more important to control the patient's position during or immediately before radiotherapy. To this end, hybrid systems were developed that combined linear accelerators and CT scanners. In 2002, the Siemens PRIMATOM became one of the first hybrid systems on the market, and image-guided radiotherapy (IGRT) emerged as the new standard. With Dynamic Targeting™ IGRT, Varian also introduced a technique for image-guided radio-therapy into its systems. Meanwhile, given that tumors and their surrounding environment can also change during radiotherapy, there was a need for systems that could provide real-time monitoring and, where necessary, dosage adjustment during treatment. Launched in 2010, the TrueBeam® system from Varian

Structure of a linear accelerator with a multileaf collimator for IMRT, 2004



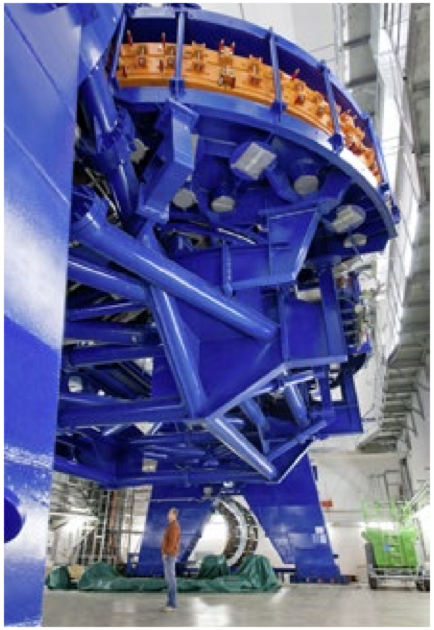
set standards in this regard, incorporating numerous technological innovations such as dynamic synchronization of imaging, patient positioning, and irradiation.

Varian, a company that has been part of Siemens Healthineers since 2021, played a significant role in driving forward the development of radiotherapy. The latest radiotherapy system, Halcyon™, simplifies and improves many processes in the field of image-guided, intensity-modulated radiotherapy and is intended to facilitate access to high-quality cancer treatment worldwide.

Yet, the quest for precision in radiotherapy finally reached its pinnacle with the development of particle therapy. In collaboration with the GSI Helmholtz Center for Heavy Ion Research, the first system in Germany was planned at Heidelberg University from 2001, and was built between 2004 and 2009. It is used for research purposes and for the treatment of patients taking part in clinical studies. Candidates for treatment include patients with particularly hard-to-treat tumors. This could be, for example, because the tumors are unresponsive to conventional radiotherapy or are surrounded by extremely radio-sensitive tissue. Rather than electrons, particle therapy employs protons or heavy ion particles accelerated to 75 percent of the speed of light in an accelerator ring many times larger than that of a Betatron. The key benefit of treatment with these particles is their inverse dose profile: They do not release their energy until deep inside the body, concentrating their destructive impact on the tumor. Particularly for tumors in critical locations, this form of treatment opens up new opportunities. However, the technical challenges involved have been immense. The entire system in Heidelberg takes up more than 5,000 square meters, while the gantry

TrueBeam® system, 2016.

Source: Varian



Gantry at the Heidelberg Ion Beam Therapy Center (HIT), 2012

Source: Universitätsklinikum Heidelberg

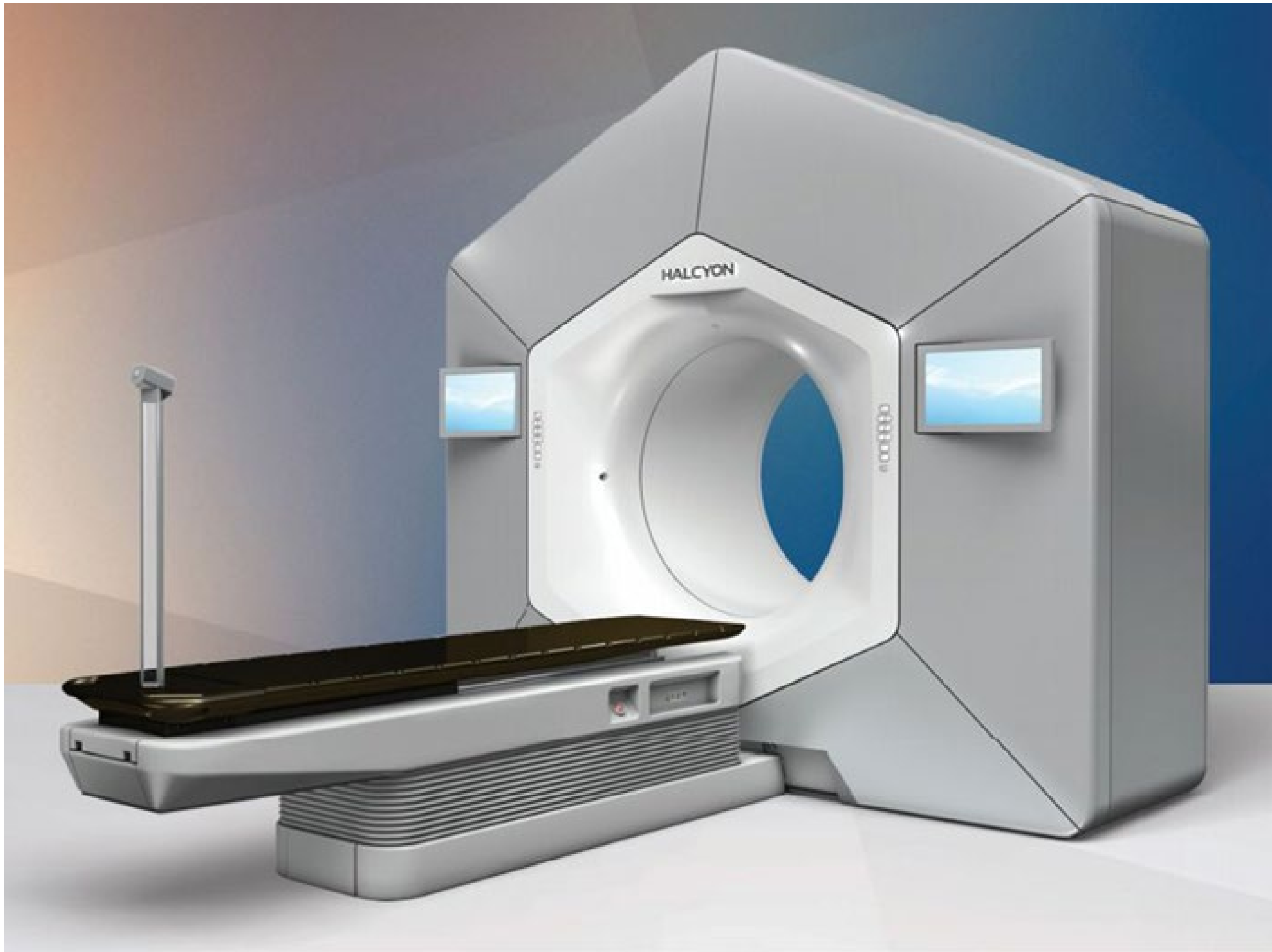
Treatment room ProBeam 360, 2021

Source: Varian

directing the ion beam alone weighs 670 tons. This allows the destructive beam to be securely aimed at a target measuring just a few millimeters in size, with a maximum deviation of only one millimeter. One form of particle therapy is proton therapy, and Varian installed its first complete ProBeam™ system for proton therapy at Scripps Proton Therapy Center in San Diego in 2014.

Prevention and risk

These developments notwithstanding, the prospects of successfully treating cancer still remain highest when the disease is detected at an early stage. For this reason, preventive checkups and screenings play a crucial role. Accordingly, in Germany, regular screening for colorectal cancer is recommended from the age of 50, and for skin cancer from the age of 35. The most prominent screening program is mammography for women between the ages of 50 and 70. Siemens Healthineers has catered to this need with its Mammomat range since 1972. Likewise, a screening program using low-dose computed tomography (LDCT) is being considered for one of the most common forms of cancer, lung cancer. For example, a study in the USA showed that this form of screening led to a 20-percent reduction in lung cancer mortality in high-risk patients. Mirroring the general trend in medicine, treatment is also increasingly personalized in the field of oncology, such that physicians can increasingly identify patients at greater risk of developing certain types of cancer, or medications that are more likely to be effective for a given patient. In the future, the ability to combine laboratory and imaging data will enable clinicians to customize treatment to the individual patient with ever greater precision, as well as allowing constant monitoring of the treatment's success.



Halcyon™ radiotherapy system, 2017

Source: Varian

Between 1974 and 1983, the quality of brain scans improved considerably

Monsieur Tan and the human brain

Neuroradiology – before and after the invention of computed tomography

As the Greek philosopher and natural scientist Aristotle pondered the enigmatic parts and organs of the human body some 2,400 years ago, he postulated that the brain was made up of the elements earth and water. According to his theory, this slippery mass inside our head, weighing approximately 1.4 kilograms, had only one task: to cool down the hot blood coming from our heart. He reached this conclusion partly based on the observation that the brain was the "coldest" and "most bloodless" part of the body. Moreover, while an injury to the heart meant instant death, a damaged brain often had less serious consequences – and could even be cured. Some 500 years later, the Greek physician Galenos of Pergamon, whose name is anglicized as Galen, contradicted Aristotle's theory. In examinations of dogs and sheep, Galen was unable to confirm the cooling function of the brain. Based on his numerous observations on animals, Galen subsequently applied his insights to humans and had the opportunity to examine wounded Roman gladiators. He studied how the gladiators' brains were affected by blows and incisions, as well as identifying the finer blood vessels of the brain and providing the first description of the central nervous system – although this turned out to be incorrect: According to Galen, nerves were hollow and resembled a system of ducts, allowing the spiritus animalis to flow through the body and control all of our physical and mental functions. Galen's theory became the accepted scientific doctrine and went almost unchanged for some 1,700 years. The history of modern neurology began in the mid-19th century. At that time – a few decades before the discovery of X-rays in 1895 – physicians still lacked the technical means to look inside the heads of living patients. However, the patient's symptoms and the subsequent autopsy did occasionally allow them to conclude how certain changes and injuries to the nervous system were connected with various ailments. These connections are exemplified by the two cases below, which are some of the most memorable in medical history: The first, that of "Monsieur Tan," because it led to the discovery of an important part of the language center in the brain, and the second, the accident suffered by Phineas Gage, because it provided a spectacular demonstration of how brain functions affect our character and even our morals.

"Tan-tan"

The 30-year-old Louis Victor Leborgne was fully conscious and alert when he was brought to a Paris hospital in 1840. Although he appeared to understand all of the physicians' questions, his answers always consisted of a single syllable – "tan" – which he repeated rhythmically, usually in sets of two, with varying pitch, and accompanied by expressive gestures. Word of Leborgne's case quickly got around, and he soon became known to the whole hospital as "Monsieur Tan" – but there was nothing anyone could do to help him. Twenty-one years later, with the cause of his speech disorder still unknown, Louis Victor Leborgne died of a different disease. The physician who had treated Leborgne, Pierre Paul Broca, performed an autopsy on him and discovered a structural change in the left hemisphere of the brain. Broca concluded that this part of the brain must be an essential part of our ability to speak.

As we now know from modern imaging techniques, this region of the cerebral cortex is indeed an essential part of the language center. Among other things, this section of the brain – known as Broca's area – is responsible for speech motor functions, articulation, and grammar. For the first time, the case of "Monsieur Tan" demonstrated the link between a speech disorder and tissue damage to the left frontal lobe. Similarly, a demonstration that other regions of the brain are also responsible for specific functions was provided by the almost implausible story of an American railroad worker whose miraculous survival of a blasting accident led to unexpected consequences for his friends and colleagues.

"Doctor, here is business enough for you."

On September 13, 1848, 25-year-old foreman Phineas Gage was overseeing the construction of a new section of railroad in the U.S. state of Vermont and set about blasting some rocks. His assistant would drill holes into the stone and fill them with gunpowder, covering the powder with sand to prevent accidental detonation. Phineas Gage would then ram this mixture deeper into the rock using his heavy tamping iron, which was over a meter long and three centimeters wide. Fairly routine; but late that afternoon, something distracted Gage from his work. As he turned around again, he rammed the tamping iron into another drill hole before his assistant could pour sand onto the gunpowder. The powder exploded, and the six-kilogram tamping iron shot through Gage's left cheek, eye, and frontal lobe – exiting through the top of his skull and landing some 25 meters away on the stony ground behind him. Phineas Gage lay unconscious for a few minutes but then stood up and was taken to his hotel in an oxcart. He sat on a chair on the veranda and waited almost 30 minutes for the doctor to arrive, greeting him with the words: "Doctor, here is business enough for you."

As a result of the accident, Gage lost his left eye and practically all of his frontal lobe – but had reportedly returned to full health within a few months. He could talk and solve intellectual problems as well as he could before the accident; his memory worked, and even his motor skills showed no signs of impairment. Yet his friends and colleagues soon noticed that Gage was "no longer Gage." Once a friendly, conscientious, and hardworking man, Gage had become a childish, coarse, and utterly unreliable individual, prone to outbursts of rage. The destruction of his frontal lobe had brought about fundamental changes in his personality. Phineas Gage's symptoms – which would today be described as frontal lobe disorder – led the neurologists of the day to conclude that the front sections of the frontal lobe must play a role in impulse control and behavioral planning, among other things. For a long time, cases such as those of Gage and "Monsieur Tan" were the only way to gain a slightly better understanding of the brain and its functions. Initially, even the discovery of X-rays would do little to change this, because the pioneers of X-ray technology faced a seemingly insurmountable problem: The soft, jelly-like brain could not be readily visualized using X-rays.

Phineas Gage with the tamping iron that passed through his head in September 1848, landing 25 meters behind him

Source: Fortschritte auf dem Gebiete der Röntgenstrahlen, Volume 2, 1898/1899

Two X-ray images from 1898, taken to determine the position of a bullet in a patient's head as accurately as possible

X-rays and a piece of kidskin

Wilhelm Conrad Röntgen discovered X-rays, as he called this unknown type of radiation, on November 8, 1895. From mid-January onward, countless images of living hands were produced around the world, and even these early images showed the bones in relatively sharp contrast and provided a clear picture of the internal structures. At the same time, the first physicians were studying the use of X-rays to image organs such as the stomach and intestines. With an exposure time of an hour, the technology was even used to capture the first images of the skull, allowing physicians to estimate the position of a bullet in a patient's head following a gunshot wound, for example. Nevertheless, one of the first neurologists to write about skull images of this kind believed that this was "likely to be the extent of the method's capabilities."

Two decades later, by which time some 200 methods had been trialed, physicians were still searching for an appropriate method for determining the precise position of foreign bodies in the brain. "Images of the skull are one of the most challenging areas of radiology," the pioneering radiologist Heinrich Albers-Schönberg wrote in 1913. The bones of the human head were, he said, too thick to allow the passage of X-rays in sufficient quantity. Nevertheless, he believed it "was certainly not impossible that as technology became more advanced, there would come a time when X-ray examinations would play a part in the localization of tumors." During the search for suitable techniques, it was important to protect patients as effectively as possible, as X-rays of the head still took several minutes in those days. "Specifically, to prevent any loss of hair in the event of repeated imaging," Albers-Schönberg explained to his students, "I place a piece of kidskin between the head and the X-ray equipment. This does not interfere with the image and affords sufficient protection."

Air in the head

Josef Rosenthal, who led the development of the first medical X-ray tube in the history of Siemens Healthineers in 1896, reported increasingly successful diagnoses by neurologists in his *Lehrbuch der Röntgenkunde* (Textbook of Radiology) in 1918. Among other cases, a 35-year-old man's epilepsy was reportedly found to be caused by a sewing needle stuck in the membrane lining his skull. When physicians performed an X-ray examination of another patient, who had previously been considered a malingerer, they identified the cause of his complaints: He had part of a knife blade stuck inside his head. For injuries to the spinal cord, X-rays had already proved to be "an extraordinarily valuable, almost indispensable tool" for the neurologists of the day. X-ray images "allowed many an accident victim whose complaints no one would have believed to receive the treatment they deserved."

Source: Max Cohn, Atlas der Röntgenstereoskopie, 1931

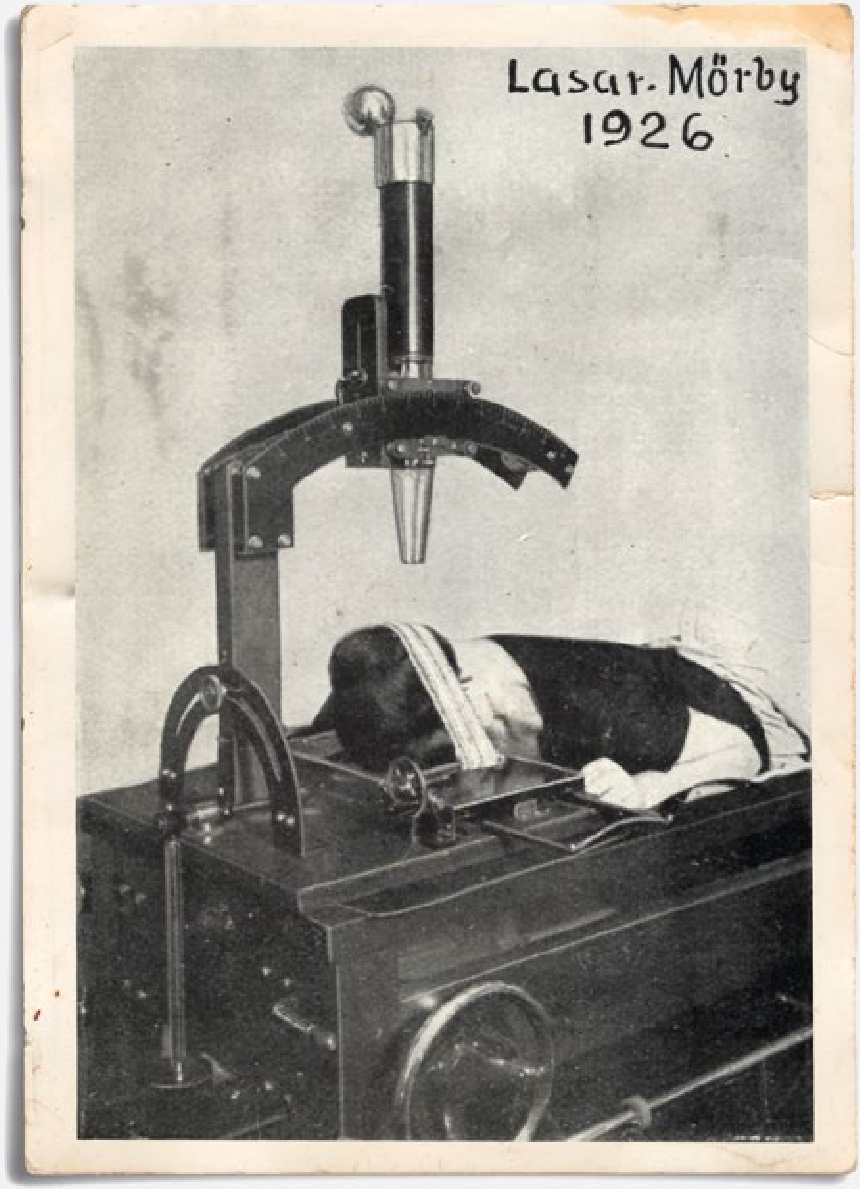
Image of the cavities in the brain, captured using iodized oil, 1931

By around 1920, it was even possible to detect some brain tumors, albeit primarily using two different methods, one of which was not very useful and the other of which was very painful for the patient. The first method could only be used at a very late stage in the disease, by which point the tumor was already so big that the pressure inside the head was deforming the inside of the skull, and allowed physicians to depict the resulting hollows in an X-ray image. The second method, which the radiologist J. W. Pierson described as "dangerous and complicated" in 1925, was known as pneumoencephalography and involved extracting cerebrospinal fluid – colloquially known as "brain fluid" – from the patient's lumbar spine and replacing it with the same amount of air, gas, or iodized oil. The subsequent X-ray image showed a relatively clear distinction between the air and the brain tissue. In addition to tumors, this allowed physicians to visualize and assess issues such as swelling and, under certain circumstances, even cerebral hemorrhages. However, the procedure was associated with a number of serious side effects. Apart from several days of vomiting and severe headaches, pneumoencephalography could also lead to seizures or even encephalitis. Writing in favor of the procedure, however, Pierson concluded that "in competent hands it should not be nearly so dangerous as neurosurgical exploration of the skull."

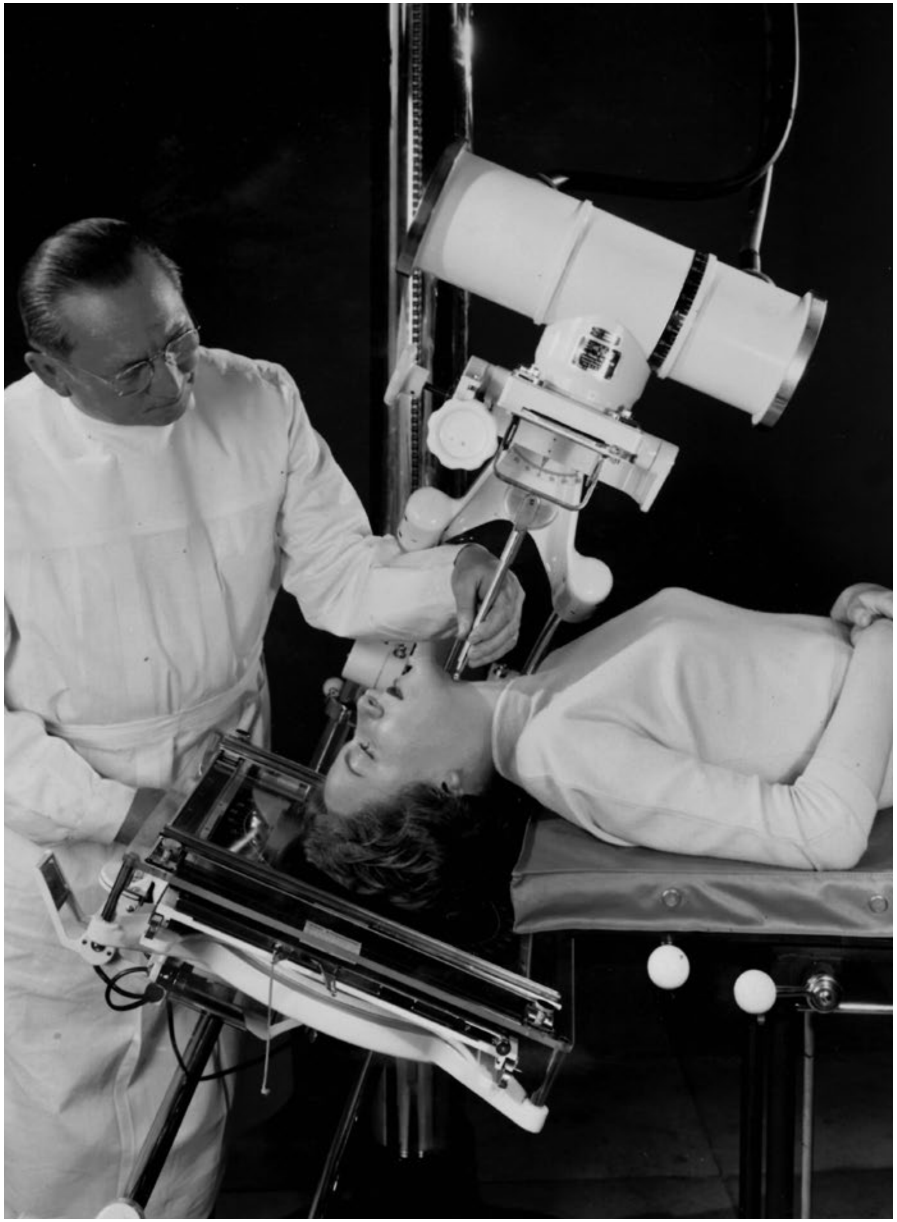
Orbiting the brain

Despite the painful nature of the procedure and its many side effects, pneumoencephalography remained the most important tool for localizing brain tumors for several decades. One of its most experienced users, the Swedish neuroradiologist Erik Lysholm, also worked on the imaging of brain diseases using X-ray contrast media during his time as Professor of Neuroradiology at the Karolinska Institute in Stockholm. From the mid-1920s onward, Lysholm developed the Lysholm Skull Unit in collaboration with Elema-Schönander – a company that later operated under the name Siemens-Elema and contributed numerous inventions to the history of Siemens Healthineers. Not least for the development of this apparatus, Erik Lysholm is now considered the founder of precision neuroradiology. This equipment for X-raying the skull quickly became world-famous and remained the standard apparatus for complex brain studies for decades, as well as providing the basis for many subsequent developments. The device brought colossal improvements in image quality compared with older techniques, but, from today's perspective, it still suffered from one significant weakness: The quality of the resulting image relied on the patient staying still throughout the examination.

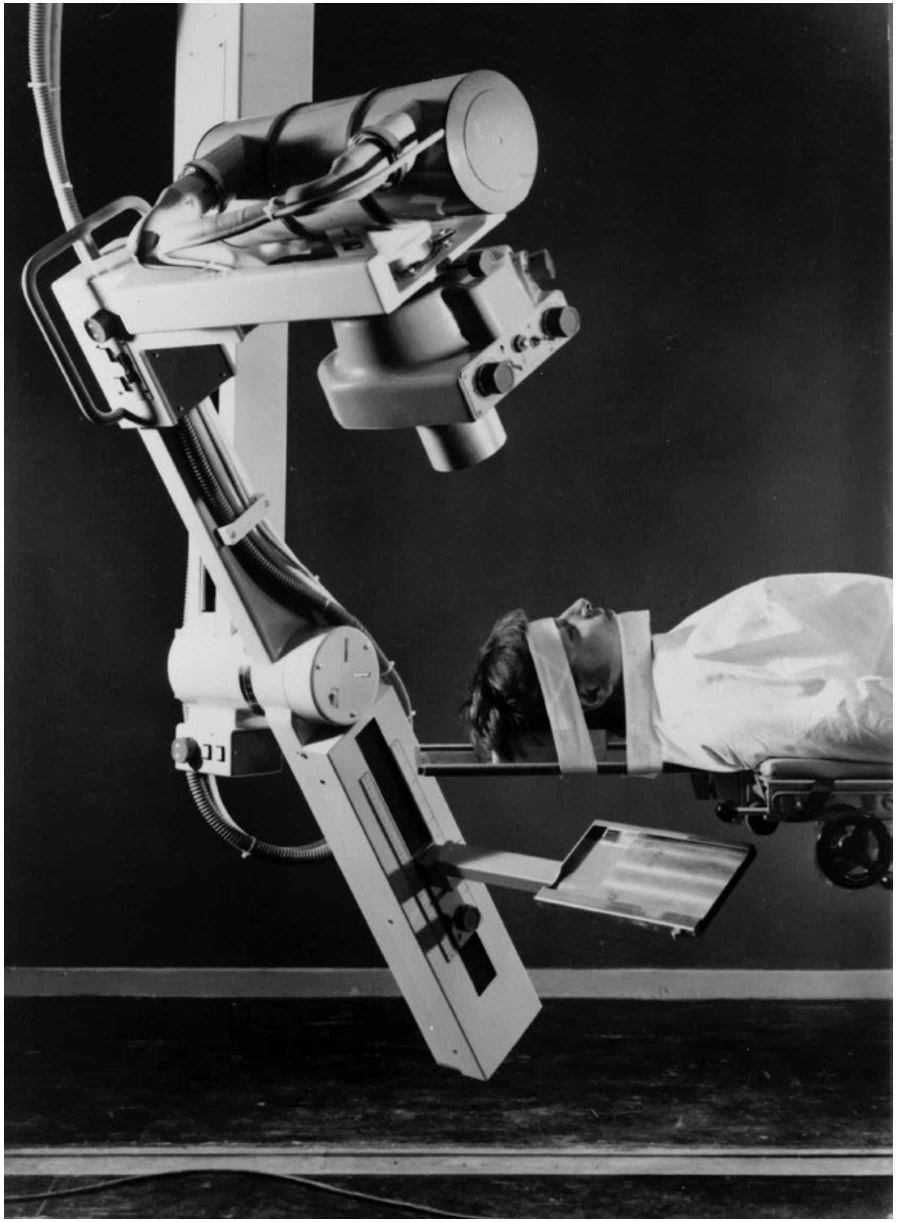
Until the end of the 1960s, all neuroradiological X-ray devices that were based on the same imaging technique as the Lysholm Skull Unit required the patient's head to be positioned as close to the X-ray film as possible. During the examination, the patient also had to adopt a number of rather uncomfortable positions. For example, certain lateral images were only possible if the patient twisted their cervical spine to an extreme angle while supporting themselves with their hand, and others required them to tilt their head as far back as possible.



The first model of the Lysholm Skull Unit served as the basis for numerous subsequent developments



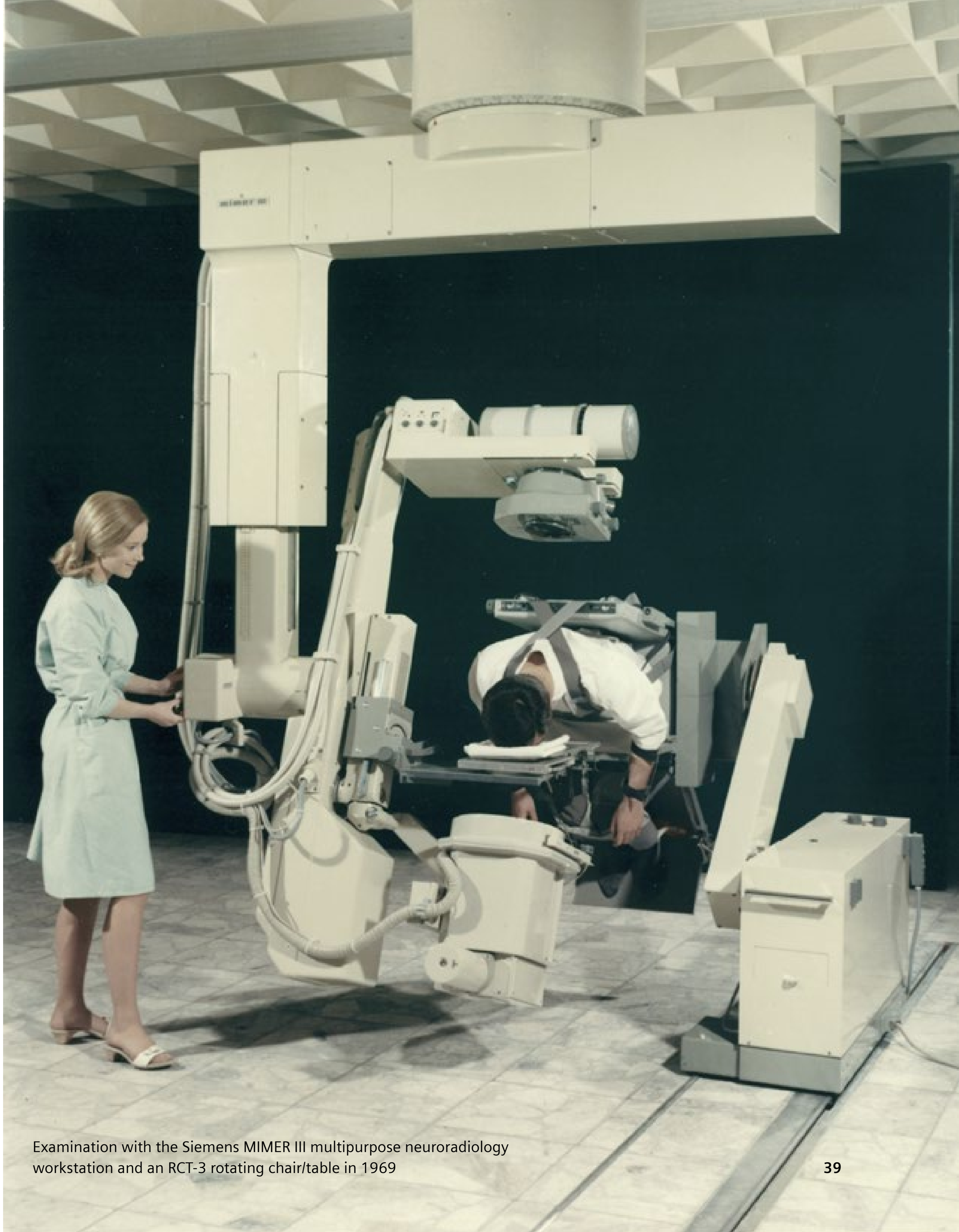
Examination with a Lysholm Skull Unit in 1956



The ceiling-mounted arm of the Orbix could be rotated freely around the patient's head

Patients with certain diseases – and many children – were therefore excluded from examinations involving this technique. It was not until the arrival of completely revamped X-ray equipment in the early 1970s that the examinations became significantly more comfortable. With the Siemens Orbix – developed by Siemens-Elema in collaboration with Erik Lindgren, the successor to Erik Lysholm in Stockholm, among others – the patient could lie on their back for any examination. The ceiling-mounted arm pivoted through 360° and could be rotated freely around the patient, whose head lay comfortably on a support while their neck rested on a stable foam pad. Although we take comfort features such as these for granted nowadays, they were considered innovations in 1970.

Although pneumoencephalography was still the most important tool for localizing brain tumors at the start of the 1970s, the X-ray equipment had by this stage achieved a remarkable degree of technical sophistication. For example, the Siemens MIMER III multipurpose neuroradiology workstation, complete with an RCT-3 rotating chair/table, automatically captured the numerous images required for pneumoencephalography without staff intervention, as well as allowing the inside of blood vessels to be visualized using angiography and even imaging of the spinal column with the help of contrast media (myelography). Unlike in the past, the radiologist no longer had to use a crank to position the X-ray device roughly by eye but could position it much more accurately using electric motors and illuminated crosshairs. Siemens opted not to continue developing the sophisticated specialized functions for pneumo-encephalography found in MIMER III – because a completely new and unexpected invention would soon render this painful procedure superfluous: computed tomography.



Examination with the Siemens MIMER III multipurpose neuroradiology workstation and an RCT-3 rotating chair/table in 1969

Viewing the brain in slices

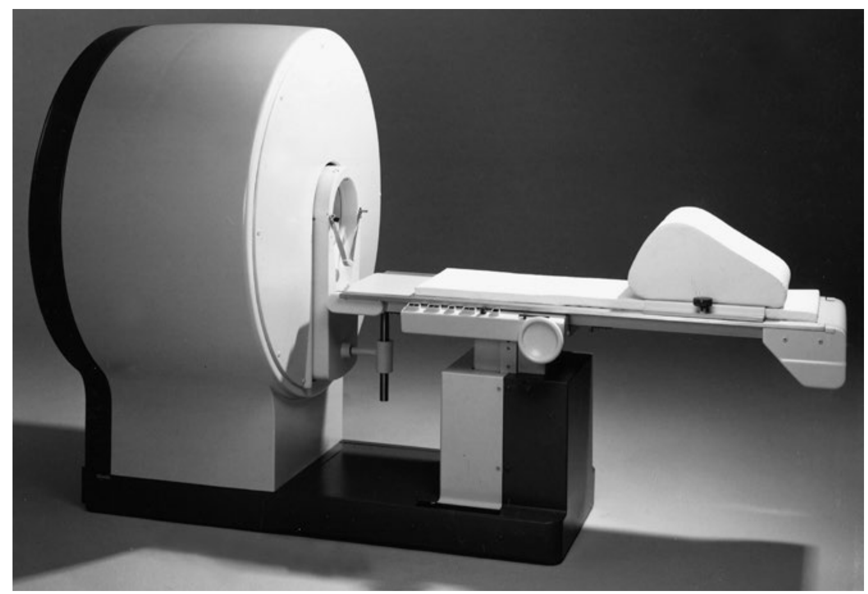
Computed tomography (CT) not only rendered pneumoencephalography superfluous, but also dispensed with one limitation of existing X-ray equipment that had previously made diagnosis more complicated: Devices such as the Lysholm Skull Unit or the Orbix imaged the patient from one direction. This resulted in two-dimensional X-ray images showing the brain and nerves as the X-ray device “saw” them from that direction. In these two-dimensional X-ray images, it was hard to tell whether a tumor was located in the front or back of the brain, how large the growth was, and how it changed over the course of therapy, for example. Moreover, conventional X-rays showed the structures inside the body superimposed on one another – in other words, the bones of the skull interfered with images of the brain. Tomography systems, on the other hand, produced slice images without superimposition, as if individual layers had been extracted from the body like slices of bread. By the early 1970s, computer technology was powerful enough to generate slices from multiple images taken from different angles. In a CT scan, the patient lies on the scanner table and is moved into the ring-shaped opening. This gantry, to use its technical name, is often colloquially referred to as the “doughnut” and contains a rotating measuring system with an X-ray tube and a detector on the opposite side. The X-rays pass through the patient and collide with the detector, which converts the measured values and relays them to a computer in order to generate the image.

The prototype of the first CT scanner in the history of Siemens Healthineers: SIRETOM in 1974

Legions of admirers

In 1972, Siemens began developing a prototype that could produce computed tomography images of the brain. Just two years later, researchers conducted the first trial runs with the cranium scanner – which went by the name SIRETOM – in a clinical setting. From June 1974 onward, a collaboration with the neurologist Hans Hacker and his team saw some 1,750 patients undergo scans at the Department of Neuroradiology at the Goethe University Frankfurt Hospital in Frankfurt/Main, Germany. Numerous physicians and medical technologists followed this first trial of SIRETOM with great interest. “Legions of visitors were brought to Frankfurt, including competitors, who admired the processing time, convenient use, and image reproduction alike,” recalls Friedrich Gudden, who was then head of CT research and development at Siemens in Erlangen. “SIRETOM was far superior to all other units on the market at the time.” Hans Hacker was another firm believer in the new technology and concluded in a report that computed tomography would “in the future be one of the most important methods used to investigate diseases and disorders of the brain, and SIRETOM can be viewed as a reliable and easy-to-operate system for this kind of scan.”

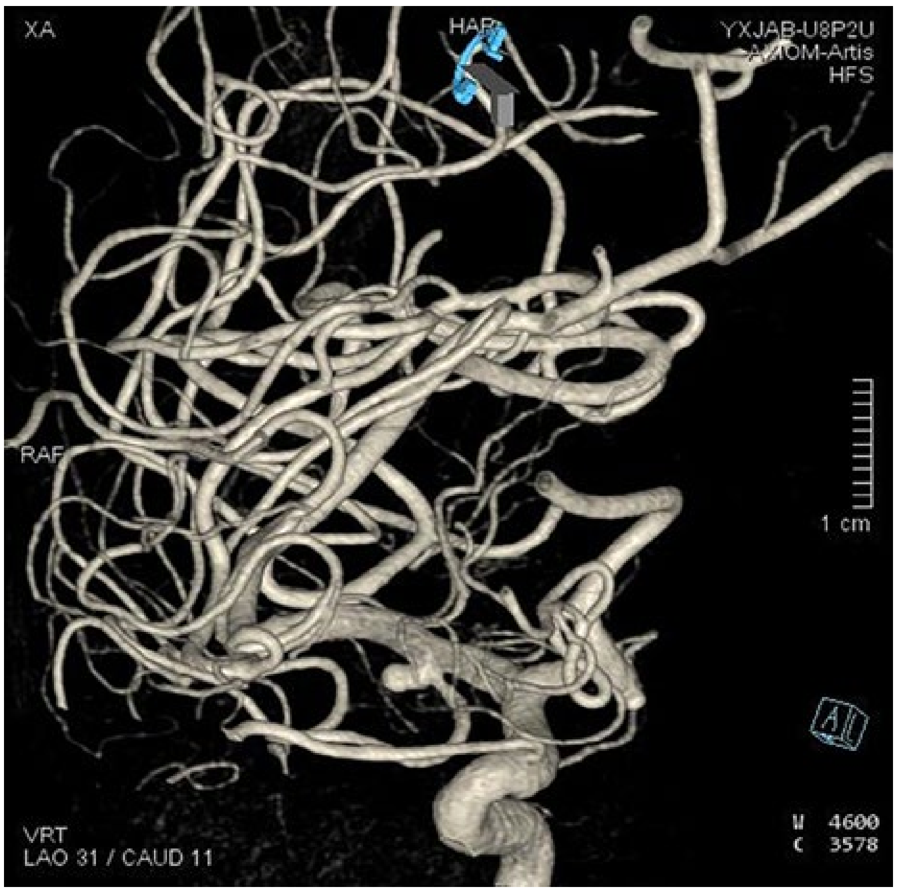
In terms of technology, there is a world of difference between our current CT scanners and SIRETOM, but even the first cranium scanners of the 1970s represented a giant leap forward compared with all of the X-ray systems previously available to neurologists. For the first time, diagnostically relevant images could be taken of the brain without requiring the patient to spend several days in hospital afterwards. With Siemens SIRETOM, patients could be scanned on an outpatient basis and without experiencing any pain whatsoever. The system depicted tumors, cysts, hemorrhages, and even tiny areas of calcification without the need for contrast media. An examination with Siemens SIRETOM took 30 minutes at most, including the time taken to position the patient, and the scan itself was completed in just four to nine minutes depending on the medical issue in question.



Series-produced model of the SIRETOM, the first Siemens CT scanner, 1975

Neuroradiology 2.0

Computed tomography completely transformed the field of neuroradiology and quickly became the method of choice for examinations of brain tissue. Just two years after SIRETOM, Siemens presented its first whole-body CT scanner, SOMATOM. Now, neurologists could also refer to slice images of the spinal cord and other nervous system structures when making their diagnoses. Image quality improved considerably within the space of a few years, as illustrated by the two brain scans on page 32. The image on the left is from 1974, while the image on the right was taken with the SOMATOM of 1983. Although the older image already allowed the physician to detect and localize tumors or hemorrhages, the image taken nine years later provided a clear view of detailed brain structures and the optical nerves.



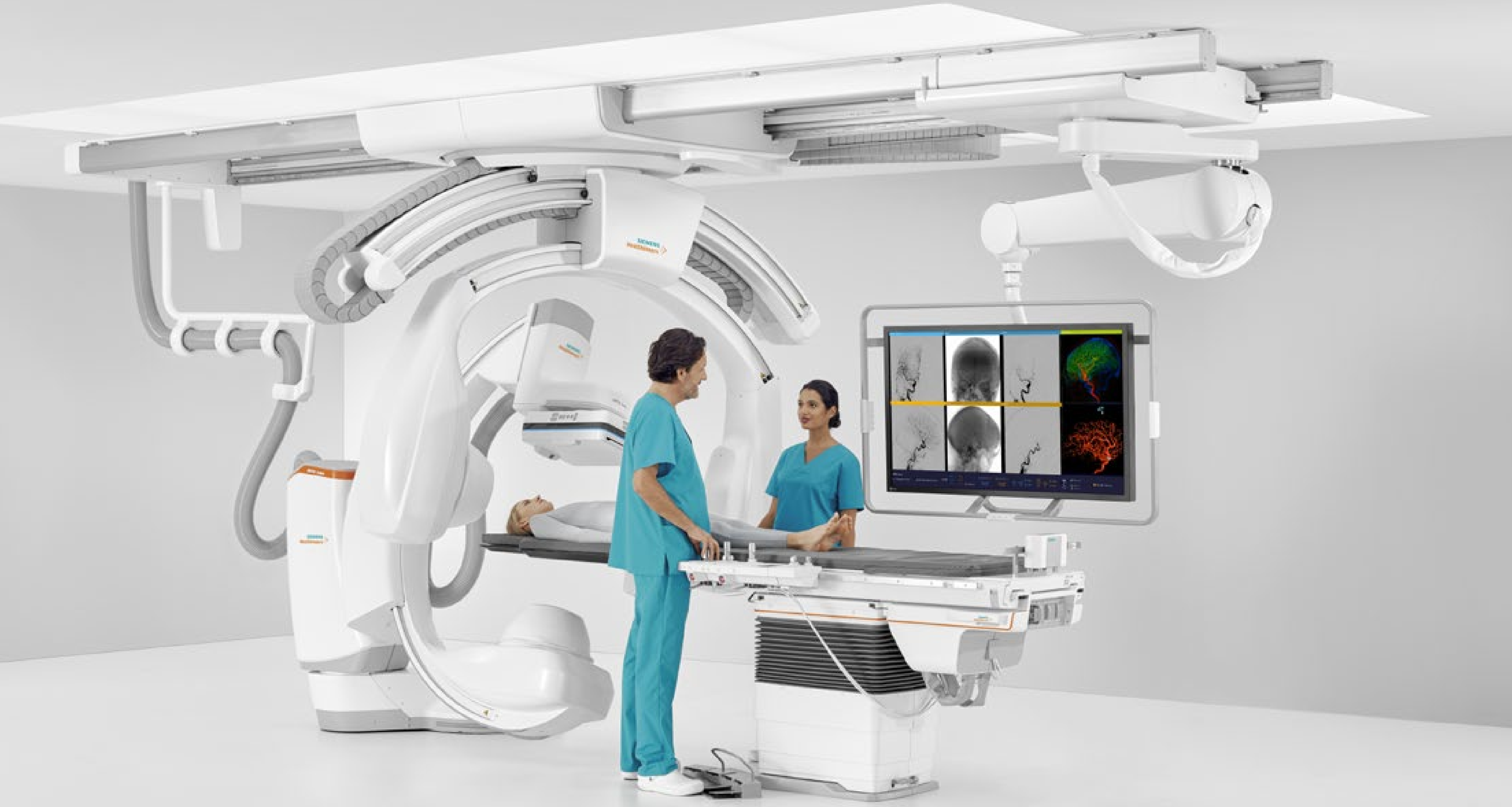
3D angiogram of the vascular structures inside the brain

Courtesy:
Professor René Chapot, MD,
Alfried Krupp Krankenhaus Essen

Back on the soccer pitch

Today, images of the living human brain are something we take for granted. Thanks to modern imaging procedures, humans can be studied as they experience thoughts and emotions; disorders can be identified with a high degree of accuracy; and lesions such as tumors can be localized with millimeter precision. Using X-rays, modern angiography systems such as ARTIS icono can visualize regions near the top and base of the skull almost without any picture noise. Especially in neurological emergencies such as bleeds on the brain and strokes, time is a determining factor for the long-term effects – as illustrated by the case of a German man named Sebastian. After the 30-year-old amateur soccer player collapsed during a cross-country run, physicians inserted a catheter through his groin and into his brain in an intervention that lasted just 23 minutes. On reaching the brain, they removed the blood clot that had caused his collapse – and Sebastian was back on the soccer pitch a week later.

Such rapid and precise interventions are becoming increasingly important in neurology (and other disciplines, such as cardiology). The aim is to adapt therapy more closely to the needs of the specific patient. The interplay between accurate imaging and high-precision robotics, supported by increasing digitalization and artificial intelligence, will continue to improve treatment methods in the coming years.



ARTIS icono can visualize regions near the top and
base of the skull almost without any picture noise, 2019

Source: Getty Images

Photography, film, and X-ray technology

How can X-ray images be shown in three dimensions?

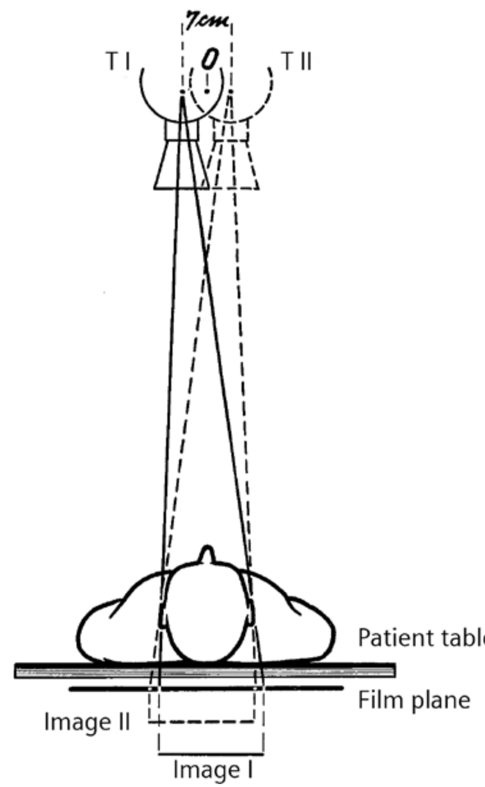
The first World Expo, known as the Great Exhibition, was held in London in 1851. Visitors were enthralled by a new technology known as stereoscopy that allowed people to view photos in 3D. The technique soon became a huge success – and scores of photographers began traveling around the world to take snapshots of exotic destinations and imposing buildings using stereoscopic cameras. Now, anyone equipped with a stereoscope could travel to distant lands from the comfort of their own armchair, and by 1900 stereoscopy had already become a popular mass medium. It is no wonder, therefore, that the discovery of X-rays was quickly followed by the first experiments into stereo X-ray images.

Research into stereo X-ray imaging was prompted by the fact that X-rays could be deceiving. This is because a normal X-ray image depicts all the structures in a particular area of the body in a single plane with deeper structures hidden by what lies in front of them. A shadow on the lungs can be an important clue in cases of suspected tuberculosis, for example. In a conventional X-ray image, however, parts of the lungs are covered by the ribs, so it is not clear whether a shadow is located in front of the lungs or actually on them. The incorporation of stereoscopy into X-ray technology allowed the images to present a spatial impression of the inside of the body.

Contemporary lithograph of the Great Exhibition held in London in 1851

There are two steps involved in X-ray stereoscopy: First, two X-ray images are taken of the same part of the body in quick succession from slightly different perspectives. The X-ray tube is positioned based on the average distance between a person's eyes (7 centimeters). Starting at the zero point, which corresponds to the bridge of the nose, the X-ray tube is first moved 3.5 centimeters to one side and then 3.5 centimeters to the other within the same plane.

Source: Janker, Robert: Röntgen-Aufnahmetechnik. Teil I. Allgemeine Grundlagen und Einstellungen, 1966, p. 15



Tube positioning for stereoscopic X-ray images

Source: Schneidrzik, W.E.J. / Kallenberg, A: Die Bronchostereographie, in: RöFo, Bd. 88, 1958, p. 159

Bronchogram of a healthy lung as a stereoscopic pair, 1958

In the second step, the two stereoscopic images must be presented to the eyes in such a way that the brain can process them as a single three-dimensional image. There are various viewing techniques that can accomplish this – such as the side-by-side method, in which the two images of the stereoscopic pair are positioned next to one another. Using a stereoscope or stereoscopic glasses, the gaze is directed so that the two images merge into one three-dimensional image.

Among other things, stereoscopy provided new opportunities for the diagnosis of tuberculosis or the localization of foreign bodies. Yet, most radiologists gave it a wide berth, because what seemed very simple at first actually presented a number of practical challenges for physician and patient alike.

Even the process of capturing the X-ray images was beset by a variety of obstacles, particularly when it came to adjusting the tubes and changing the photographic plate. The procedure was not only awkward and time-consuming but also required a great deal of accuracy on the part of the physician. The patient had to remain absolutely still, without moving a single centimeter throughout the examination. Considering that, in around 1900, it still took several minutes to capture the images, it is easy to imagine just how difficult a task this was. There was also the tricky matter of how to view the resulting X-rays stereoscopically. Although a wide range of conventional stereoscopes were available commercially, these were designed for normal photos rather than large-format X-rays. Accordingly, the images first had to be scaled down using photographic techniques – which, of course, resulted in a loss of image quality.

Starting in 1900, both Reiniger, Gebbert & Schall and Siemens & Halske attempted to overcome these challenges and simplify the procedure of stereoscopy. For this, they used a series of specialized tools and apparatus including stereo X-ray tubes with two focal spots, special cassettes, and tripods. From 1909 onward, an apparatus according to the design of Dr. Franz M. Groedel even took over the role of the physician. Once switched on, it carried out the individual steps automatically as if by magic and could produce a stereoscopic image of the thorax, for example, in one to two seconds. In 1903, Reiniger, Gebbert & Schall launched a prism stereoscope according to Dr. Walter, a solution that allowed stereoscopic X-ray images to be viewed in their original size.

In the 1920s, Siemens developers were inspired by another technology from the world of photography and film. In 1922, New York's Selwyn Theatre became the first movie theater to use the Teleview system – invented by Laurens Hammond, this was a forerunner of the shutter technology now used in 3D television, for example. Synchronized viewing devices were attached to the armrest of each theater

Teleview system, 1922

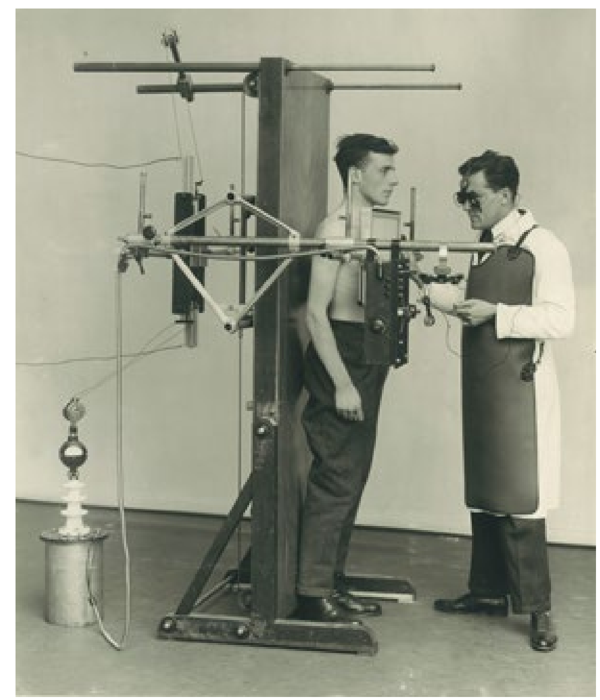
Dr. Franz M. Groedel's stereo apparatus

Prism stereoscope according to Dr. Walter from Reiniger, Gebbert & Schall's 1905 catalog

seat to provide the audience with an immersive viewing experience as they watched the 3D movie *The Man from M.A.R.S.*

The company Siemens-Reiniger-Veifa subsequently launched a stereo X-ray device based on the shutter system in 1927. The apparatus was fitted with two tubes that alternated to produce a moving image on a fluorescent screen from slightly different perspectives. The centerpiece of the device was a pair of "shutter glasses" that were responsible for the 3D effect. These were synchronized with the images and darkened each eye in turn so that the viewer could only see the image meant for the correct eye.

Stereo X-ray unit from Siemens-Reiniger-Veifa, 1927



Forming a 3D image, layer by layer

Until the 1980s, stereoscopy was the only way of adding a third dimension to X-ray images. Back then, few could have imagined that physicians in the year 2020 would be able to hold a patient's heart, for example, in their hands in the form of a 3D projection.

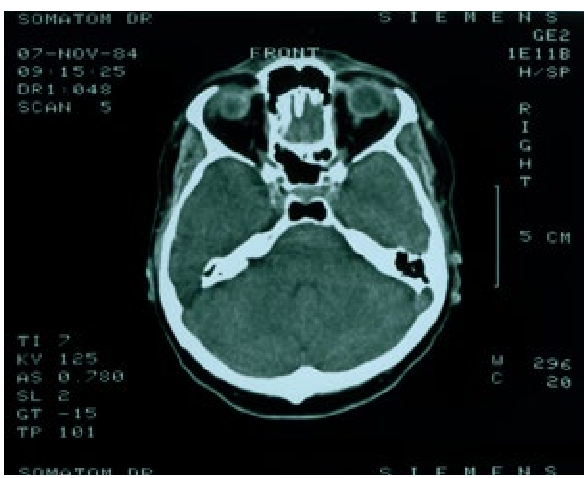
The advent of computerization in the 1970s marked a decisive turning point in 3D imaging and led to the development of a new imaging procedure known as computed tomography (CT). In a CT scanner, the body is X-rayed from all sides, and a detector measures the incoming radiation. This data is then sent to a computer, which uses it to generate cross-sectional images of the body without superimposition.

In addition to normal slice images, this method also allowed 3D reconstructions to be prepared for the first time – but the technology was not yet sophisticated enough, and the computers were far too slow. After all, in order to reconstruct 3D images from individual cross sections, it is necessary to capture a continuous series of ultra-thin slices within a short time and in high image quality. The image data collected in this step is processed using special computer programs to create three-dimensional digital models of anatomical structures such as bones, organs, skin, and blood.

In the mid-1980s, Siemens presented its new 3D-Display software for the three-dimensional imaging of surfaces. In combination with the SOMATOM DR CT scanner, it was now possible to produce not only cross-sectional and classical X-ray images for overview purposes but also 3D reconstructions – all with a single device. Whereas each cross-sectional image showed only a thin layer of the body, the 3D reconstruction provided an overview of the anatomy, making it easier for physicians to plan operations or to assess a fracture, for example.

Early 3D images were only able to depict simple, superficial structures, but technological advances now make it possible to visualize even tiny details such as minuscule stents inside blood vessels in color. Despite this enormous technological advance, conventional 3D reconstruction still has its limits. Not only do the images look artificial, but it is also difficult to assess things such as how close a blood vessel is to a bone. A crucial factor is missing: light! But how can you bring light into the darkness?

Cross-sectional image, overview image, and 3D reconstruction recorded with SOMATOM DR, 1984/1986



A CT scan to check the positioning of a stent in the thoracic aorta. The image does not show the wall of the blood vessel, but rather the grid-like stent and blood flow within it

Photorealistic visualization of a CT scan using Cinematic Rendering

A virtual journey inside the body

The new visualization technology known as Cinematic Rendering* represents a quantum leap forward and is now ushering in an entirely new era in 3D imaging. Based on image data, this method can produce photorealistic images of the inside of the body. Suddenly, details that could not be displayed before become visible, such as distances or even underlying structures.

It was actually the computer-animated mythical being Gollum that provided the impetus for the technology's development. This character from *The Lord of the Rings* film trilogy gave the developers at Siemens Healthineers an idea: They wondered how it was possible for Gollum to look so strikingly real alongside human actors despite having been inserted into the scenes after they were filmed. The answer was a technique known as "image-based lighting calculation," and a team of researchers led by Klaus Engel at Siemens Healthineers used this know-how from the animation film industry to develop a technique for the photorealistic visualization of clinical images.

But how does this new technology work? Data from medical imaging techniques are used as the basis for abstract algorithms to calculate on a computer what it would look like if light were to fall on the inside of the body. The calculation process takes a range of different questions into account. How would the light penetrate the tissue and be reflected on the surface? Where would shadows be visible?

**For research, education and communication use only. Not for clinical use.*

The anatomical theaters of the future

Cinematic Rendering opens up entirely new opportunities in medicine and has revolutionized medical education by allowing anatomy to be taught on living humans for the first time. Today, visitors to the world's only "Deep Space 8K" installation at the Ars Electronica Center Linz can get an idea of what the anatomical theaters of the future might look like. In front of the audience, Cinematic Rendering is used to reproduce the three-dimensional worlds found deep inside the body. Professor Franz Fellner explains the anatomy as he navigates his way through the body using a games console controller. As head of the Central Radiology Institute at Kepler University Hospital Linz, Fellner was one of the first to apply the visualization technology, and uses it to teach anatomy.

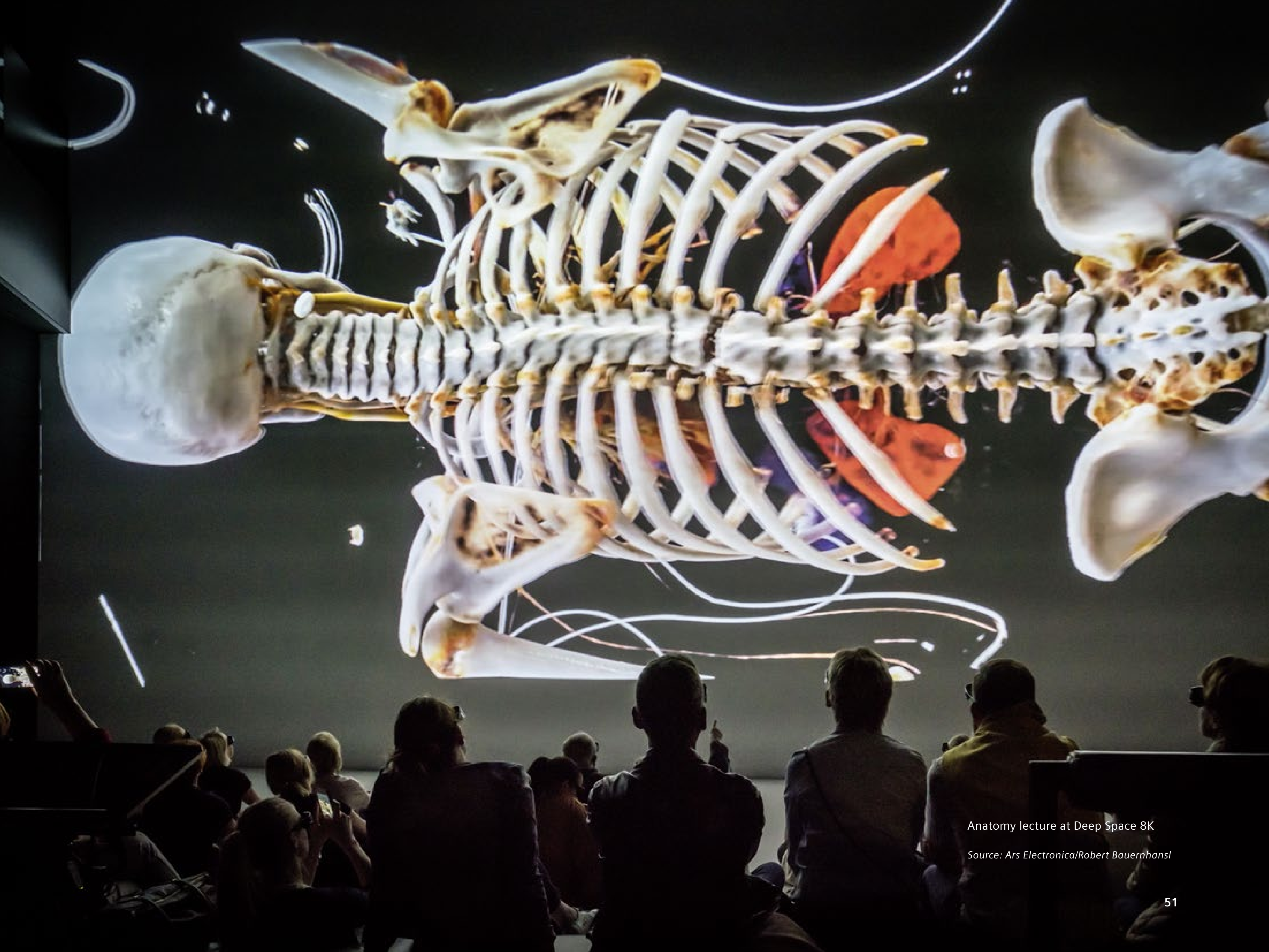
In addition to medical education, Cinematic Rendering is also helpful for patient communication. When the physician and patient sit down together to discuss findings or a pending operation, they typically refer to diagnostic images from previous examinations – which are very difficult for patients to understand. With the photorealistic rendering of clinical images, however, it is easier to comprehend the processes taking place inside the body as well as the forthcoming procedure.

Cinematic Rendering for surgery

Based on a recent evaluation study at University Hospital Erlangen the technique also delivers genuine added value in everyday clinical practice, as it makes it easier to diagnose certain diseases and to plan surgery. The images are so vivid that they can give the surgeon a highly detailed idea of the specific anatomical structures that will be found in that patient during the operation. This application is still in the development phase and is being trialed in close cooperation with a select group of physicians and hospitals. Meanwhile, our developers are working hand in hand with doctors from around the world. This includes obtaining feedback, discussing points of detail, and jointly considering how the process can be refined – for example, with a view to improving surgical outcomes.

A long way off? Picture this: A group of physicians from various different specialties gather around a floating, photorealistic hologram of a thorax to jointly plan a complex operation on the heart. The lead cardiologist gives a few short voice commands to zoom into the hologram. Soon, only the heart and coronary vessels are visible. The team discusses the correct surgical approach and, with a few quick manipulations, they rotate the three-dimensional image several times before diving into a virtual representation of the ventricles of the heart.
The real world and virtual reality merge with one another.

Although this may seem like science fiction, it is now becoming a reality with the coming together of two technologies: Cinematic Rendering and Microsoft HoloLens 2. In the future, Siemens Healthineers will offer its 3D visualization technology as an app for these mixed reality glasses in order to facilitate the coordination of multidisciplinary teams of physicians.



Anatomy lecture at Deep Space 8K

Source: Ars Electronica/Robert Bauernhansl

Dentistry is one area of application for mobile devices. This advertising photo from 1952 shows the X-ray Sphere fitted with the pointed dental cone

X-ray images at 2 horsepower

How X-rays went mobile

How many horses does it take to produce an X-ray image? It may sound like the start of a bad joke, but this is actually a serious question. The answer is two, with the proviso that it is advisable to use only “especially well-trained animals.” This doesn’t mean, however, that every radiologist needs to keep horses at their practices. Perhaps we’d better start from the beginning.

Soon after Röntgen published his article *On a New Kind of Rays*, one thing became abundantly clear: X-rays, as Röntgen called them, were ushering in a revolution in medical diagnostics. For the first time, it was possible to look inside the human body without opening it up surgically. Broken bones could now be diagnosed without having to palpate or mobilize the fracture, and foreign objects could be localized accurately without requiring the physician to search the wound with their finger or a probe – both of which were extremely painful procedures. It’s no wonder, therefore, that the armed forces – since soldiers were often the victims of such injuries – showed an early interest in the new technology. By February 4, 1896, the *Münchener medizinische Wochenschrift* (Munich Medical Weekly) was reporting that the ministry responsible in Berlin was keen to investigate whether “Röntgen’s discovery can be applied to battlefield medicine and used for the benefit of sick and wounded soldiers.”

It was not long before the first applications began to emerge in this area. As Wilhelm Conrad Röntgen himself reported, images of bones could be viewed directly on a fluorescent screen or recorded on a photographic plate. Particularly in the early days of military radiology, an examination with a fluorescent screen was the preferred method. Although images on photographic plates were more detailed and provided a permanent record of the X-ray image, the method was too time-consuming for everyday practice in military hospitals because of the long exposure times – 20 to 30 minutes per X-ray in some cases, and sometimes longer – and the fact that images first had to be developed. With a fluorescent screen, on the other hand, the image was available immediately – although it couldn’t be recorded in a permanent form.

The first X-ray equipment used by the military barely differed from that used in hospitals and medical practices. For example, the English military surgeon Walter Beevor chose a device that exactly matched the X-ray unit at St. Thomas’ Hospital in London. He had the equipment stowed in wooden cases, which each weighed about 100 pounds and were hung from a rod carried by two people. One key challenge was therefore to pack the X-ray equipment so that it could withstand both wind and weather as well as reaching the target location quickly and undamaged.

Companies such as Siemens & Halske (S&H) in Berlin soon began manufacturing complete sets of X-ray equipment mounted on carts for transport. In its 1901 catalog, S&H advertised a mobile device for X-ray examinations in military settings. This consisted of two carts that could be pulled by two horses (no, not the two horses in the opening question!). The portable equipment included a complete set of X-ray instruments. The inductor and interrupter were housed in heavy oak boxes to protect them from damage.

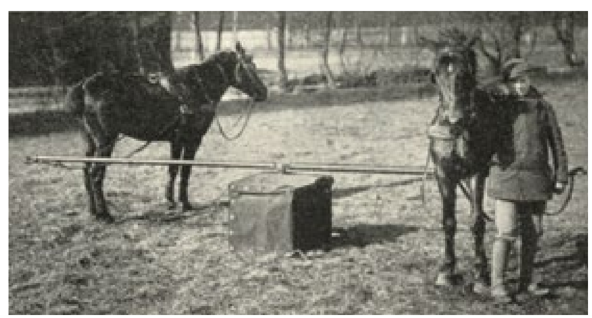
X-ray cart belonging to the Prussian Army, manufactured by Siemens & Halske, c. 1904

Achieving a dependable power supply was a particular problem in the early days of mobile X-ray systems. Especially when using the equipment for military applications, physicians could not rely on the presence of a reliable local power grid. Apart from a conventional power supply, they essentially had two sources of power at their disposal: batteries – but these always had to be recharged after images were captured; and dynamos – but these always required a suitable drive mechanism. Whether for charging the batteries or for driving the dynamo, the first thing that both approaches unavoidably required was a degree of creativity. Power was generated using all kinds of things – from a tandem bicycle to the machinery of a flour mill. Another type of technology was also becoming increasingly common: "The increasing use of motor vehicles by the army, whose engines are also very well suited to driving dynamos, should further increase the number of X-ray stations and help to accommodate them better; and, from our own experience, it is easy to imagine that an average automobile, while being used for the rapid transport of medical personnel, could also carry a full set of X-ray apparatus along with its own source of electricity." The author of this text, taken from a 1903 textbook on X-ray technology, was confident that vehicle manufacturers would come to their senses: "As soon as the automotive industry no longer finds satisfaction in the manufacturing of sports cars, it will turn to designing truly practical utility vehicles and ones that also meet the requirement of ours with ease."

Nevertheless, variants without a motorized drive continued to be used. In 1907, Siemens & Halske launched a version of a horse-driven dynamo aimed especially at "all rural physicians and such operations that are located far away from a power station" and could not therefore use X-ray equipment in their work. The dynamo was driven by two horses or other draft animals and supplied the electricity for an X-ray system as well as for other apparatus needed for treatment. It could also be used to charge a battery, which provided a source of power so that X-ray examinations could be performed without the dynamo. "Another advantage of portable devices is that they can be used not only in the physician's home but also in the homes of patients that are hard to transport." These days, X-ray apparatus is no longer taken to patients' homes, but these two objectives remain a constant focus of medical technology companies today: the examination must be as comfortable as possible for patients and must be made accessible to people with mobility issues. After all, a reliable diagnosis is an essential part of successful treatment.

Initially, portable devices were not powerful enough for complex examinations, such as those of moving organs like the heart and stomach, or for imaging the thoraxes of obese patients. These cases would have required a longer exposure time, causing the image to become blurry due to patient movement and exposing them to an unnecessarily large dose of radiation. Yet these relatively cheap and compact portable X-ray devices meant that physicians could continue to use X-rays as a diagnostic tool even outside of the hospital setting. "Of course, this requires physicians to acquire certain technical skills [...] but that should not be an insurmountable obstacle for them, provided that their thirst for knowledge was not quenched on leaving university," as another textbook remarked. On the contrary, even older colleagues were encouraged to incorporate X-ray technology into their everyday practice: "Moreover, those with a passion, talent, and determination for learning, even in their advanced years, should not deny themselves the benefits of this tool, which is now available not only cheaply but also in good quality."

The X-ray equipment unloaded from the
X-ray cart in front of the examination tent

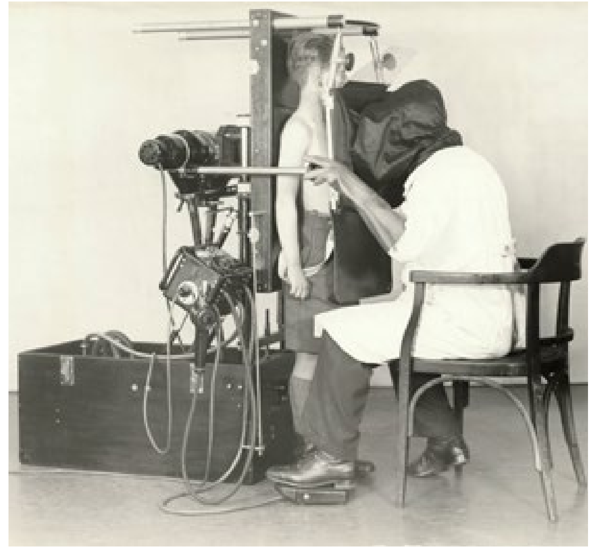


The horse-driven dynamo from
Siemens & Halske in use, 1907

Like a tin can

For some time, even mobile X-ray equipment such as the device according to Dr. Redeker or the Nanos X-ray system remained relatively unwieldy. The foundation stone for truly compact X-ray apparatus was laid in 1919, when the American Harry F. Waite registered a patent in the USA. Waite's idea was to mount the high-voltage transformer and X-ray tube together inside a single radiation protection housing to create what is known as a single tank generator. This was the principle behind a highly successful product in the history of Siemens Healthineers: the Siemens X-ray Sphere. In this device, a high-voltage transformer and X-ray tube were installed under oil inside a silver metal sphere and – so to speak – "hermetically sealed off from the outside air like the contents of a tin can." The sphere was shielded from radiation and was electrically insulated, providing protection for physicians and patients alike. It could be connected to a conventional plug socket, and its compact construction made it an extremely versatile piece of apparatus: the X-ray Sphere weighed just 12 kilograms and had a diameter of 22 centimeters – about the size of a soccer ball.

Like a soccer ball, the X-ray Sphere was also characterized by a certain amount of durability. Although they were not meant to be kicked around, X-ray Spheres often fell to the floor from table height or even rolled down staircases without showing any damage – apart from a few bumps or dents – and with their functionality completely intact. Siemens-Reiniger-Werke was therefore confident of the product's virtues: "An X-ray Sphere could lie underwater for weeks without incurring any risk: if you take it out again and dry it off, it is once again ready for operation."



X-ray examination using the apparatus according to Dr. Redeker, 1933

Transporting the Nanos in a sedan, 1932. When taken apart, the Nanos filled two pieces of luggage, each weighing 28 kilograms

The 1,000th X-ray Sphere, November 1935

The Siemens X-ray Sphere was put to good marketing effect at the 1936 Winter Olympics in Garmisch-Partenkirchen

X-ray Sphere for dentistry, 1960

Mobile devices are also ideally suited to veterinary medicine

Indeed, the peculiar story of two X-ray Spheres serves as proof of the devices' durability. The spheres belonged to the Swedish Red Cross and were being used in Africa when they fell victim to looters, who threw them away as they fled – presumably to hasten their escape by shedding unnecessary ballast. As a result, the two spheres were left lying in marshland for weeks during the rainy season before being recovered and ultimately finding their way back to their original owners. The spheres were dirty and dented and "didn't look as good as they should for a piece of apparatus in a physician's examination room," but a thorough inspection by Siemens-Reiniger-Werke revealed that they were still in full working order and safe to use! To highlight their durability, one of the spheres was even put on display in the company's exhibition space in Berlin and made available to those interested in testing whether it was in working order.

The structure of the X-ray Sphere meant it was suitable for all climatic zones and didn't require any particular precautions to ensure consistent quality of results. It is no surprise, therefore, that the X-ray Sphere quickly became a worldwide bestseller. The first sphere to be delivered to a customer passed through the X-ray testing bay on September 29, 1934, before being supplied to the state hospital in Rudolstadt, Thuringia. Shortly before Christmas the following year, the 1,000th X-ray Sphere was already passing through the testing bay; and just under four years after the first sphere was delivered, the 5,000th X-ray Sphere was shipped to Buenos Aires. This rapid pace was set to continue: By the end of 1950 – just over 15 years after the X-ray Spheres were launched – 23,309 of them had been sold worldwide, and many thousands more were purchased by the time production came to an end in 1974.

Examination with the
X-ray Sphere, 1965

Serial images from Rio

This bus is a "mobile X-ray clinic" equipped with the Orthoskop X-ray device from Siemens-Reiniger-Werke and a complete darkroom setup, among other things. It was used in the Philippines in the 1930s

X-ray technology plays a vital role in many areas of medicine, but in the mid-20th century it became particularly important for combating one specific disease that has plagued humankind for thousands of years: tuberculosis (also known as consumption). Indeed, in one of the oldest pieces of evidence, the pathogen was detected in a 9,000-year-old skeleton. Even today, tuberculosis still ranks among the ten most common causes of death. According to an estimate by the World Health Organization (WHO), about a quarter of the world's population was infected with the pathogen in 2018. Of those, some 10 million developed the disease and 1.2 million died. The insidious thing about the disease is that those affected often show no symptoms whatsoever for a very long period of time and initially have no idea that they have been infected. Even once the disease manifests, its symptoms can be so weak that affected individuals do not seek medical help, allowing the disease to spread even further. It is therefore vital to diagnose tuberculosis at an early stage.

Although Robert Koch (1843–1910) identified the cause of the disease as Mycobacterium tuberculosis in 1882, the process for diagnosing tuberculosis was for a long time limited to percussing patients' chests and listening to them with a stethoscope. In the 1920s, X-ray technology was sophisticated enough to be used as a reliable and, indeed, the most important diagnostic tool for detecting tuberculosis. Yet X-rays were too expensive for large demographic groups that were vital for effectively stemming the spread of the disease. As technology advanced, a new method known as photofluorography became established at the end of the 1930s. Instead of producing a classical X-ray image, this technique used a small-format camera to photograph the image on the fluorescent screen during the examination. By making the process cheaper and faster, it allowed a large number of people to be examined in a short time. The first serviceable photofluorography unit was developed by the physician Manouel de Abreu in collaboration with the Brazilian subsidiary of Siemens-Reiniger-Werke, Casa Lohner in Rio de Janeiro. In 1936, the first mass screening station equipped with the photofluorography unit began operating in Brazil. The device was ultimately developed into the Siemens serial X-ray camera according to de Abreu-Holfelder, which was used in Germany from 1938 onward. In the context of mass screening programs, it became increasingly common to install X-ray equipment in buses. This allowed the examination room to be taken directly to workplaces or schools, for example, and also made it easier to examine large demographic groups. Mass screenings were conducted in Germany until 1988. Among other things, screenings of this kind helped to stem the spread of tuberculosis in industrialized nations.

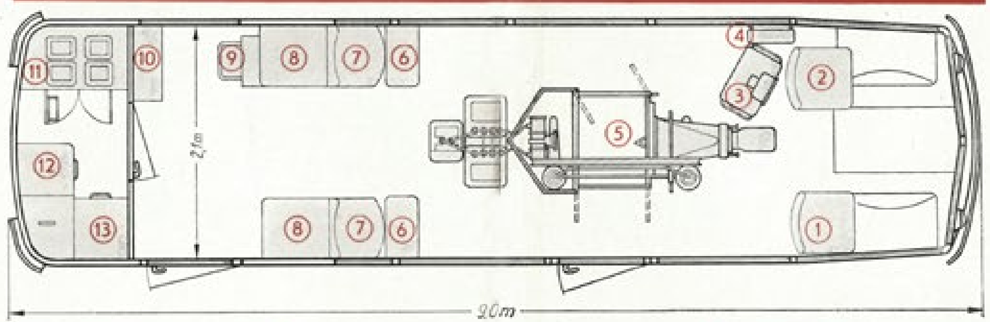
Seriomat fluorography unit for mass screening. Advertising photo from 1968

Practical arrangement of photofluorographic unit on the bus

Image above:
View through the rear vehicle entrance.
Right: index card and filing cabinet with built-in washbasin. Left: case for the "IONTOMAT" automatic X-ray exposure timer.

Image below:
Darkroom. Right: tanks for developing and fixing baths. The drip tank for wet films is mounted on the open cabinet door. Left: cabinet with drawers for darkroom accessories.

Image above: side view of bus with doors open
Image below: scale drawing of bus floor plan



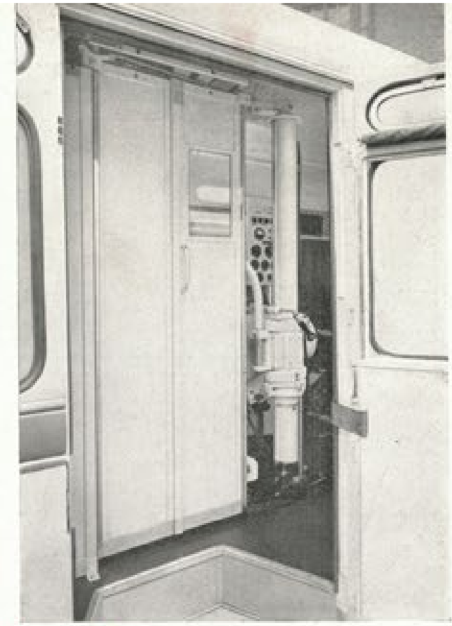


Image above:
View of "SERIOMAT" cabin through front vehicle entrance.

Center image below:
View from the back of the bus looking forward, showing the "SERIOMAT" standing in the middle of the vehicle.

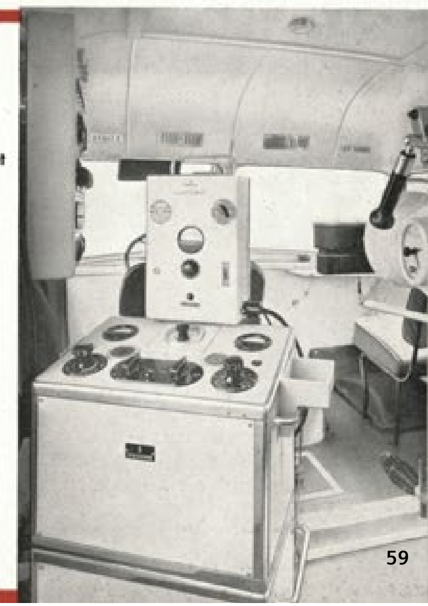
Image below:
The control desk in the front of the bus with the "IONTOMAT" automatic X-ray exposure timer.
Top left: control panel with fuse elements for all of the electrical installations.

Scale drawing:

1. Passenger seat
2. Driver seat
3. Control desk
4. Control panel
5. Photofluorographic unit "SERIOMAT"
6. Folding tables
7. Seats for staff

Scale drawing:

8. Closet and index card cabinet
9. Washbasin
10. Case for the "IONTOMAT"
11. Darkroom with developing and fixing baths
12. Cabinet for darkroom accessories
13. Film drying cabinet



Slices on wheels

Of course, there was still a need for mobile X-ray equipment that physicians could use in the operating room or at the bedside. When Siemens launched the Mobilett in 1982, the device couldn't compete with the weight of small devices such as the X-ray Sphere, but it was still classed as a lightweight at 230 kilograms. Weighing over 100 kilograms less than similar instruments produced by competitors, it was easy to move around while offering all the power of stationary devices. The Mobilett and Polymobil, which was also introduced in the 1980s, marked the beginning of two product lines that still appear in the portfolio of Siemens Healthineers today.

One area of the mobile applications of X-rays is yet to be addressed: computed tomography (CT). But how can a CT scanner weighing something in the region of 2 tons be made a portable device? The answer is to adopt the same principle as has proven successful for X-ray buses, except that the CT scanner is installed in a truck rather than a bus. This approach is used for lung cancer screening in the United Kingdom. As with many diseases, the successful treatment of lung cancer relies on detecting the disease as early as possible. The screening program developed by a partnership between Siemens Healthineers and Cobalt Imaging examines individuals exposed to risk factors for lung cancer. As with the X-ray buses, the advantage here is that the mobile scanner can reach people who live far away from hospitals.

And that's not all: In December 2019, Siemens Healthineers presented its new mobile SOMATOM On.site* head scanner at the world's preeminent radiology conference, the RSNA in Chicago. SOMATOM On.site allows examinations of patients in intensive care to be carried out directly at the bedside. This removes the need for the time- and labor-intensive process of transporting patients from the intensive care unit (ICU) to radiology.

Mobile X-ray technology has come a long way since its early days, when power was generated by horses, to the mobile cranial CT scanners of today, which can be wheeled to a patient's bedside in the ICU – and the fascinating story of the technology's development is certainly not over yet.

**SOMATOM On.site is not commercially available in all countries. Its future availability cannot be guaranteed.*

The Mobilett in an advertising photo from 1983

Polymobil, 1985

Polymobil was also used in veterinary medicine. Advertising photo from 1985

SOMATOM On.site mobile head CT scanner, 2019

The preproduction model of SIRETOM in 1975

A gentleman's crazy idea and other "fairly ingenious designs"

The history of computed tomography

In London, in fall 1971, a radiologist and an engineer found themselves jumping up and down for joy – as one of them later recalled – "like football players who had just scored a winning goal." In their hands, the two researchers were holding a completely new type of X-ray image – known as a tomogram – that depicted a human brain in unprecedented quality. Indeed, looking at the image, the radiologist, James Ambrose, could see his 41-year-old patient's brain "in a great deal more detail than we'd expected" and could clearly make out the cortex, the spaces filled with cerebrospinal fluid, and even the white matter. The engineer, Godfrey Hounsfield, had developed the new X-ray technology almost single-handedly. With the prototype of his "3D X-ray machine," Hounsfield ushered in the development of what has become one of the most important techniques in medical imaging: computed tomography (CT).

The invention of CT is considered to be the beginning of modern X-ray technology. Yet what makes a CT scan so different from a classical X-ray image? What is it that makes tomograms so useful for physicians – to the extent that many fantasized about them soon after X-rays were discovered? The answer is that conventional X-ray devices depict the patient from one angle, producing two-dimensional pictures in which shallower body structures are superimposed on those beneath them, so that the lungs, for example, are partially covered by the structures of the ribs. By contrast, tomograms – also known as slice images – portray the inside of the body in thin slices without superimposition, allowing the physician to view a patient's anatomy as if individual thin slices had been extracted from the body.

From a pyramid to a bacon slicer

"Suppose that certain rays from the sun could penetrate deeply into a pyramid." The history of computed tomography began with a simple thought experiment while Godfrey Hounsfield was out on a ramble with his friend Roger Voles in the mid-1960s. "If we put a detector outside the pyramid on the far side from the sun and move the detector, day-by-day, [...] the whole volume of the pyramid could be explored for undiscovered chambers." This idea stuck with Hounsfield, and soon the pyramid became a box in which he wanted to visualize not only chambers but the entire contents. He realized that scans would have to be taken of the item over 180 degrees in order to collect three-dimensional data. To simplify the calculation of the measured values, Hounsfield planned to divide this three-dimensional data up into several layers, "like putting the object through a bacon slicer." Until 1967, Godfrey Hounsfield's ideas were nothing but speculation – interesting puzzles born out of scientific curiosity. Then his employer, the electronics and record company EMI, unexpectedly brought his current project to an end.

Sir Godfrey Hounsfield, the inventor of computed tomography

The legend of the Beatles – and performing miracles with very little money

Legend has it that Godfrey Hounsfield was given free rein to choose his next project and that – when it came to developing the first CT scanner – he could draw upon huge revenue streams that EMI had generated from the success of the Beatles. In fact, quite the opposite was true. In the early days, Hounsfield had to fight for funding for his project, as EMI initially had no ambitions of entering the medical technology market. After several months of persuasion, he earned the confidence of his superiors – although one of them described the idea as "crazy," presumably in the positive sense of the word. In order to build a prototype, Hounsfield was given exactly a quarter of what he requested. With this budget, he performed "miracles with very little money," in the words of William E. Ingham, who was director of research at EMI at the time.

To save money, Godfrey Hounsfield and his small team of developers improvised at every opportunity: They used an old lathe as the basic framework of the laboratory prototype, and for the data storage device they borrowed a paper-tape punch, which they used to record the measured values on strips of paper, each scan taking the form of 28,800 holes on 60-meter strips. "I have never, before or since," recalled Stephen Bates, the team's software engineer, "been involved in any project that took so many shortcuts or utilized so many items of seemingly unsuitable pieces of equipment." Despite all of the obstacles, the team turned Hounsfield's ideas into a working scanner in the space of a year. In early 1969, with an exposure time of nine days, they produced the first CT scan in history: an image of some plastic laboratory utensils. Within a few months – using more suitable components thanks to a larger budget from EMI as well as support from the British Department of Health and Social Security – they brought the exposure time down to around nine hours before further reducing it to about five minutes just a few months later.

Source: Science Museum/Science and Society Picture Library

The prototype of the first CT scanner set a new course for the development of X-ray technology

Doubters became believers

The first clinical prototype, which the team installed in James Ambrose's department at Atkinson Morley Hospital in Wimbledon on October 1, 1971, already bore a striking resemblance to modern CT scanners. However, because the system – and the hospital as a whole – lacked a computer to generate the image, the data collected from the first patient's brain was stored on a magnetic tape and taken by car to an EMI lab about 20 kilometers away. Two days later, as they held the diagnostic image in their hands, Hounsfield and Ambrose found themselves jumping up and down for joy. They began conducting further studies and published their results on April 20, 1972, at a radiology conference in London – triggering the greatest sensation in medical X-ray technology since the discovery of X-rays.

William E. Ingham later recalled that "all doubters in the medical profession and the doubters in the company were all suddenly believers." Practically from one day to the next, computed tomography set a new course for the development of medical X-ray technology. Godfrey Hounsfield's invention rendered the technique known as pneumoencephalography, which was common until that point, completely superfluous. In this often very painful and onerous procedure, cerebrospinal fluid was extracted via the lumbar region of the patient's spine and replaced with air to allow visualization of the brain using X-rays. Pneumoencephalography routinely led to several days of hospitalization and side effects – from vomiting to seizures or even meningitis. With computed tomography, on the other hand, patients could be scanned on an outpatient basis and without experiencing any pain whatsoever – and even the first prototype from EMI delivered much more contrast-rich and accurate results.

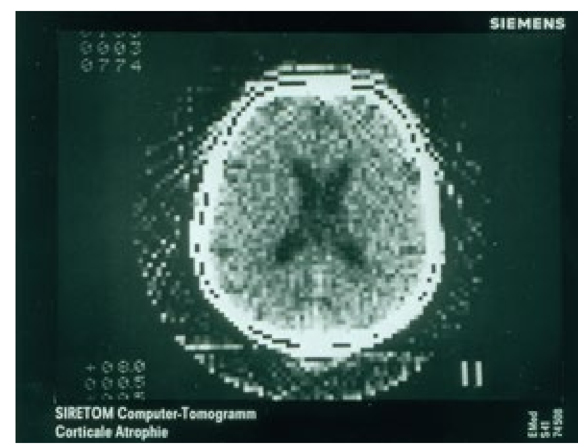
These impressive images triggered a veritable epidemic of "CT fever." Godfrey Hounsfield's invention and the new kind of X-ray images were the subject of reports not only in medical journals but also in almost all British newspapers and magazines – starting with the *Times* and then others including the *Guardian*, the *Daily Telegrap*h, and the *BBC*.

In addition to EMI, a further 17 companies began working on the development of CT scanners. Right from the outset, technical advances in computed tomography came in leaps and bounds. Incredibly, in October 1968, Godfrey Hounsfield had correctly predicted many of the inventions that would follow over the next 40 years – sometimes even down to the technical details, as was the case with the development of multislice CT scanners in 1998. However, some of the major developments from Siemens Healthineers that would shape computed tomography over the years were impossible to predict, as they were based on entirely new approaches – or even on seemingly very peculiar ideas.

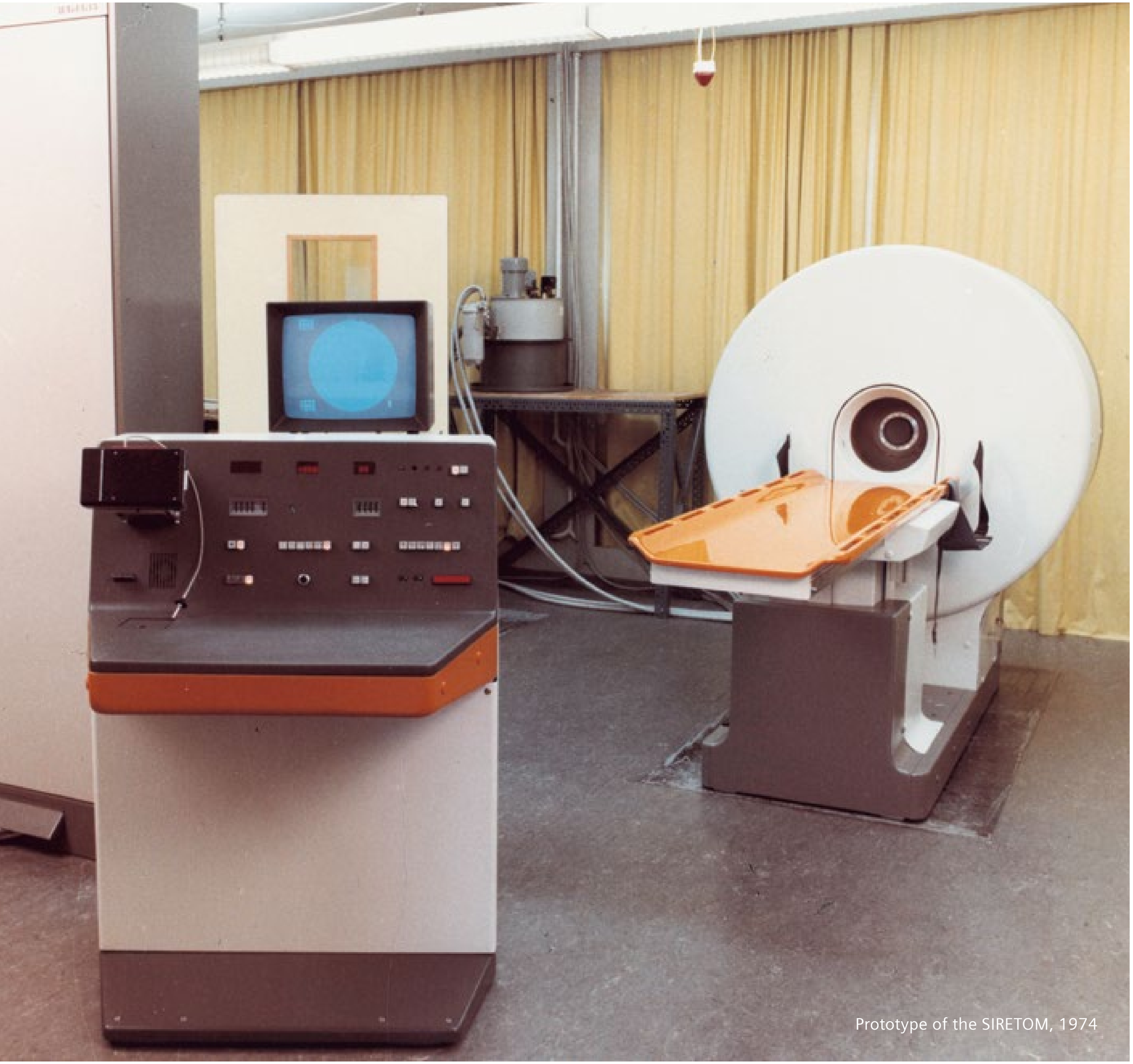
Tremendous enthusiasm at Siemens

The history of computed tomography at Siemens Healthineers began with a trip to London. The head of development in the medical technology arm at Siemens, Oskar Dünisch, and the head of Siemens X-ray development, Friedrich Gudden, visited EMI's research laboratory in summer 1972 to discuss the further development of computed tomography. The visit "was highly informative," Gudden wrote in his memoirs. "Excellent food and Godfrey Hounsfield, the inventor of computed tomography, joined in. He made an excellent impression on me, calm and unpretentious, a real British gentleman. And what he explained was fascinating – for example, that collecting the measurements for an image took nine days at the start."

The same year, a development department dedicated specifically to CT technology was established in the fundamental research unit at Siemens in Erlangen. The goal was to come up with a powerful prototype optimized for workflows in hospitals and medical practices. The pioneering figures were Friedrich Gudden, Gerhard Linke, Karlheinz Pauli, Benedikt Steinle, and Reiner Liebetruth. Steinle, for example, developed a method of reconstructing images that was later used by all other companies as well, while Liebetruth introduced flicker-free image display on TV screens. The team grew and received support from other Siemens teams as well. "Unforgettable" is how Gudden describes "the tremendous enthusiasm of our [...] significantly larger development team." Work continued every day until late into the night, and Gudden often drove employees who relied on public transit home personally after midnight. The excitement even caught on among employees of DEC, an American computer manufacturer that provided the computer used for the CT scanner. Specialists from the service team helped Siemens technicians eliminate defects in the images and "were pleased at the ongoing improvement in the images, as were we."



One of the first images of the brain taken with the prototype of the SIRETOM CT scanner from Siemens


Prototype of the SIRETOM, 1974

When they first began this work, the technicians and engineers at Siemens were able to build on their experiences with X-ray technology. Many components had already been developed and simply needed to be adapted to their new purpose. For example, a therapeutic X-ray tube turned out to be particularly suitable for use as a radiation source in computed tomography. Other aspects were developed from scratch, including the detector and a new system that converted the computer's calculations into digital images and displayed them on a 44-centimeter monitor. A second screen built into the control console made it possible to take Polaroid pictures using a built-in camera. Scan results could also be recorded on tape if desired.

Laughing or crying – depending on their nature

In the first half of 1974, the preliminary work was completed, initial trial runs were possible, and the prototype had been given a name: The first computed tomography system from Siemens was named SIRETOM and was to be trialed in clinical settings as soon as possible. To this end, Siemens formed a close partnership with Professor Hans Hacker and his team at the neuroradiology department at Goethe University Medical Center in Frankfurt. Between June 1974 and February 1975, the SIRETOM prototype was used to examine around 1,750 patients, and the trial was followed with keen interest by physicians and technicians. Some years later, Friedrich Gudden told of how "legions of visitors were brought to Frankfurt, including competitors, who admired the processing time, convenient use, and image reproduction alike." He also pointed out that the unit was far superior to all others on the market at the time. Nevertheless, it was still the only prototype of its kind and a long way from series production. "If we had been able to deliver at the time, any number of them would have been sold. When American doctors asked about the delivery time and heard our answer, they either laughed or cried, depending on their nature."

Hans Hacker was another firm believer in the new technology. In a report, he concluded that computed tomography would be "one of the most important methods used to investigate diseases and disorders of the brain in the future, and SIRETOM can be viewed as a reliable and easy-to-operate system for this kind of scan." Over the course of 1975, Siemens presented the scanner to the medical community at the European Congress of Radiology (ECR) in Edinburgh, and at the Annual Meeting of the Radiological Society of North America (RSNA) in Chicago. Then, on December 1, 1975, the time had finally come: Professor Hacker's prototype was dismantled, and he was the first to receive a series-produced model of the Siemens SIRETOM cranium scanner.

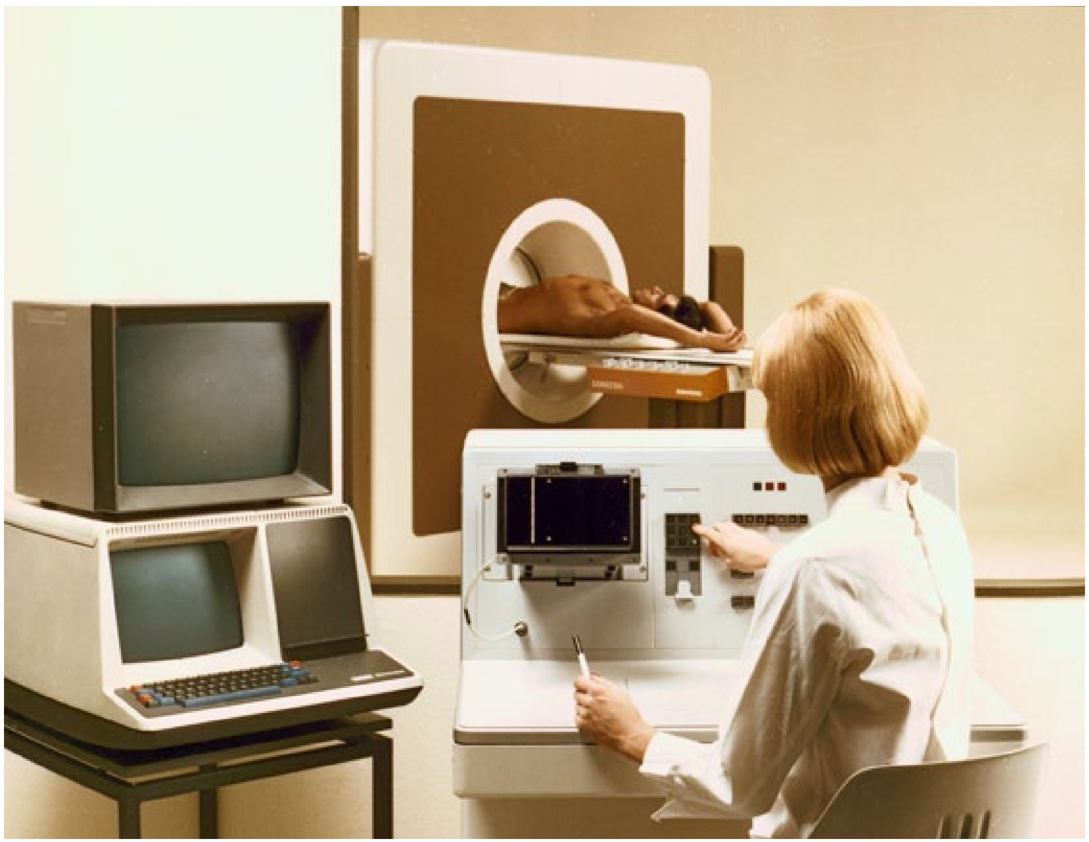
The presentation of SIRETOM at the 1975 Annual Meeting of the RSNA, in Chicago

Every ten years

The history of computed tomography now stretches back roughly 50 years and can be divided fairly neatly into decades: Approximately every ten years, huge advances in technology have led to new potential applications and more-detailed images. Each of these technological milestones was then put to maximum use over subsequent years – often by pushing them to the limits of physics itself – until the next major invention brought new impetus and new avenues for improvement. From the outset, the engineers were operating at the cutting edge of technical capabilities.

Indeed, the step up from the cranium scanner to the whole-body CT scanner called for the development of an entirely new mechanism. In SIRETOM, the X-ray tube and the detector opposite it rotated around the patient's head in 179 small steps, producing an image of the brain in just under five minutes. In the first whole-body CT scanner in the history of Siemens Healthineers, the SOMATOM from 1977, the tube and detector completed a 360-degree rotation around the patient in a single motion, taking just four seconds to produce an image of any chosen area of the body. However, this mechanism subjected the components in the system to enormous centrifugal forces. Moreover, because the X-ray tube and detector were connected to the power supply and the image generation computer via cables, they could not rotate continuously around the patient. Instead, they were accelerated in one direction, stopped after a 360-degree rotation, and then accelerated in the opposite direction. To further reduce scan times and thereby to improve image quality, engineers went to work on a wide range of solutions in the 1980s.

The technology introduced by Siemens in 1987 is still used in most CT scanners today: Instead of cables, the rotating components were supplied with electricity via slip rings. This meant that it was no longer necessary to stop after each rotation – the system could rotate continuously and collect data without interruption. SOMATOM Plus was therefore not only the first of a new generation of CT scanners but also the fastest CT scanner of its time, taking just one second to complete a 360-degree rotation. The system also laid the foundation for one of the greatest innovations in the history of computed tomography: spiral CT.

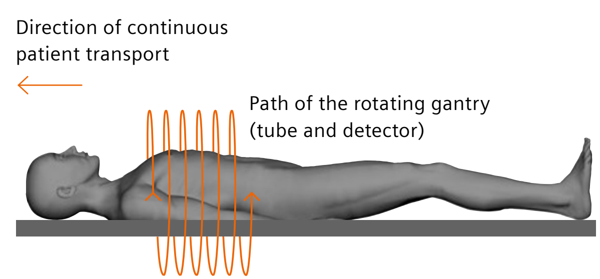


The first whole-body CT scanner in the history of Siemens Healthineers: SOMATOM in 1977

A seemingly very peculiar idea

Spiral CT does exactly what engineers and designers had been trying to avoid in computed tomography until then: It moves the patient inside the scanner. In conventional CT systems, the table stayed in a fixed position while the tube and detector circled the patient to produce a scan of one slice of the patient's body. Once the image was captured, the table moved a few millimeters into the ring-shaped opening of the scanner (the gantry), and the next slice was recorded. If the patient moved during the scan, the individual slices at the end of the scan could be mismatched to such an extent that image defects made diagnosis difficult or even impossible. In spiral CT, the idea is to move the patient continuously through the gantry while the X-rays scan the body in a spiral path. The medical community's response to this suggestion was skeptical at first, as it should theoretically have made the images blurry and unusable. Critics even described spiral CT as "a method of producing image defects in CT."

Spiral CT



Spiral CT moves the patient during the scan

The first of a new generation of CT scanners:
SOMATOM Plus, 1987

SOMATOM AR, a "fairly ingenious design",1994

At Siemens in 1988, a team led by physicist Willi A. Kalender began implementing this seemingly very peculiar idea, for spiral CT promised a huge leap in performance if only the issue of motion blurring could be resolved. The solution lay in mathematics, and complicated algorithms had to be added to the image generation software in order to factor the movement of the table into the measurements. In 1989, because controlling the processes within the system was much more complicated in spiral CT, Kalender and his team built a prototype featuring many other system components that were also significantly more powerful than in conventional systems. Just a year later, following numerous clinical tests, Siemens launched the world's first spiral CT scanner: SOMATOM Plus-S. This system scanned a volume of up to 30 centimeters in a single pass without any gaps – for example, in order to scan a whole organ. With spiral CT, movements happening inside the patient's body are no longer an issue.

Astonished engineers

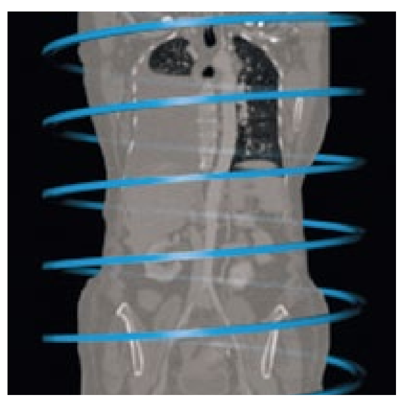
Normally, innovations are introduced from the top down – in other words, they are developed for high-end systems and gradually move down to the systems in lower price segments. In the early 1990s, a Siemens team consisting of former ultrasound engineers and experienced CT engineers bucked that trend with SOMATOM AR, an exceptionally compact entry-level unit that implemented numerous technical innovations for the first time. Among other things, SOMATOM AR cost just one third of the price of previous entry-level systems, could be installed in just two days, and required so little energy that power could be supplied from a normal wall socket. The communications interface of the CT scanner was so powerful that it became the standard for Siemens medical technology, and SOMATOM AR was also the first system with preproduced wiring instead of the wire harnesses that had been customary until then – a move that dramatically reduced the possible sources of error. The device was a complete success, and Siemens built around three times more SOMATOM AR units than planned. Almost a quarter of a century later, in 2014, Siemens staff discovered a 1992-built SOMATOM AR in China that was still running perfectly and scanning 15 to 20 patients per day.

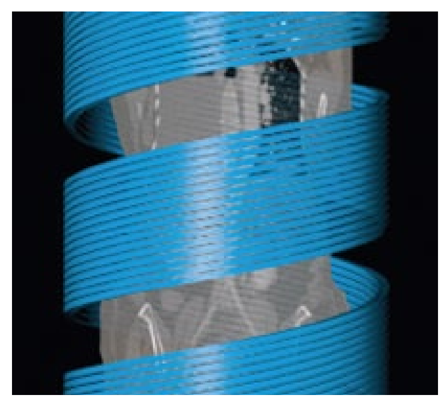
According to systems engineer Andres Sommer, the compact design of SOMATOM AR was made possible by various factors, including a "fairly ingenious design of the tilt bases." For the first time, the entire tilt mechanism, which allowed the scanner to tilt for certain types of scan, was contained within the unit casing. It almost didn't come to that, however: "When we had set up the unit for the first time and used the tilt, a very heavy colleague, about 160 kilograms, was lying on the table," Sommer recalls. "As the tilt increased, he was squeezed more and more in the 60-centimeter opening. We were all stumped as to whether we should build the system that way." The team worked on other tasks for a time, but the subject of tilting eventually returned to the agenda, and the heavy colleague found himself back in the gantry as a test subject. The engineers were astonished to see that there were suddenly "no problems at all with the tilt. Everything was fine, and everyone was happy. What we hadn't noticed was that our colleague had lost 30 kilograms in the meantime, so he met the requirements for the table."

Welcome to the future

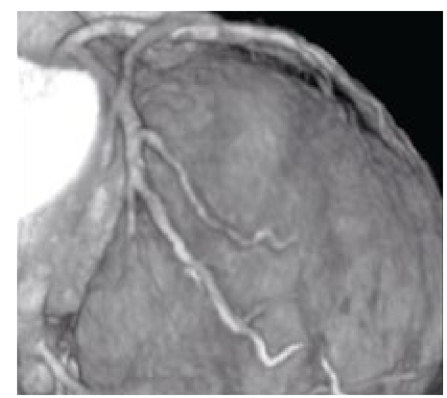
In 1968, Godfrey Hounsfield had predicted that so-called multislice detectors would be "a possible future solution" to achieving significant improvements in the performance of computed tomography. Exactly 30 years later, that technology became a reality. Whereas conventional detectors scan one slice per revolution, multislice systems divide the detector into several rows that process the signals transmitted by the X-ray tube independently of one another. In SOMATOM Volume Zoom, the gantry rotated around the patient twice per second, recording four slices at the same time. The detectors from Siemens were also divided up so that the slices were very narrow on the inside and became wider at the edges. This allowed the physician to choose between a quick scan of large parts of the body or a more-detailed scan of smaller regions – the resolution of the image was therefore up to eight times higher in 1998 than in the previous year.

Once again, this explosion in performance raised computed tomography to a new level in several respects: For one, physicians now increasingly used three-dimensional images – instead of individual slices – from inside the body for certain types of examination. Until then, vascular examinations had been performed invasively, generally using catheters. Multislice detectors ushered in the era of routine vascular imaging using CT scanners, and the first image of the coronary vessels using SOMATOM Volume Zoom at Munich's Klinikum Grosshadern was of particular historical significance. Although this image still took around 40 seconds to capture in 1999, Siemens recognized the potential of the technology and worked with clinical partners to drive forward the development of cardiac CT imaging. By 2001, SOMATOM Sensation 16 could even visualize narrowing and deposits in the coronary vessels thanks to the special HeartView CT software and was nominated for the German Future Prize in 2002. Thanks to systems such as SOMATOM Sensation 64, with its 64-slice detector, images of the heart became more and more detailed – and then a simple but brilliant idea led to the development of a CT scanner that was faster than any heartbeat: SOMATOM Definition.





A comparison of conventional detectors and multislice CT



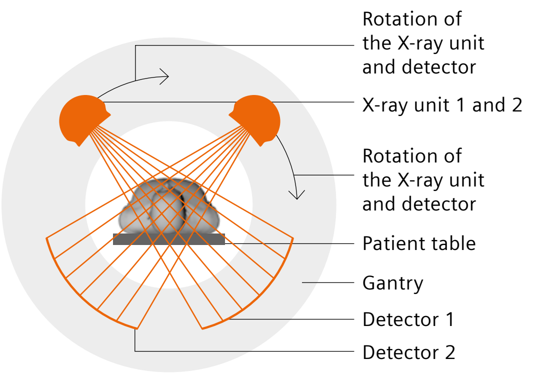
The first CT scan of the coronary vessels still took around 40 seconds to capture in 1999

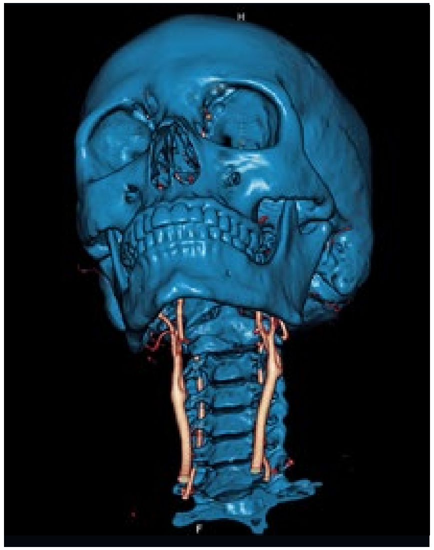
Like a Mercedes on a coffee table

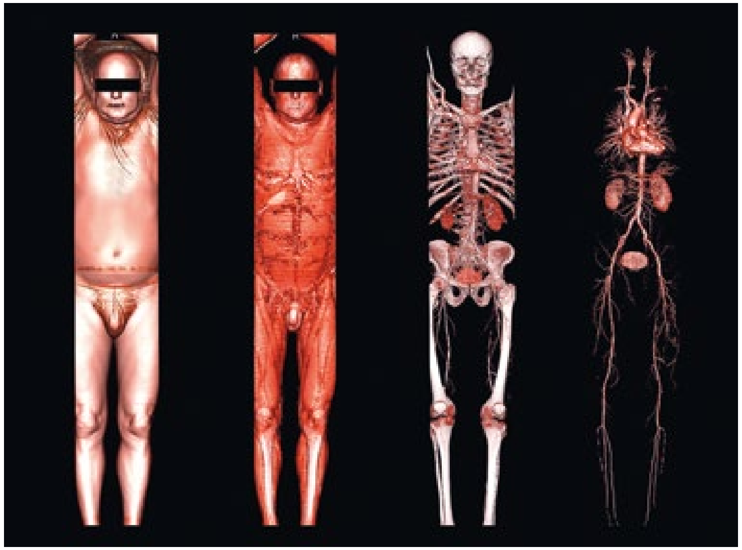
SOMATOM Definition was the first system in the world in which two X-ray tubes and two detectors rotated around the patient. When it developed this technology – known as Dual Source CT – in 2005, Siemens doubled the power of high-end CT scanners in one fell swoop while almost halving the radiation dose: SOMATOM Definition set completely new standards for scan speed, image resolution, and the temporal resolution of images – a particularly significant factor in cardiac CT imaging. Before then, patients with a high heart rate had to take beta-blockers to lower their resting pulse rate before undergoing a scan. With Dual Source CT, for the first time, the scanner was now fast enough to eliminate the need for these drugs. The reason for this lay in the scanning procedure: A CT scanner with one X-ray tube and one detector collected the data over a 180-degree rotation of the gantry, whereas SOMATOM Definition with dual source technology could do this over a rotation of just 90 degrees. With its two X-ray tubes and two detectors rotating around the patient fully in 0.33 seconds, a scan of the heart took just 0.083 seconds and was therefore faster than a heartbeat.

The huge forces acting inside a CT scanner can be illustrated by reference to the current high-end system from Siemens Healthineers. Developed by a team of 600 people over a period of five years, SOMATOM Force pushes the limits of present-day technological feasibility: The 1.6-tonne gantry of this Dual Source CT scanner rotates around the patient four times per second. That's like a Mercedes E-Class car tracing a circular path on a small, round coffee table with five times the acceleration force of a fighter jet. The patient moves through the gantry on the table of SOMATOM Force at a speed of up to 73.7 centimeters per second, so the system can scan an adult's entire upper body in under one second.

Operating principle of Dual Source CT







Left: The skull and cervical spine of a 59-year-old man, captured using the world's first CT scanner with two X-ray tubes and two detectors

Right: Scans at different levels of the body in the same man, 2006

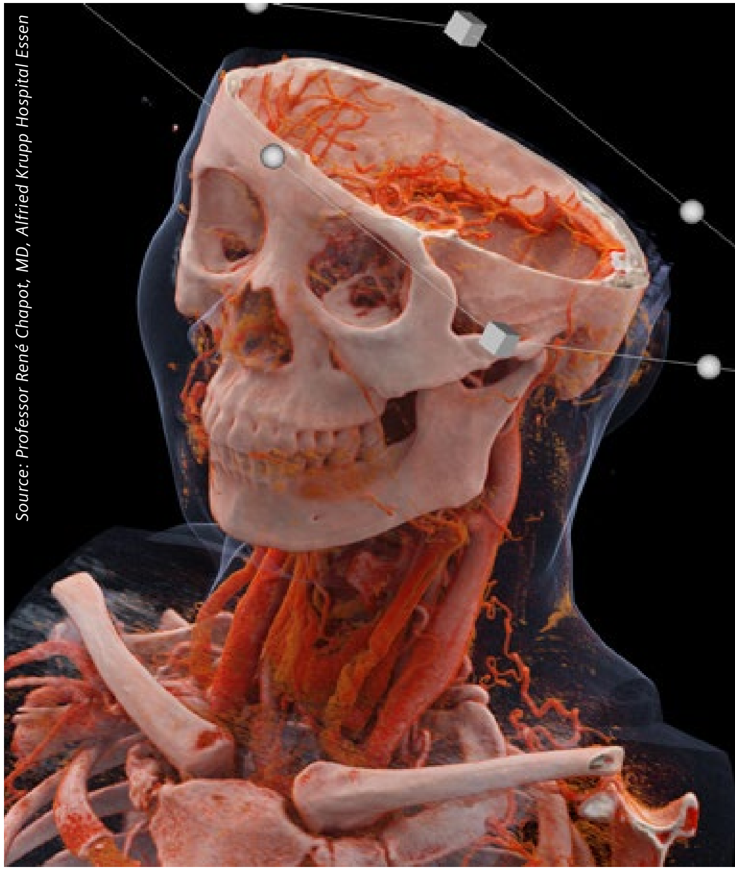
The high-end SOMATOM Force CT scanner, developed by a 600-person team over five years

A hybrid of computed tomography and PET:
the BIOGRAPH Vision PET/CT scanner, 2018

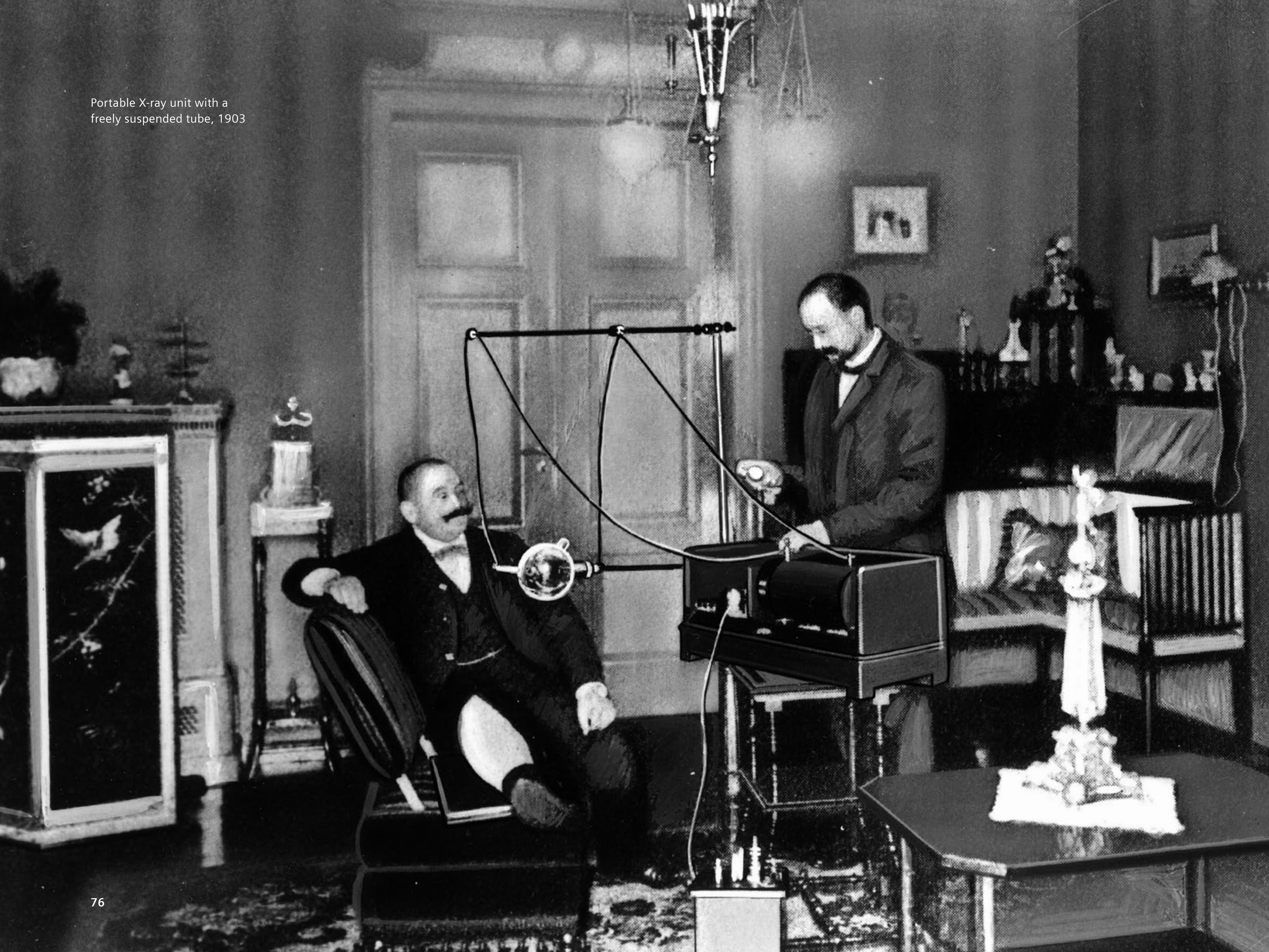
Way beyond expectations

Some 50 years on from Godfrey Hounsfield's "crazy idea," physicians can now visualize a patient's anatomy down to the tiniest structures – as small as 0.24 millimeters in the case of SOMATOM Force. For certain scans in cancer diagnostics or cardiology, for example, computed tomography is combined with molecular imaging techniques from nuclear medicine: SPECT and PET produce three-dimensional slice images that offer an accurate visualization of metabolic processes. Yet the exact location of metabolism in the body is hard or impossible to make out from these images. In the early years of PET, physicians therefore spent considerable time sitting in front of screens, comparing nuclear medical images with CT scans of the patient in order to work out where exactly in the body the metabolic processes of a metastasis, for example, were taking place. For about 20 years, the strengths of computed tomography have been combined with those of SPECT or PET to create hybrid systems. BIOGRAPH, the first PET/CT scanner in the history of Siemens Healthineers, was named "Invention of the Year 2000" by *TIME Magazine*, and numerous hospitals adopted the system as soon as series production began. The combination with CT imaging turned PET into an immensely more powerful diagnostic tool. Among imaging techniques, PET/CT was one of the quickest to achieve widespread popularity in the history of medical technology. Large hospitals and health centers began replacing PET scanners with PET/CT hybrids in 2002, and sales of pure PET systems were discontinued in 2006.

Over the years, computed tomography has far surpassed the high expectations placed on it in the early pioneering days. CT scanners can now be found in tens of thousands of hospitals and health centers around the world, where they are used, among other things, to plan operations, to monitor treatment progress, and in emergency situations such as for accident victims or in cases of suspected stroke. Modern CT scanners still operate according to the basic principle thought up by Godfrey Hounsfield – but they are worlds apart from the early devices in terms of technology. Major milestones such as Spiral CT and Dual Source CT will certainly not be the last developments in the history of computed tomography – for as Godfrey Hounsfield once remarked: "Many discoveries are probably lurking around the corner, just waiting for someone to bring them to life."


Source: Professor René Chapot, MD, Alfried Krupp Hospital Essen

Latest rendering technology like Cinematic Rendering can create impressive insights into the human body from CT images



Portable X-ray unit with a
freely suspended tube, 1903

Light and shadow

How we learned to rein in the risks of X-rays

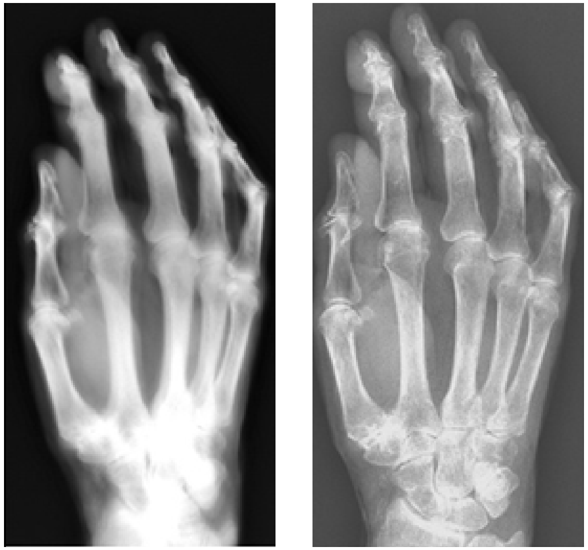
In 2010, the Dutch radiologist Gerrit Kemerink X-rayed a hand at Maastricht University Medical Center. There wouldn't normally be anything unusual about that – except this was the hand of a dead body and Kemerink was using an X-ray unit from 1896. Recorded in a darkened room, the images turned out "surprisingly well" and offered a clear depiction of the hand's anatomical details. However, Kemerink's measurements during the examination with the historical apparatus indicated a radiation dose of 74 mSv, which is 1,500 times that of a comparable examination with modern equipment. In those days, capturing just a single X-ray image resulted in 75 times the recommended annual dose for a normal person today. This highlights the fact that early operators and patients were exposing themselves to enormous doses in a very short space of time. It was a far cry from our current knowledge of X-rays and their responsible use.

The dark side

Röntgen's discovery was followed by a huge wave of euphoria. Numerous physicists, technicians, and physicians around the world began experimenting with X-rays. At this stage, however, the handling of the rays was extremely unsophisticated, as no one had any idea of the dark side of this new radiation. Particularly in medicine, X-rays were used as a diagnostic tool to search for diseases, but the examinations in that era only distantly resembled the ones we're familiar with today – and the atmosphere in many turn-of-the-century medical practices was more like that of a living room. The patient assumed the examination position, the physician switched on the X-ray equipment with the X-ray tube hanging freely in its bracket, and the entire room was flooded with radiation. The examination could take anything from minutes to hours, during which the physician and patient were completely unprotected from the rays.

Reports soon emerged of the side effects of X-ray exposure, such as hair loss and sunburn. In spring 1896, the *Deutsche Medizinische Wochenschrift* (German Medical Weekly) reported that "it is probably not yet widely known that the much-discussed X-rays, like the rays of the sun, are capable of burning the skin." These skin reactions were not taken seriously at first. Indeed, some even thought that the rays offered an ideal way of removing unwanted hair.

A year later, the *British Medical Journal* reported other undesired effects, including serious irritation of the eyes and – in the case of longer exposure – vomiting and headaches. Such reports became increasingly widespread in the years following the discovery of X-rays, with the skin damage in particular turning out to be much more problematic than first assumed. This "X-ray dermatitis" primarily affected the skin of the hands and was very common in physicians, nurses, and radiographers in the early days of X-ray examinations.



Comparison of the two hand X-rays from Gerrit Kemerink's experiment: on the left, the image taken with the 1896 apparatus; on the right, the image captured with a modern X-ray unit from 2010

Source: Professor Gerrit Kemerink, Department of Radiology, Maastricht University Medical Center

Early X-ray damage to the hands of the 28-year-old RGS employee Otto Schreiber in an image taken in 1910

Otto Schreiber, 1916

Friedrich Dessauer with protective goggles, c. 1950

The disease was chronic, came in bouts, and was very painful for those affected. In 1903, the well-known pioneer of radiology Albers-Schönberg wrote: "There is no actual therapy that would be capable of eliminating these conditions."

"I am afraid"

Things slowly started to change between 1900 and 1910, when the carefree use of X-rays began to claim its first victims, with the skin damage often developing into cancer. In 1904, the death of Clarence Dally caused a stir among the emerging community of radiology researchers. As an assistant to Thomas Edison, Dally had been tasked with conducting research into X-rays. Edison was horrified by his assistant's suffering and abandoned all further work on the radiation. Until his dying day in 1931, he refused to undergo another X-ray examination, and is recorded as saying: "Don't talk to me about X-rays. [...] I am afraid of them." Dally is considered the first person to die of radiation exposure in the USA, and his case received worldwide attention and a huge media response.

A similar fate awaited the radiographer Otto Schreiber, an employee of Reiniger, Gebbert & Schall (RGS) in Erlangen – one of the predecessor companies of Siemens Healthineers. Working at RGS from 1907 onward, Schreiber was tasked with improving the company's radiographic technology, which resulted in frequent radiation exposure for his hands in particular. The first radiation damage appeared in 1909, and by 1924 he had lost both of his arms. In 1925, at the age of 43, Schreiber succumbed to the effects of his experiments with radiation. Another victim was Friedrich Dessauer, the founder of Veifa-Werke – also a predecessor company. Dessauer suffered serious radiation damage as a result of his early research and had to undergo more than 120 operations over the course of his life.

Several other names could also be mentioned here. Many of these pioneers continued working despite their various ailments, knowingly exposing themselves to further harm, and accepted their fate as a necessary evil in the service of medicine.

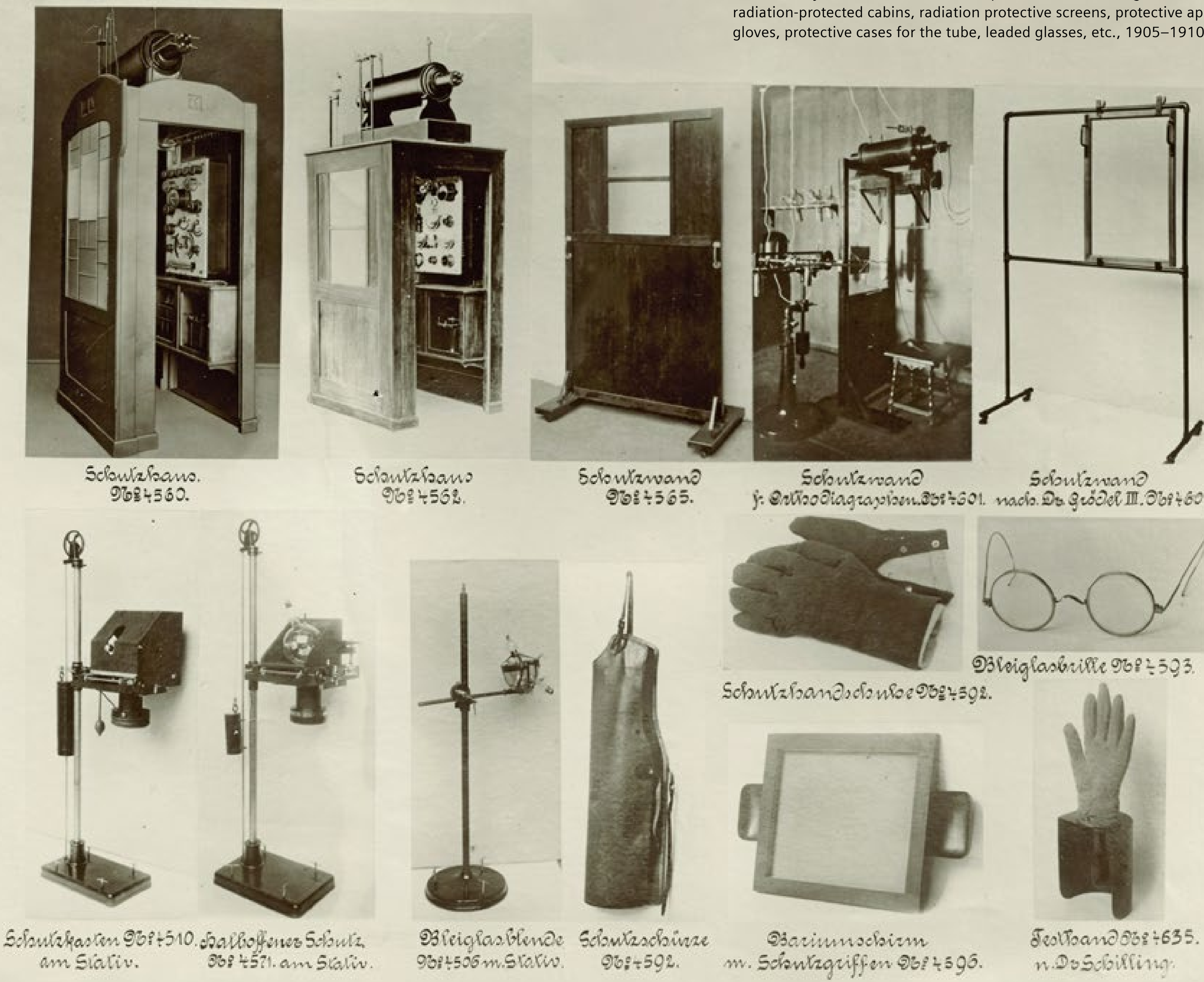
In 1936, a memorial to the victims of radiation was inaugurated outside St. George's Hospital in Hamburg. As there wasn't enough space for all the names, a book was also produced and published in order to serve as a record of those who died. This *Ehrenbuch der Radiologen aller Nationen* (Book in Honor of Radiologists of All Nations) includes the names of Albers-Schönberg, Dally, Schreiber, and Dessauer, among many others. The timing of the memorial was by no means a coincidence. By the mid-1930s, radiology had become an established medical discipline, and the "dark" early years of X-ray casualties had essentially been consigned to the history books. For the users of X-rays, the risk of dying as a direct result of radiation exposure had fallen to almost zero by 1935. As well as greater awareness of the dangers, this was primarily down to the increasingly comprehensive protective measures that were introduced from 1900 onward.

Protection from the rays

Initial attempts to remedy the situation focused on the need for radiation-proof clothing – from protective gloves and aprons made of leather or leaded rubber, to face shields and even a special cover for beards. Indeed, physicians put together entire radiation-protection suits, which resembled suits of armor and were frightening for patients. Referring to a protective helmet made of cardboard and lead, Albers-Schönberg wrote: "As the unfamiliar sight may be frightening for apprehensive patients, such as children, the helmet is only put on at the last moment once the examination room has been darkened."

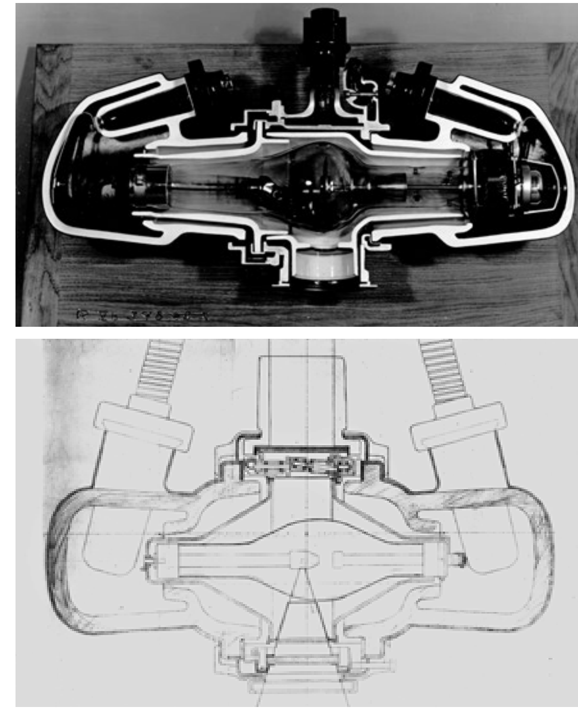
Radiation protection suit that resembled a suit of armor, 1912

Various X-ray accessories for radiation protection from Reiniger, Gebbert & Schall: radiation-protected cabins, radiation protective screens, protective aprons and gloves, protective cases for the tube, leaded glasses, etc., 1905–1910

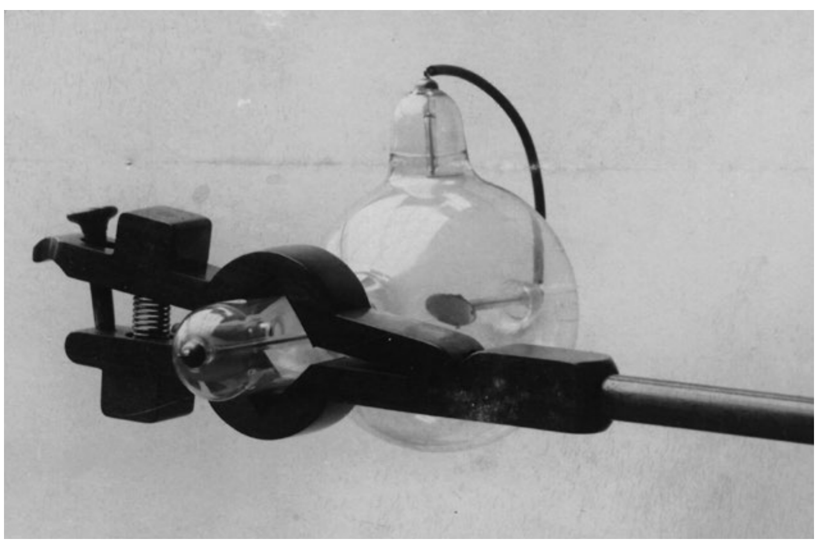


The industry also offered mobile X-ray protective screens with lead-glass windows or radiation-protected cabins, which the physician or nurse could sit behind or inside to protect themselves from the radiation. The exposed tubes were also gradually covered and fitted with apertures so that only the concentrated cone of radiation was allowed to escape.

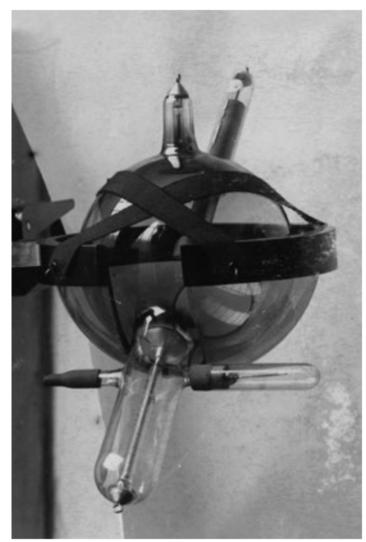
Many of these protective measures remain just as current today. The patient and physician still wear protective aprons, and the operating personnel normally leave the examination area while the X-ray image is captured. These areas are now located in separate rooms to the workstations and lounge areas, and the tube is no longer suspended freely in the room but instead contained inside a radiation-proof housing. An aperture opens for a mere fraction of a second to allow only as much radiation to escape as is necessary for the current examination, practically eliminating the risk of direct radiation damage, such as burns. A drastic reduction in exposure times was instrumental in achieving effective radiation protection. In the first few years, this reduction was primarily down to improvements in radiographic technology, such as more sensitive photographic layers and the switch from photographic plates to film and ultimately to film cassettes with intensifying screens. The higher efficiency of the tubes and generators also helped to bring down imaging times. For example, the average exposure time for a hand fell from between 15 and 20 minutes in 1896 to between 0.25 and 0.5 seconds in 1913. Today, it takes just a few milliseconds.



Cross section and drawing from 1935 and 1937: Complete radiation protection was provided by the “Tutohaube”, which enclosed the X-ray tube so that only the primary beam could escape



Exposed X-ray tube in a bracket, 1898



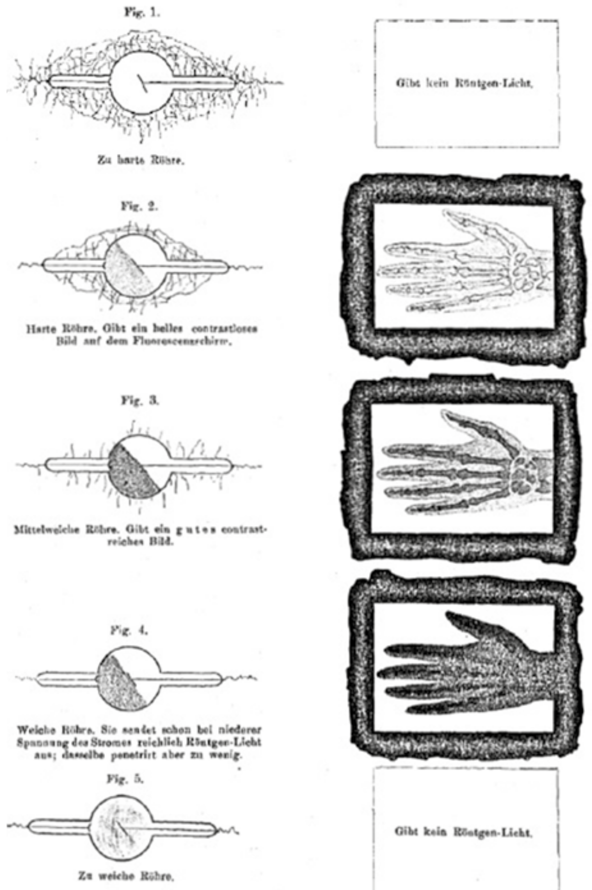
Hemispherical lead-glass protector with X-ray tube, 1905: From 1900 onward, the focus increasingly shifted to covering the tubes – although many of these coverings were initially incomplete

Heightened awareness

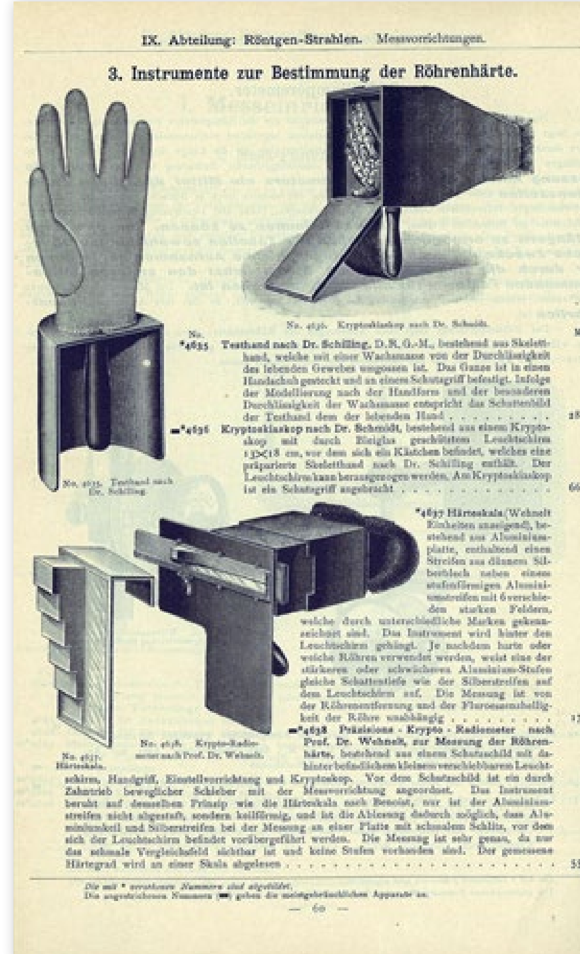
In addition to the technical means of radiation protection, it was also important to raise awareness of the correct handling of X-rays. In the first few decades, this task fell primarily to the radiologists themselves. In 1908, for example, the radiation therapist Victor Blum gave the first description of the "as low as reasonably achievable" (ALARA) principle, which is still applied today: "We set ourselves the rule of using the lowest possible dose of effective X-ray light that was enough to achieve the desired result in a normal person." Radiation protection was also one of the key topics at the first German Radiology Congress in 1905. Recommendations included not subjecting patients to multiple X-ray examinations in too frequent succession and not exceeding an exposure time of four minutes. There were also some strange-sounding recommendations by today's standards, such as regular handwashing and thorough ventilation.

The dose makes the poison

Essentially, people have wanted to be able to measure the radiation from X-ray tubes in some form since X-rays were discovered. Physicians quickly realized that it was vital to determine the type and quantity of radiation – that is, the radiation hardness and radiation intensity. In the early days, it was common for physicians to take a test X-ray of their own hand in order to measure the radiation hardness, which is a key factor in the resulting image quality. This explains why it was primarily their hands that were the first to show signs of X-ray damage.



Kienböck scale for estimating radiation hardness based on a test X-ray, 1900

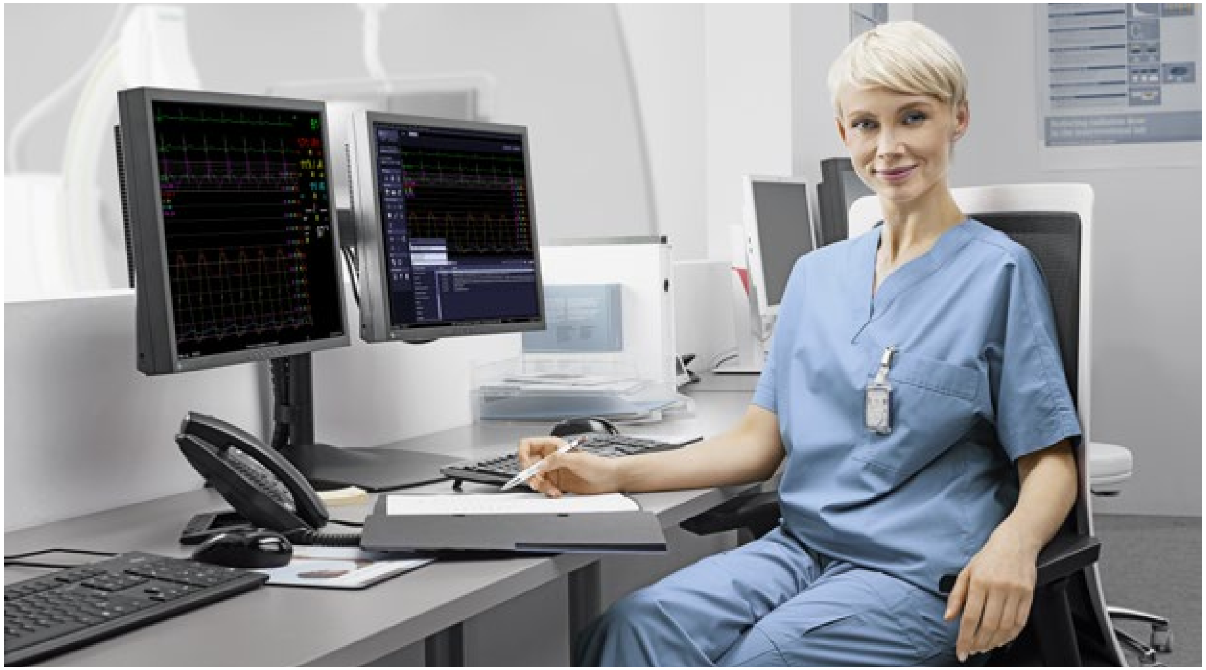


Various measuring instruments for determining the radiation hardness, including the Dr. Schilling test hand and the Wehnelt cryptoradiometer, RGS catalog, 1907

From 1900 onward, various physicians and physicists spearheaded the development of a whole host of measuring instruments, each with their own methods and scales. Many of these instruments tested the hardness of the rays – that is, their ability to penetrate metal plates of varying thickness. By the early 1920s, there were no fewer than six different methods and scales for determining the hardness. Similarly, it was essential for physicians in the emerging field of radiotherapy to be able to determine the radiation intensity, or rather the quantity of radiation. This is what we now refer to as the "dose" – the amount of radiation that is needed to achieve certain effects or that must not be reached if harm is to be prevented. Again, physicians initially used their own bodies – and specifically the reddening of their skin – as a "dosimeter." However, this "erythema dose" wasn't a particularly precise unit of measurement given the limited comparability of skin reactions in different individuals. When the early dosimeters were developed, they were generally based on the coloration or blackening of specific photosensitive materials by the X-rays. Even today, this principle still serves as the basis for the film dosimeters commonly worn by individuals who are subject to occupational radiation exposure.

Ultimately, the dose was determined based on the ability of X-rays to ionize air, which was measured in an ionization chamber. In 1922, RGS launched the Ionto Quantimeter for measuring ion dose. This dose was expressed in units of "roentgens" (R) in Germany in 1924. This unit was subsequently adopted at the International Congress of Radiology in 1928 and is defined as follows: A dose of 1 roentgen produces about 2 billion ion pairs per cubic meter of air. At last, a reliable physical unit had been found for measuring the dose emitted by an X-ray source, and efforts could be made to reduce this dose while achieving the same or even better results. Nowadays, comparative dose units are expressed as "effective dose" and measured in millisieverts (mSv). At present, effective dose is limited by law to 1 millisievert (mSv) per calendar year in order to protect members of the general public. For individuals who are occupationally exposed to radiation, the limit is 20 mSv per year.

Measurement of radiation intensity (dose) using the Kienböck Quantimeter, 1905



Operator room with the Sensis Vibe workstation: Woman wearing a film dosimeter on her breast pocket to detect whether she is exposed to radiation in the workplace, 2011

Possible long-term consequences

With the risks of direct and/or deterministic radiation damage all but eliminated from the 1930s onward, the period following World War II saw the focus shift to stochastic radiation damage – that is, the long-term consequences of radiation exposure, such as cancer. As the world had just entered the atomic age, there was increasing concern about the effects of ionizing radiation, of which X-rays are just one type. In 1927, the American biologist Hermann Muller had already demonstrated a positive correlation – in fruit flies, in this case – between the gene mutation rate and the radiation dose, with increased mutation rates providing an early indication of possible genetic damage. It was for this finding that he was awarded the Nobel Prize in Medicine in 1946.

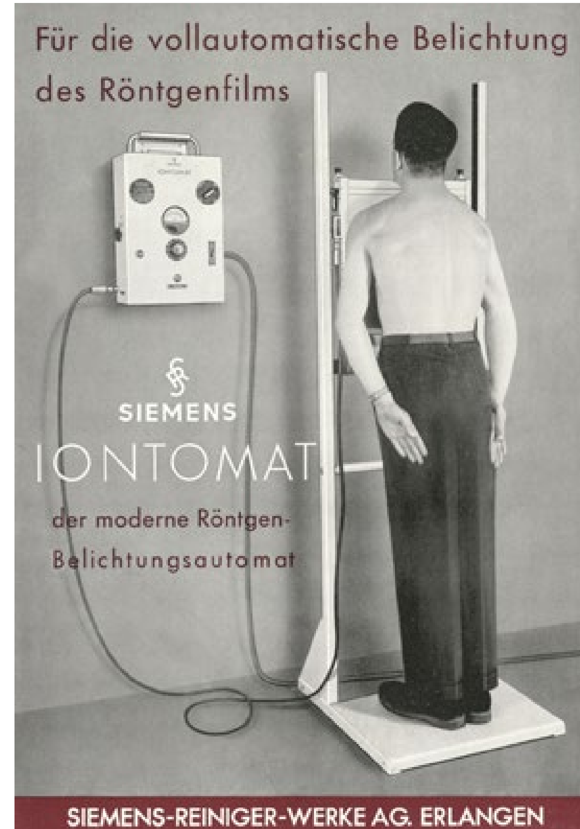
Poster about radiation protection from 1947:
In the atomic age, radiation protection was once again at the forefront of people's minds

The key scientific evidence came from research into the survivors of the atomic bombings at Hiroshima and Nagasaki. These studies suggested a linear relationship between dose and risk with no threshold level – meaning that even at low doses, there was a chance that people would subsequently develop cancer. This view is still accepted by the majority of scientists today and continues to motivate efforts to achieve further reductions in dose.

As low as possible

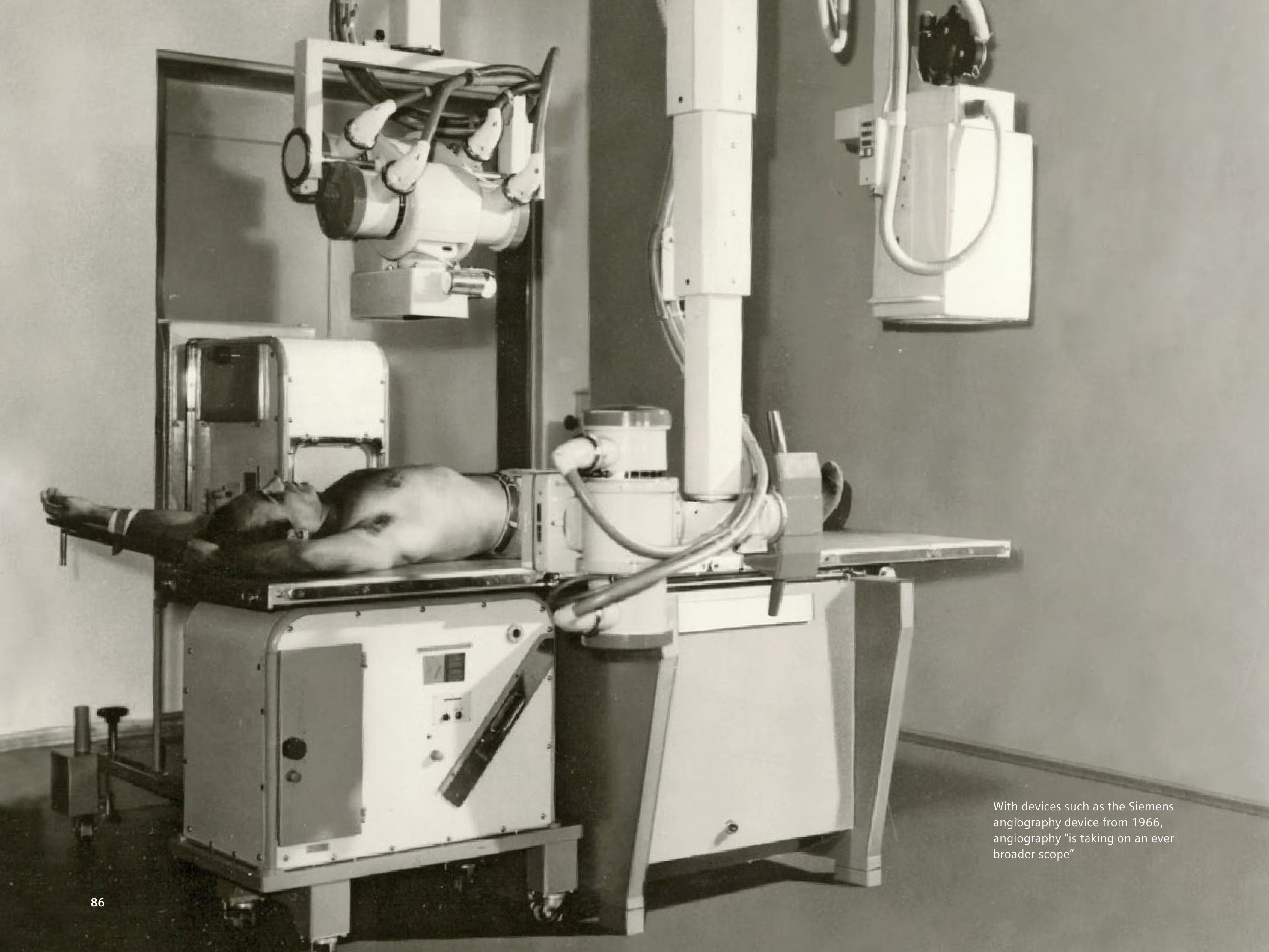
Numerous technical improvements in X-ray equipment over the last 124 years – from better radiographic technology to more powerful X-ray tubes – have led to a reduction in exposure times and radiation dose.

The advent of digital technology in the 1970s and 1980s opened up innovative new ways to significantly lower the dose. The field of radiation protection continues to benefit from technical developments. Indeed, the radiologist Dominik Zinsser, MD, from University Hospital Tübingen wrote in 2018: "At the same time, the trend is toward increasing monitoring and optimization of the radiation dose applied to the patient. The challenge for radiology is to translate the possibilities that arise into clinical routine." In other words, dose reductions can only be partly achieved through technical innovations, and much of the responsibility for reducing the dose still lies with the operators – as it did in the early days. However, it is important to emphasize that dose reduction is not an end in itself: A supposedly gentle low-dose examination will deliver insufficient image quality if the chosen dose is too low, thereby harming the patient without providing any additional benefit because the examination will need to be repeated at a sufficient (higher) dose. Nevertheless, the advantages of a radiological examination normally far outweigh the risks of radiation exposure.



Advertising image from 1949: The IONTOMAT automatic exposure control is one example of the advances in radiographic technology. It reduced the dose by switching off automatically once the X-ray image had achieved sufficient quality

Monitoring software on modern CT scanners helps to optimize the examination in order to minimize the radiation dose, 2017



With devices such as the Siemens angiography device from 1966, angiography “is taking on an ever broader scope”

Artificial shadows and "beautifully made" catheters

How a wish that came true for a former minister for foreign affairs led to the development of modern angiography

António Egas Moniz, Nobel Prize Photo from 1949

By the time the Portuguese neurologist António Egas Moniz received the Nobel Prize in Medicine in 1949, he could already look back on an eventful and unconventional career path. He was considered a brilliant individual of diverse talents and had achieved great things in various occupations, including as a writer, a politician, and a physician. Newspapers at the time featured the name António Egas Moniz in various different sections. In the aftermath of World War I, for example, Moniz led the Portuguese delegation to the Peace Conference in Versailles as the country's minister for foreign affairs. A few years later, he achieved a breakthrough in the development of angiography – a technique allowing the visualization of arteries and veins in an X-ray image. He went on to invent psychosurgery, a specialty that involved severing specific neural pathways in patients' brains in order to cure them of psychoses or severe cases of anxiety. Soon afterward, he made the headlines again when he was shot eight times by a schizophrenic patient. When his psychosurgical procedure, known as leucotomy, earned Moniz the Nobel Prize, the jury's decision came as a surprise – and not only to passionate critics of the technique. Even Moniz's long-standing research partner Pedro Manuel de Almeida Lima was surprised that "he was awarded the Nobel Prize not for the invention of angiography but for developing the first surgical procedure for treating specific mental illnesses."

In retrospect, we can say that leucotomy remained a standard procedure for the treatment of schizophrenic or severely depressed patients until the 1960s, before being replaced entirely by far more accurate techniques and new psychiatric drugs. Angiography, on the other hand, remains a vital tool for the diagnosis and treatment of vascular diseases to this day – partly thanks to the numerous specialized systems developed since the 1950s. So how exactly can X-rays be used to visualize arteries, veins, and other "hollow" vessels? The basic principle is relatively simple and was understood long before Moniz made his breakthrough. Indeed, when he embarked upon his research in 1924, Moniz was able to build on the work of numerous pioneering radiologists who had gone before him.

Stallions and culinary contrast agents

In March 1896, around two months after the discovery of X-rays was announced, the *Deutsche Medizinische Wochenschrift* (German Medical Weekly) reported that "in recent weeks, it has barely been possible to set foot in the lecture halls of our scientific societies without encountering a new series of X-ray photographs." Among the countless X-ray images, one photograph of "an amputated hand injected with Teichmann's mixture" was said to be "particularly noteworthy." The mixture was made up of lime, petroleum, and cinnabar, and represented the first implementation of the fundamental principle of angiography – that is, that the cavities of the body can be visualized by injecting an agent that stands out from surrounding tissue as darker or lighter shadows in the X-ray image. Although the image of an amputated hand, taken in Vienna on January 17, 1896, made medical history as the world's first angiogram, the technique was still a long way from entering clinical practice. Not only were lime, petroleum, and cinnabar wholly unsuitable for use as contrast agents in living people, but it also took about 57 minutes to capture the image using the technology available at the time.

Many physicians immediately began searching for suitable contrast agents, while others investigated alternative methods of imaging organs and vessels. The idea of using catheters to visualize the cavities of the body went on to play an important role in the future of angiography and was used for the first time by several doctors independently. For example, in 1897, a specialist in internal medicine known as Georg Rosenfeld suggested examining the stomach via the esophagus by inserting a probe, "such as those used to catheterize stallions in veterinary medicine. Probes of this kind are highly flexible, about 110 centimeters long, and impenetrable to X-rays."


Source: German Röntgen Museum

The world's first angiogram, taken on January 17, 1896 in Vienna

From 1903 onward, a simple yet ingenious idea allowed physicians to visualize the contours of the stomach. Hermann Rieder, a professor of physical therapy at a Munich hospital, instructed his patients to eat 400 grams of mashed potato, flour, and milk prior to the examination. The porridge also contained 30 grams of bismuth that would absorb the X-rays, causing the stomach to cast a dark shadow in the X-ray image and stand out clearly from surrounding tissues. This "contrast meal" was much more patient-friendly than any of the methods explored in the past.

A similar approach was pursued by the pioneering radiologist Friedrich Dessauer, who was one of the founding fathers of Siemens Healthineers and developed various techniques for imaging the esophagus and its disorders. Writing in 1905, Dessauer described how he would diagnose constrictions by asking the patient to eat the soft inside of a bread roll in the manner that usually made them feel as though it was stuck in their esophagus. The patient would then swallow a capsule filled with bismuth, which was "stopped in its tracks by the preceding lump of bread." This allowed Dessauer to localize the narrow section of the esophagus fairly accurately by those days' standards.

Despite early successes in the years around 1900, many pioneers believed there was little potential for further progress. For example, Hermann Gocht, the author of the world's first textbook on radiology, wrote: "The results are unlikely to improve considerably, even in the future." Given how things looked at the time, Gocht was absolutely right. The problem was not the contrast agents – indeed, their development was making significant progress. Rather, it was the X-ray technology itself that was unable to meet the demanding requirements when it came to imaging vessels. No one could have predicted the huge technological advances that would soon follow.

X-ray technology was developing rapidly, regardless of the requirements of specific procedures such as angiography. The two main components – the X-ray tubes and the generators – quickly underwent huge improvements in output, stability, and reliability. Devices such as the Blitzapparat, developed by Friedrich Dessauer in 1909, captured X-ray images so quickly that they could even produce a clear outline of the heart, and the technique known as X-ray cinematography could record several X-ray images per second from the mid-1910s onward. From 1923, new examination methods such as myelography allowed physicians to estimate the size and position of tumors in the spinal column. Developed by the French radiologist Jean Athanase Sicard, this technique involved injecting an oily iodine solution into the spinal canal as a contrast agent before taking an X-ray image. António Egas Moniz benefited from these and similar developments when he began his work in 1924.

A wish comes true

At the age of 51, after abandoning his career as a politician, Moniz was keen to find a new method that allowed him to plan the removal of brain tumors as accurately as possible. Moniz and his "loyal and hard-working colleague" Pedro Manuel de Almeida Lima began searching for suitable "radiopaque substances" – contrast agents that were safe to use in living people. They found that they could "almost completely prevent" the side effects of administering a contrast agent by injecting it into the patient's carotid artery slowly, over the course of one and a half minutes. Nevertheless, it was not until their ninth patient – a "20-year-old man with a large pituitary tumor" – that they actually found a suitable procedure that was free of side effects. The patient became the first living person to have their cerebral arteries visualized using X-ray technology.

At that time, Moniz was yet to begin using the term angiography. The prefix angio- is derived from the Greek aggeĩon and is used to refer to (blood) vessels in general. Strictly speaking, Moniz and his team were performing a procedure known as "cerebral angiography" – in other words, they were visualizing the arteries in their patient's cerebrum (the Latin term for the brain). On June 28, 1927, they injected the young man with a water-soluble contrast agent containing 25 percent sodium iodide. The resulting X-ray image revealed how arteries left the carotid " at a point much farther forward than normal, which is compatible with the disorders that the patient's large tumor must have caused in the front of the brain's circulatory system." Never before in medical history had it been possible to determine the position of a brain tumor as accurately as this without opening the patient's skull. "Finally," Moniz later remarked, "our wish had come true: Cerebral arteriography had become a reality."

A sensational self-experiment

"It is an unusual fact of medical history," wrote one of the most important psychopathologists of the 20th century, Henrique João de Barahona Fernandes, "that angiography immediately gained the greatest international acceptance, especially in Europe and later in North America, and was soon practiced widely." By the end of the 1920s, it was possible to discern structures in X-ray images that would have been blurry or even invisible without contrast agents. This was thanks not only to Moniz's research but also to the numerous physicians who steadily refined his technique.

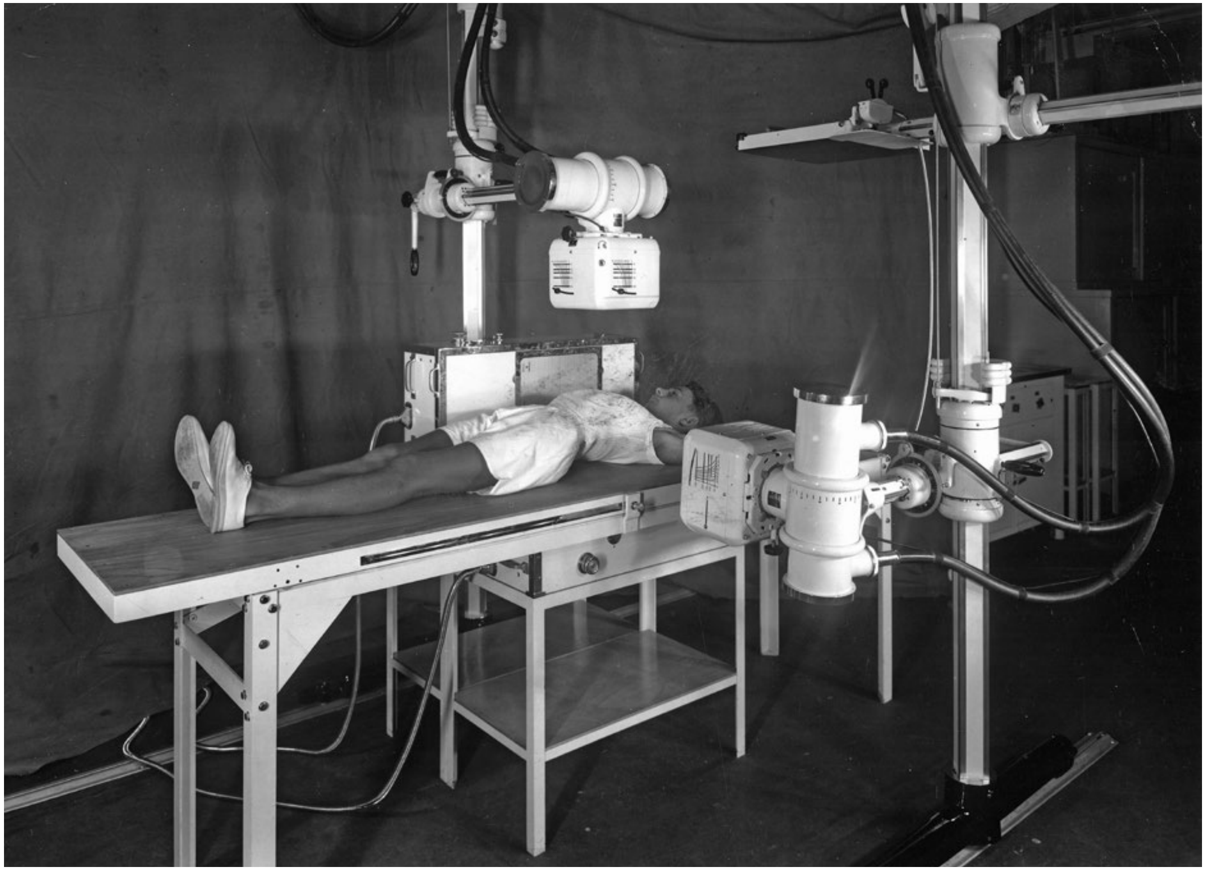
Initially, research focused on the field of neurology. The Lysholm Skull Unit, the first device in the history of Siemens Healthineers to be designed especially for contrast examinations, quickly achieved world-wide renown and remained the standard apparatus for cerebral angiography for three decades. The modern field of coronary angiography – that is, the examination of the coronary vessels using contrast agents and X-rays – is rooted in a sensational self-experiment by the young German physician Werner Forssmann. In 1929, Forssmann secretly – and against the advice of his clinical director – introduced a rubber tube into his right atrium through a vein in his right arm. By doing so, he initially tarnished his reputation as a cardiologist and earned the disapproval of the famous surgeon Ferdinand Sauerbruch, who remarked: “For such tricks you may receive your PhD in a circus but not at a respectable German medical department.” Little could he have known that, 27 years later, Forssmann would be awarded the Nobel Prize in Medicine – in part for demonstrating that contrast agents could be used safely in cardiac examinations.

The research conducted by the Swedish radiologist Sven-Ivar Seldinger was less sensational but played an equally important role in the emergence of modern angiography. In the early 1950s, Seldinger developed a much safer method of puncturing blood vessels for the insertion of catheters. In medicine, the term puncture – from Latin punctura, “prick” – refers to the targeted insertion of sharp instruments such as catheters and needles. In the Seldinger technique, the physician uses a needle to insert a “sheath” into the patient’s arm or neck, for example. Through this sheath, they then insert a guide wire – a thin steel wire with multiple windings that give it a high degree of flexibility. Finally, a catheter can be passed along the wire in order to reach the target site. Sven-Ivar Seldinger developed the method specifically for use in angiography, where it remains one of the standard procedures to this day, but it is also used to gain access to arteries and veins for other purposes.

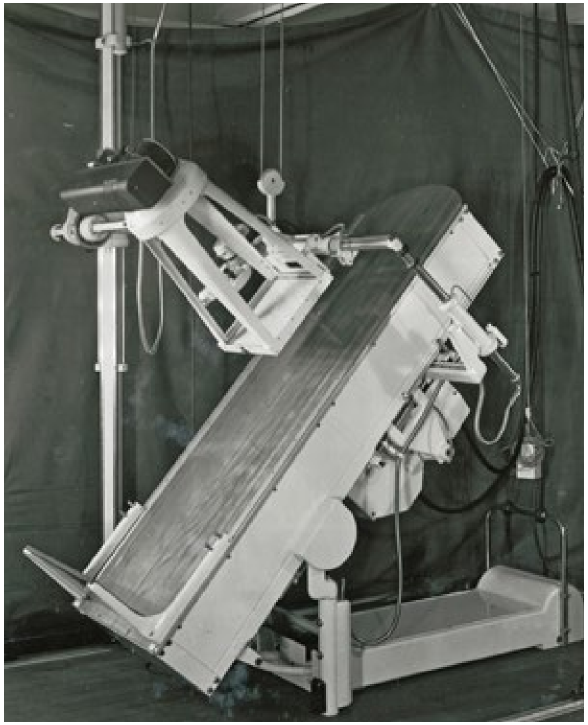
Well-coordinated teams and automatic apparatus

“The key factors [in applications of angiography] are sufficient practice and experience and a well-coordinated team consisting of a physician, nurse, and radiographer,” wrote the German neurosurgeon Wilhelm Tönnis in his 1959 textbook, which is still available today. “This allows usable results to be obtained even in primitive conditions.” However, physicians planning certain types of treatment would “find automatic apparatus to be indispensable.” Here, Tönnis was referring to a specific technique known as serial angiography, which became increasingly established in clinical practice over the course of the 1950s.

In his work on angiography, António Egas Moniz had already recognized the need for multiple X-ray images in quick succession. For example, this would

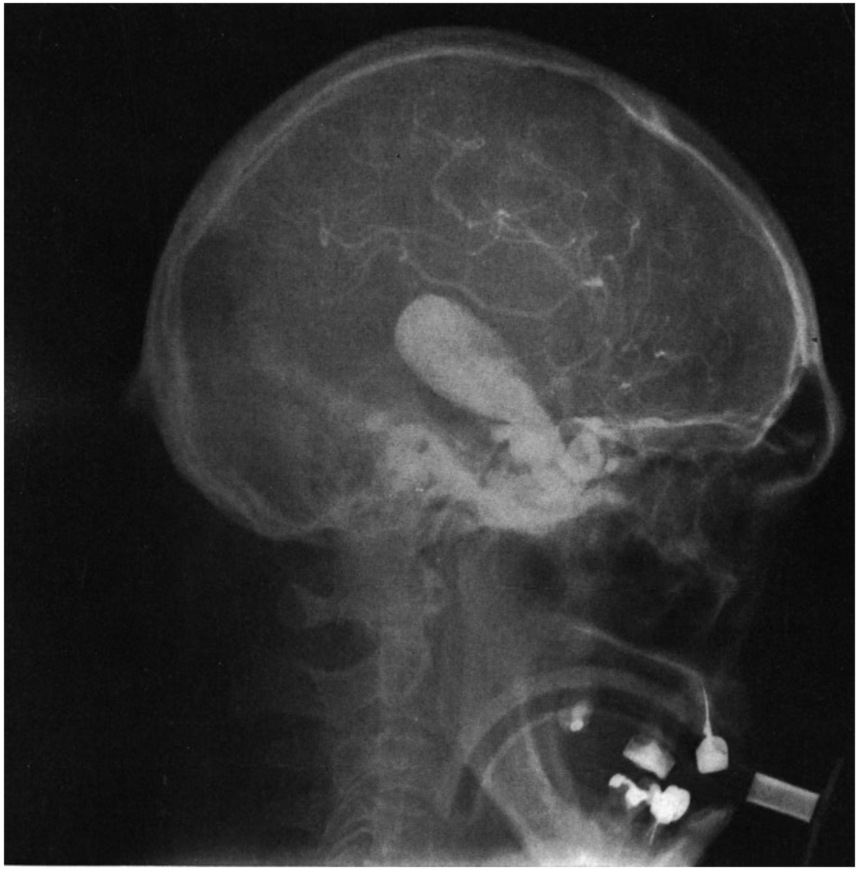


One of the first angiography recordings from two directions with a Siemens device from 1952 allow the physician to observe where the circulation was obstructed and what was causing the problem. Siemens developed the Angiograph, its first device optimized for these requirements, in collaboration with Robert Janker, one of the most famous radiologists of his time. Over the years, Janker went on to receive multiple awards for his pioneering work, including the Great Cross of Merit of the Federal Republic of Germany as well as numerous scientific prizes, such as the Röntgen Medal. In the Angiograph, Siemens implemented Janker's idea of storing the X-ray images on a roll of film, allowing up to five images to be captured per second under red light in a darkened room. The Siemens Angiograph switched off the lights in the room automatically and recorded the serial angiograms before switching the lights on again. Among other things, the device allowed physicians to visualize gastric function, observe the esophagus during swallowing, or guide a catheter to the heart.



The Angiograph: Developed by Siemens in collaboration with one of the leading radiologists of the time

Oskar Dünisch, who was head of development in the medical technology arm at Siemens at the time, recalled that "angiography led to a flood of new insights and new surgical procedures" between 1950 and 1980. "It ushered in a gigantic leap forward in X-ray technology." That period saw the development of extremely elaborate systems, which allowed physicians to visualize even the exceptionally rapid organ movements in small children. A process of "extraordinarily complicated technical implementation" led to a dramatic increase in the rate of image capture – from 12 images per second in the 1950s to up to 150 per second in the 1970s. Angiography "grew broader and broader in scope" over time, according to Dünisch, and "expanded diagnostic capabilities by at least 30 percent." In terms of their basic construction, these units already resembled modern equipment. The characteristic C-arm, with the X-ray tube and X-ray film mounted at opposite ends, emerged as a standard feature from the late 1960s onward.



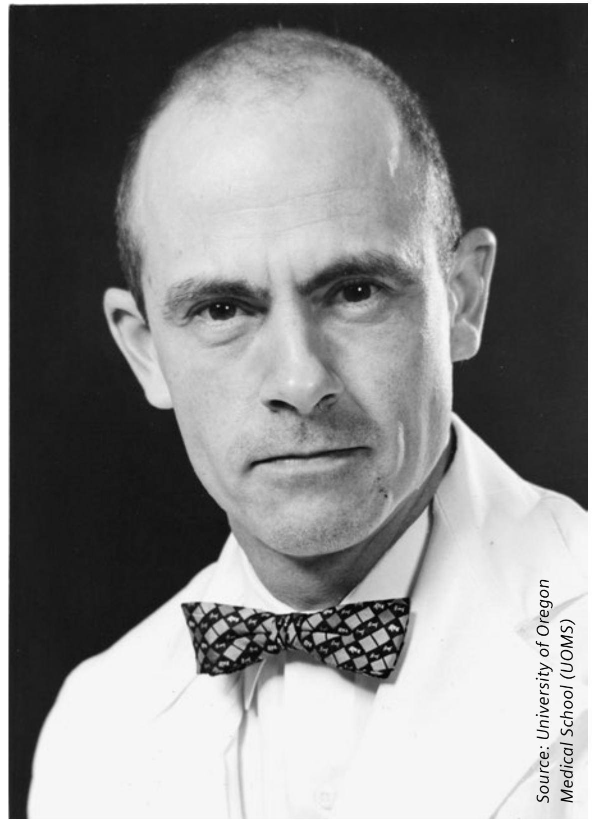
Angiography of the arteries of the brain from 1968

A plumber for blood vessels

When the American radiologist Charles Dotter needed new catheters for his research in 1963, he speculated that, if none were available, physicians could build catheters themselves from guitar strings, VW speedometer cables, or a piece of intercom cable found in a wastebasket, for example. Indeed, while attending the Annual Meeting of the Radiological Society of North America, Dotter borrowed a blowtorch, disappeared to his hotel room, and emerged the next morning with ten "beautifully made" catheters. Charles Dotter's love of handicrafts probably also gave rise to his motto: "If a plumber can do it to pipes, we can do it to blood vessels."

Yet which aspect of a plumber's work did Dotter believe a radiologist could replicate? And what does it have to do with angiography? Dotter was summarizing – "in a gross oversimplification, of course" – something he had discovered by accident in 1963. Until then, the narrowing of blood vessels could only be treated using a scalpel and a needle and thread. For open surgery such as this, patients were put under anesthetic and spent several days in hospital afterward. Dotter's accidental discovery and his subsequent research would transform the world of vascular therapy: As he prepared to perform an angiogram on a patient with a narrowed renal artery, he accidentally dislodged the blockage with the catheter, allowing blood to flow freely again – as the X-ray images clearly showed. From that point onward, Dotter dedicated his entire career to "catheter therapy" and to his goal of treating patients with a catheter instead of a scalpel whenever possible.

The first "normal" patient to receive catheter therapy was an 82-year-old woman by the name of Laura



Charles Dotter, the "father" of interventional radiology

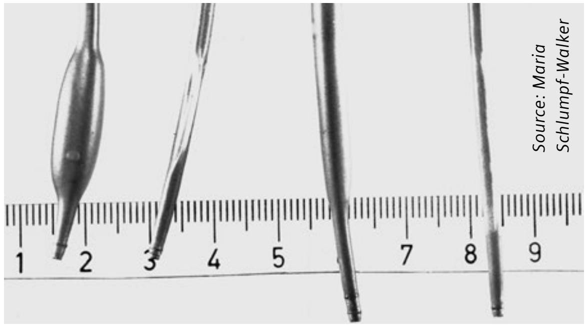
The basis of catheter therapy: conventional Dotter catheters

Shaw, whose left foot had been in pain for weeks. The tissue had turned black and seemed to be wasting away day by day. All of her doctors recommended amputation – but Shaw stubbornly refused. When Dotter was eventually brought in to examine her, he identified the cause of her suffering: The artery in her left thigh was almost completely obstructed. Dotter decided to use one of his self-built catheters to unblock it. After a few minutes, the foot was warm and blood was flowing all the way down to the toes again. A week later, the pain had disappeared – and three years down the line, just before her death, Shaw famously said she was "still walking on [her] own two feet."

Handicraft evenings around the kitchen table

What links a laser pointer and one of the most widely used surgical techniques of the modern era? The answer is that both were invented on the same kitchen table. In the late 1960s, when barely anyone was using Dotter's method, the German angiologist Andreas Grüntzig heard about catheter therapy – and became obsessed with the idea. Grüntzig was also looking for a way to treat circulatory disorders without resorting to surgery. After finishing his working day at the Cantonal Hospital of Zurich, he went home to tinker with new methods in his kitchen with the help of his wife Michaela, his laboratory assistant Maria Schlumpf, and her husband Walter. In one of their many experiments, they used a power drill to spin an elastic wire at 3,000 rpm in the hope of dilating narrowed sections of vessel wall. They quickly abandoned their attempts to treat blood vessels using lasers, though this did mean that Grüntzig no longer needed a pointing stick for his lectures. Schlumpf later recalled the evenings in 1972, when the four would-be inventors considered how a catheter could best be adapted to the anatomy of blood vessels: "A balloon – that was the idea!"

Maria Schlumpf while crafting in Grüntzig's kitchen



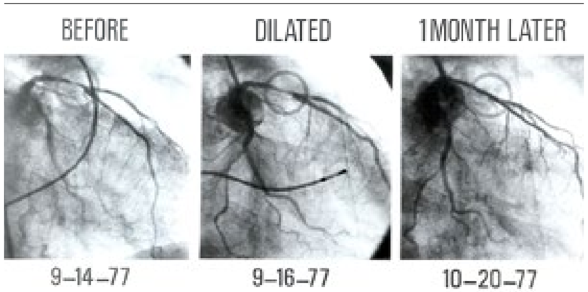
Hand-bound pelvic and femoral catheters, 1975

"Over subsequent evenings, we tinkered away with various catheters and rubber materials that were lying around in Grüntzig's kitchen." The idea was for the balloon to fold up into a small space like a fire hose and yet to hold its shape when filled with high-pressure water. "After hundreds of experiments, we finally managed to produce usable, sausage-shaped balloon segments," recalled Schlumpf. "That was the breakthrough!" They glued the two ends of the balloons shut by hand, wrapped them in nylon thread, and used clothespins to hang them up to dry on a line in the kitchen. "Every evening, we worked with Michaela and Walter to make balloons of different lengths and diameters."

These "handicrafts" in a Zurich kitchen turned out to be some of the most momentous inventions in the history of medicine and medical technology. In early February 1974, Grüntzig performed an angiogram to measure the narrowing (stenosis) of a patient's

Source: Maria Schlumpf-Walker

Andreas Grüntzig in the laboratory preparing a catheter, 1980

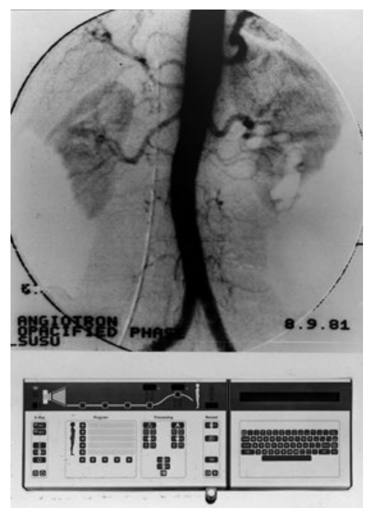


Source: Maria Schlumpf-Walker

Clinical images of coronary arteries before and after surgery

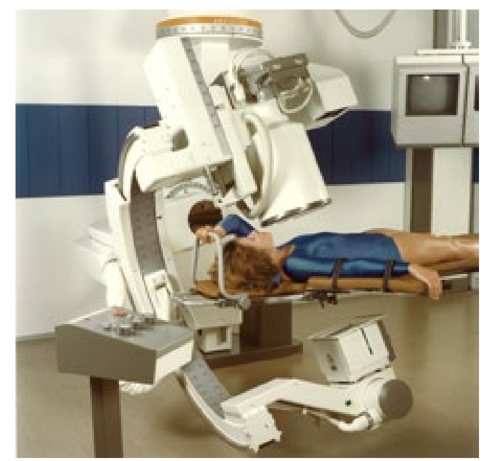
iliac artery and to fashion a balloon catheter of the correct size. On February 12, 1974, he dilated the stenosis and withdrew the balloon catheter from the artery without difficulty. On September 16, 1977, after three more years of research, he spared his patient Dölf Bachmann from having to undergo a bypass operation. Bachmann, a 38-year-old insurance salesman, was at serious risk of suffering a heart attack but was determined to avoid open heart surgery under general anesthetic – and liked the idea of being the first patient to be treated with a new technique. Monitoring the procedure by X-ray, Grüntzig inserted the catheter into Bachmann's thigh, guided it into his heart, and dilated the coronary artery, which showed narrowing of about 80 percent. Normal blood flow was restored. This first example of "percutaneous transluminal coronary angioplasty" (PTCA) earned Grüntzig and his mentor, Charles Dotter, a nomination for the 1976 Nobel Prize in Medicine – although they didn't ultimately win the award, for it would be several years before the importance of their pioneering work became clear.

The vessels of both kidneys, taken with the Siemens Angiotron and one of the first digital methods for image enhancement, 1981



From the margins to the front line

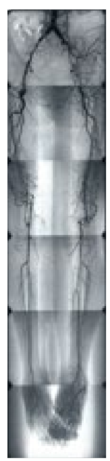
Dotter, Grüntzig, and numerous other physicians of the 1960s and 1970s succeeded in demonstrating that the principle of angiography was suitable for use in therapy. Their pioneering work ultimately gave rise to the medical discipline that we now call interventional radiology. To support radiologists working in this fledgling specialty, Siemens developed several devices debuting the same basic construction as is found in our modern systems. For example, from 1972 onward, a cardiac angiogram performed with the Siemens Cardoskop U involved an imaging device that resembled a C-arm rotating around the recumbent patient. In several respects, the Siemens Angioskop of 1977 marked the arrival of the first generation of our modern angiography systems in operating rooms. The Angioskop was the first device with a C-arm that could be moved freely around the patient in every direction – albeit still by hand at this stage.



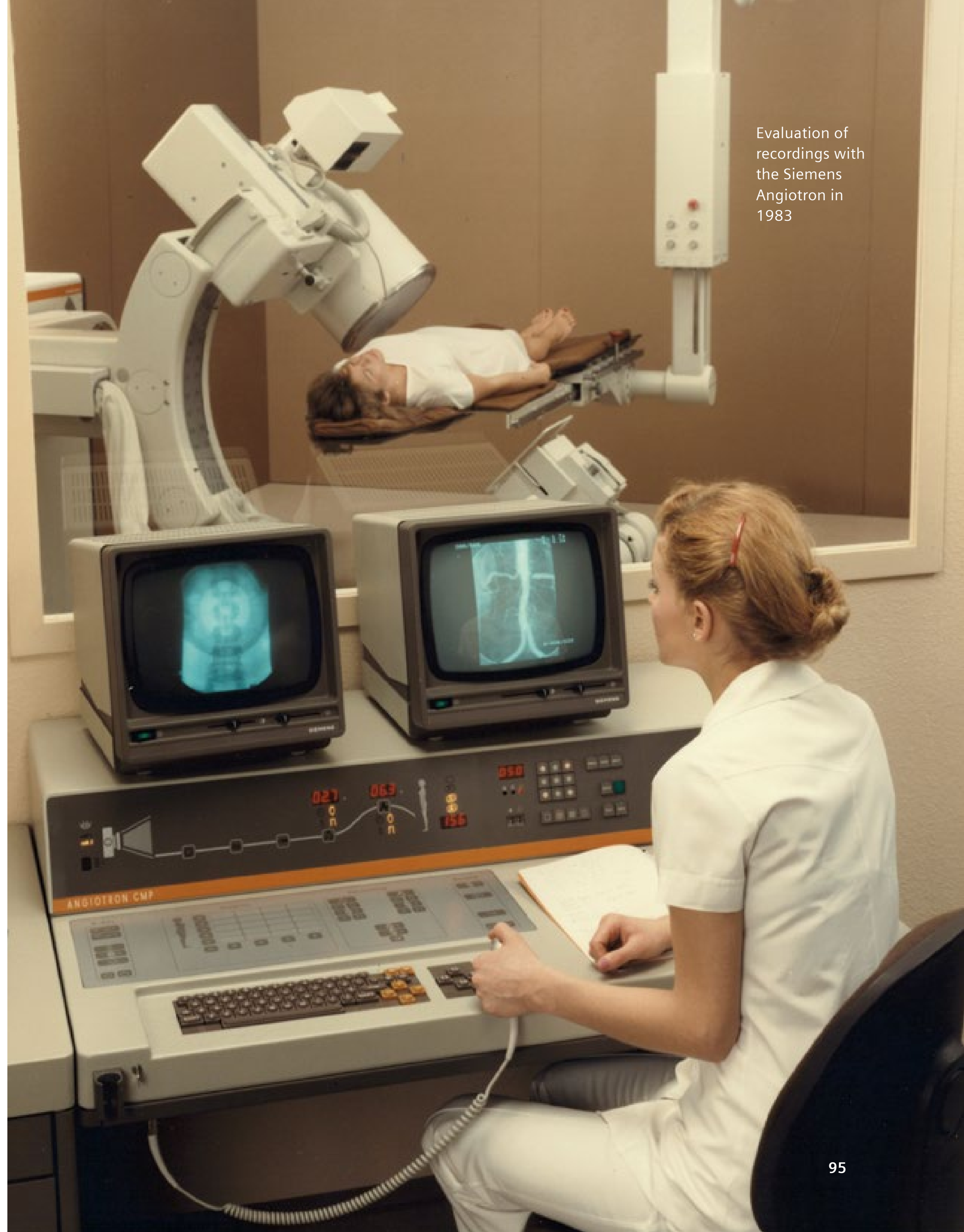
The Angioskop's C-arm can be freely rotated around the patient in any direction, 1980

In the early 1980s, interventional radiology was still something of a marginal discipline, enjoying only cautious acceptance from many physicians – but the major milestones that followed would convert these "minimally invasive therapies" into the first-choice treatment for many diseases. In the mid-1980s, the development of the stent paved the way for safer and more successful long-term treatment of certain types of vascular stenosis. The second generation of angiography units saw the arrival of computer control systems, with the 1987 Siemens Multiskop featuring the first software-controlled anti-collision system. This protected the patient and the physician as the C-arm moved to the examination position at the push of a button. The follow-up model, Multistar, was described in one advertising brochure as being "perfect for angiography and intervention." The centerpiece of Siemens Multistar was a new kind of ceiling-mounted gantry supporting two C-arms, whose "floating pivot points" allowed them to move around the patient independently for the first time.

With the computer-controlled Siemens Multiskop, the C-arm takes the examination position at the push of a button, 1986



Clinical image of the leg arteries in 1993



Evaluation of recordings with the Siemens Angiotron in 1983

Therapy today and tomorrow

Soon after the turn of the millennium, Siemens gradually introduced numerous new technologies as part of the new AXIOM Artis family. For example, the new solid-state detectors converted X-rays so efficiently that they matched the sensitivity of analog X-ray film for the first time. Their nine million active pixels – more than appear on the projection screen of a modern digital movie theater – meant that even the tiniest details were visible on the monitor. From 2005 onward, the *syngo* DynaCT software could be used in conjunction with angiographic C-arm systems to generate slice images resembling CT scans. Physicians could therefore view three-dimensional images directly at the operating table, providing them with vital information during an intervention. The world's first angiography system with industrial robotic technology, Artis zeego, represents another major milestone in three-dimensional imaging by allowing the physician to visualize the entire abdominal cavity or the liver using angiography during a biopsy, for example. Once the minimally invasive procedure is completed, Artis zeego can be placed in an extremely compact "park" position, which is essential for saving space in hybrid operating rooms that are used for multiple surgical disciplines.

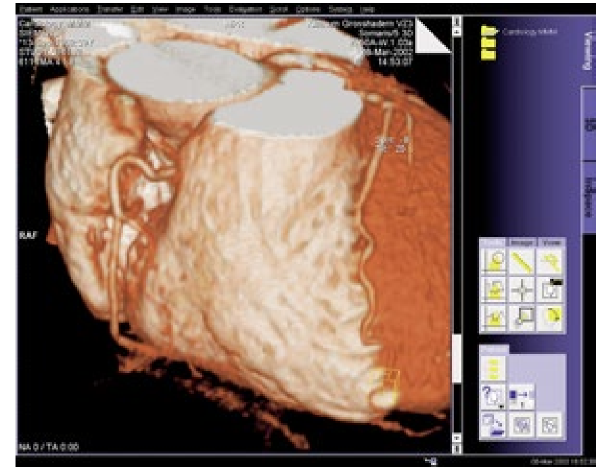
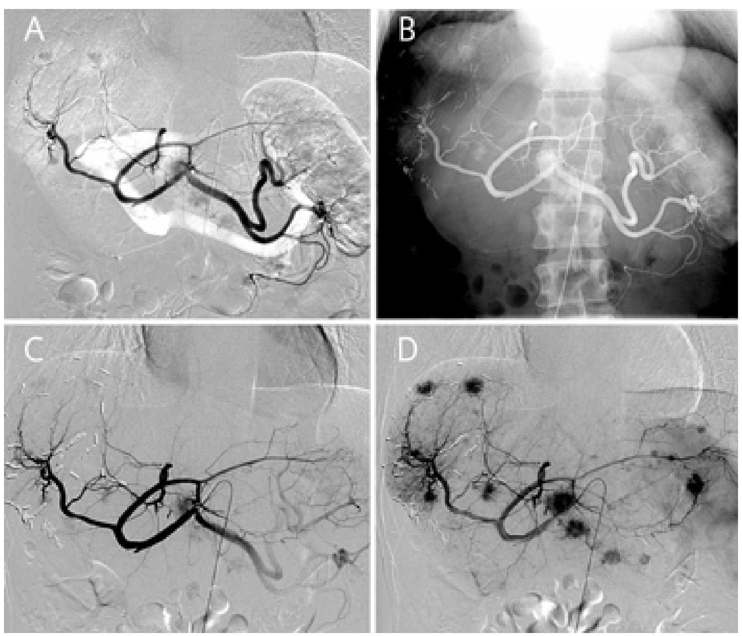
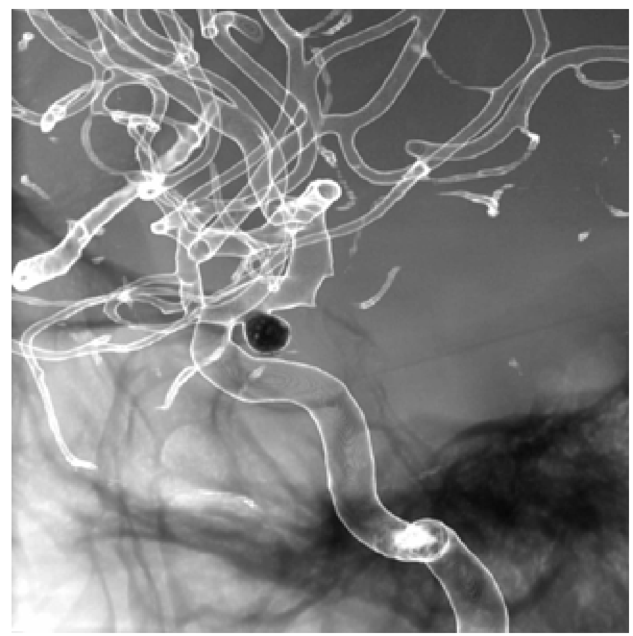


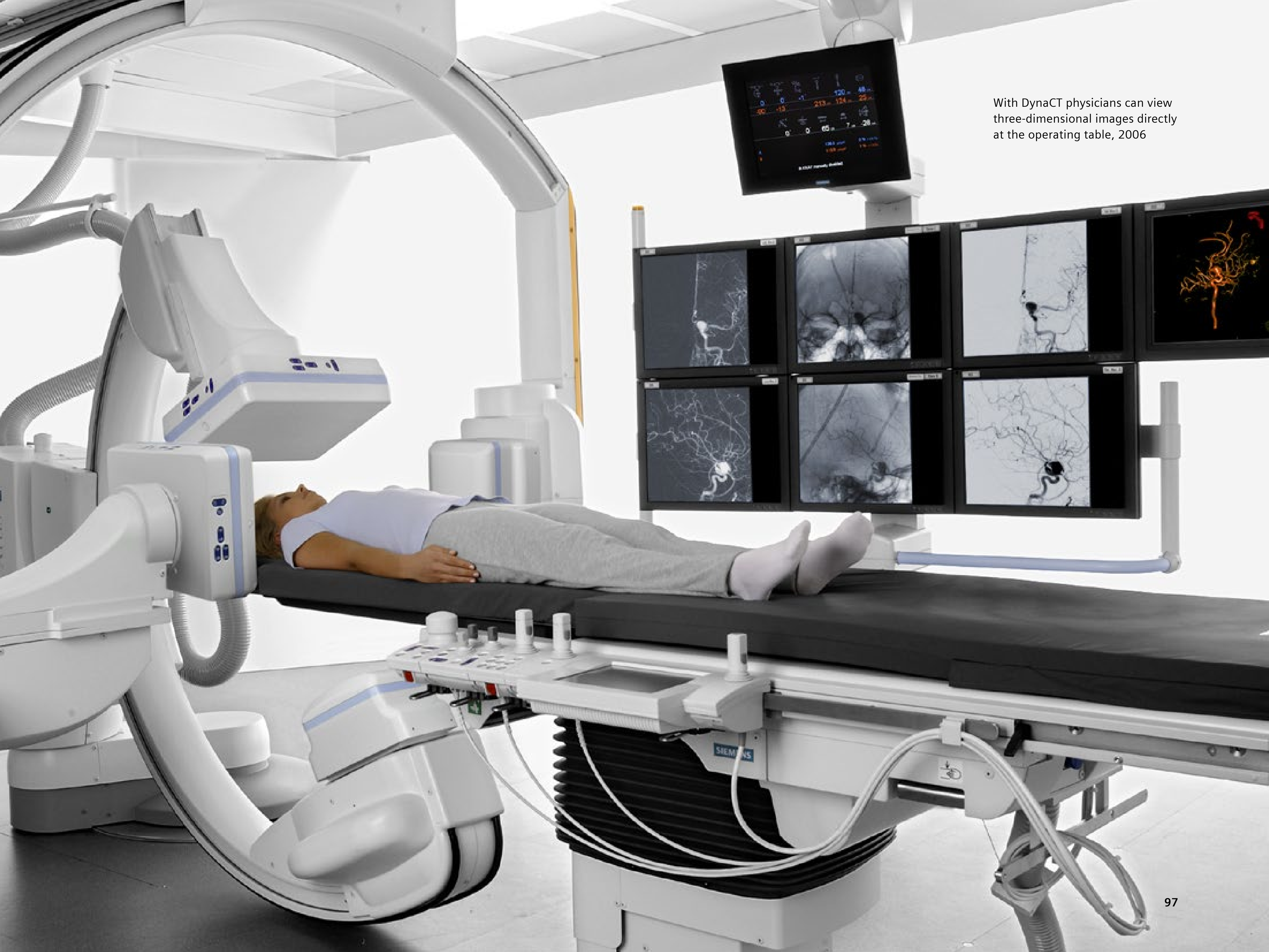
Image of the heart with the AXIOM Artis *d*BC, the world's first system with a double C-arm, 2003





Left: Angiograms of a 33-year-old patient showing the arteries and veins of the abdomen and the hepatic artery, 2004

Right: The *syngo* iPilot software from 2006 helps the doctor, for example, with minimally invasive therapy for brain vessels



With DynaCT physicians can view three-dimensional images directly at the operating table, 2006

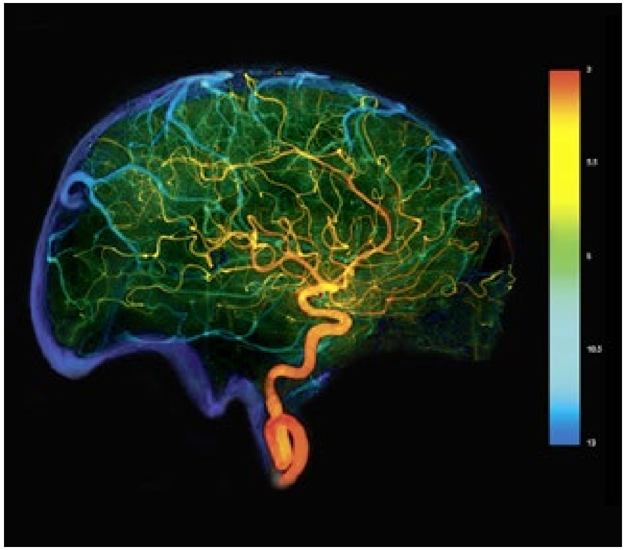
The industrial robot technology integrated in Artis zeego enables the doctor to position the C-arm almost anywhere around the patient, 2008

With the new X-ray tube in Artis Q and Q.zen small vessels can be visualized up to 70 percent more clearly than with previous tube technology, 2013

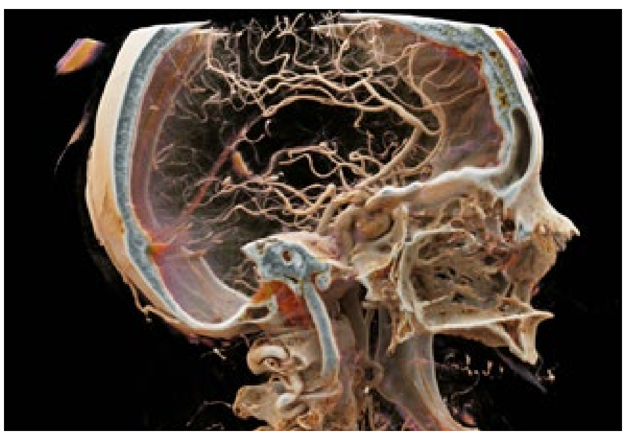
The last ten years have been some of the most eventful in the history of angiography systems from Siemens Healthineers, with a vast number of enhancements paving the way for many new applications. Since 2014, for example, the refinements made to *syngo* DynaCT have allowed it to display time-resolved 3D images for the first time. In other words, as well as capturing 3D images of the vessels, physicians can now also visualize the blood flow on a monitor. Software applications such as CLEARstent Live assist in the treatment of coronary vessels by allowing physicians to observe the opening of the stent and verify its positioning.

The engineers behind these technological advances take all aspects into account. For example, they based the development of the 2016 ARTIS pheno on a new hygiene concept with large, sealed surfaces and as few gaps as possible to ensure that the system was much easier to disinfect than older units. ARTIS pheno is not only the first angiography system sold under the brand name of Siemens Healthineers, but also the first such device to accommodate patients weighing up to 280 kilograms. If necessary, its table can also be tilted in order to stabilize the blood pressure or make breathing easier.

The “therapy of tomorrow” is already taking shape. Our systems allow the delivery of minimally invasive therapies with robotic assistance. Thanks to integrated imaging capabilities, they make it easier for physicians to precisely control everything from guide catheters and guide wires to stent implants without having to stand at the operating table. Physicians sit in a radiation-shielded workstation or in the operator room and use a set of joysticks and touchscreen controls that translate the physician’s movements into device control. Metaphorically speaking, the combination of exact imaging and robotic-assisted interventions enhances both the eyes and hands of the operator.



The *syngo* iFlow software shows how the contrast medium spreads within the vessels, where it arrives first and where it arrives last, 2009



Cinematic Rendering based on image data from an examination with an angiography system and the *syngo* DynaCT software, 2016

Source: University Medical Center Göttingen, Professor Michael Knauth, MD/ PD Marios Psychogios, MD, Göttingen, Germany

The robot-assisted angiography system ARTIS pheno for use in minimally invasive surgery, interventional radiology and interventional cardiology, 2016

Source: Getty Images

Ancient Egyptian papyrus depicting the judgment of the dead, c. 1250 BC

Matters of the heart

Examining the heart using X-ray technology

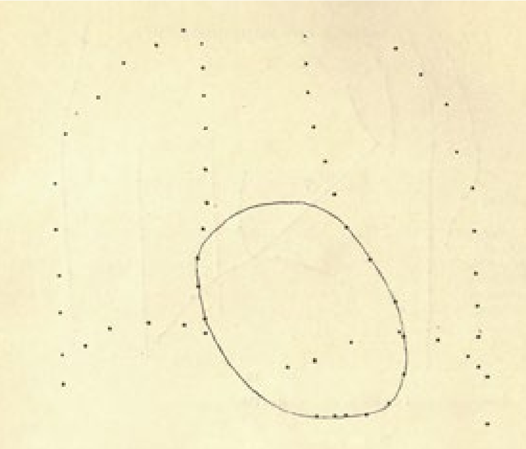
The seat of the soul, the sign of love, and the symbol of life – for millennia, there has been a certain mythology associated with the heart. Back in ancient Egypt, it was seen as the center of thought and feeling and, as such, was the only organ to be left inside the bodies of the dead when they were embalmed. Tradition held that it would be weighed in the next world to determine whether the individual would be admitted to the afterlife. Christianity also ascribes an important role to the heart: In the Catholic faith, a whole devotion has emerged around the Sacred Heart of Jesus, which is styled as the embodiment of God's love for humankind. Although advances in scientific research gradually debunked the myths of the heart, it remained a mystery to the medical profession for a long time. Indeed, it was almost impossible to examine the heart of a living person until the early 20th century.

A key turning point came with the discovery of X-rays. For the first time, it was possible to visualize the heart inside the bodies of living people – although an X-ray examination required considerable patience around the turn of the 20th century. In those days, the process of capturing the image took several minutes, during which the patient was required to stay perfectly still. As the heart would beat hundreds of times over an exposure time of this length, it appeared as nothing more than a blurry shadow in the resulting X-ray image.

Obtaining results dot by dot

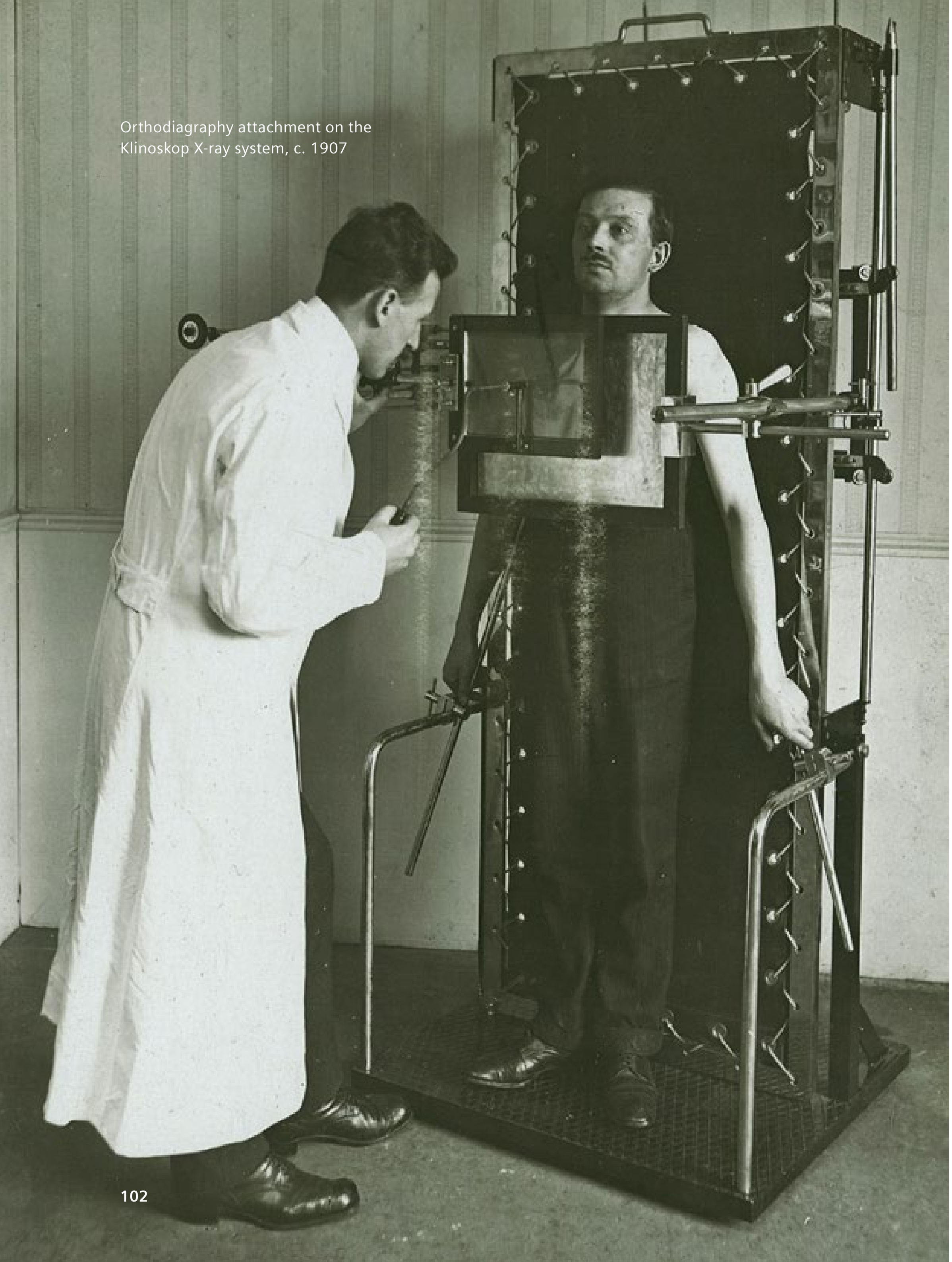
Despite these limitations, keen experimenters in the early days of X-ray technology developed devices to help physicians obtain information about the shape, size, and position of the heart. One such pioneer was Max Levy-Dorn, who launched an orthodiagraph in collaboration with Reiniger, Gebbert & Schall in 1905. The device was made up of three parts: Behind the patient was an X-ray tube, and mounted in front of them were a lead plate and a fluorescent screen covered with tracing paper. During the examination, the physician moved the tube and lead plate in parallel until the plate covered the heart right up to its edge. This position was then marked on the paper with a dot. The physician slowly worked their way around the whole organ in order to map its outline. If that sounds complicated, it's because it was – this highly complex examination called for a great deal of experience on the part of the operator. The result was a true-to-scale representation of the heart that looked, on first glance, like a game of connect the dots.

Advertisement for an orthodiagraph from Reiniger, Gebbert & Schall, 1905



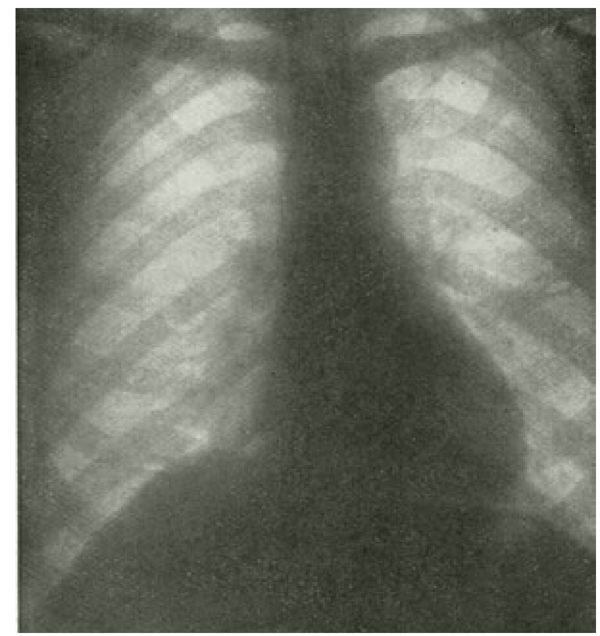
Source: Francke, Karl. Die Orthodiagraphie, 1906, p. 69

Orthodiagram of the heart of a healthy man. The unconnected dots represent the lungs

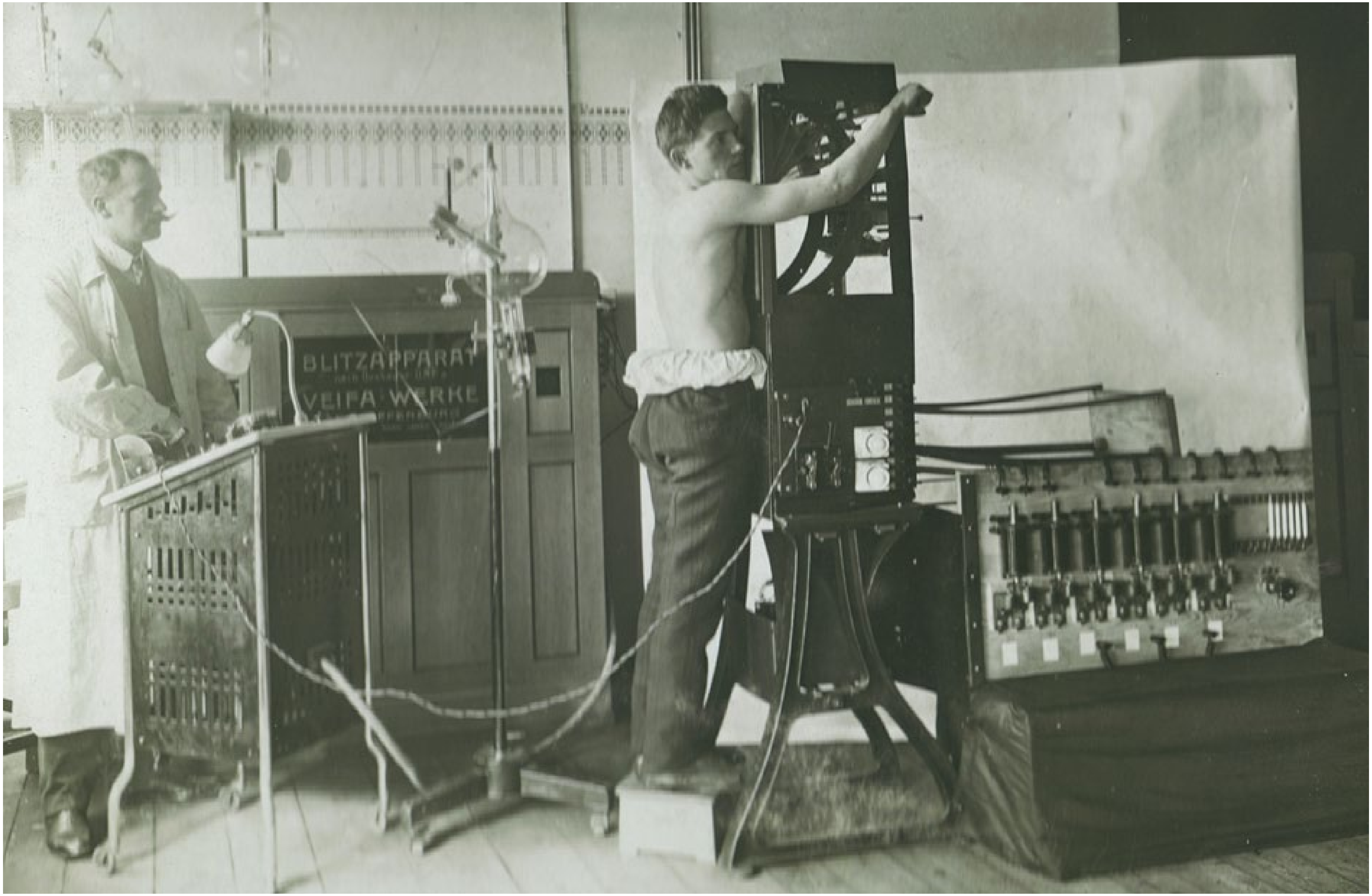


Orthodiagraphy attachment on the Klinoskop X-ray system, c. 1907

Whereas orthodiagraphic examinations took a long time, a new design introduced by Friedrich Dessauer in 1909 allowed physicians to obtain results quite literally in a flash: Once the Blitzapparat was powered up, there was a small explosion and a brief flash of the X-ray tube – and the image was in the can. Soon afterwards, the physician would be holding an X-ray image showing a clear outline of the heart. It may sound routine from today's perspective, but this was a spectacular development at the time. The Blitzapparat was the first X-ray unit that allowed physicians to capture images in the space of just a few milliseconds. This short exposure time allowed the first clear depiction of the heart in X-ray images.



X-ray of a thorax taken with the Blitzapparat and showing a clear image of the heart, c. 1911

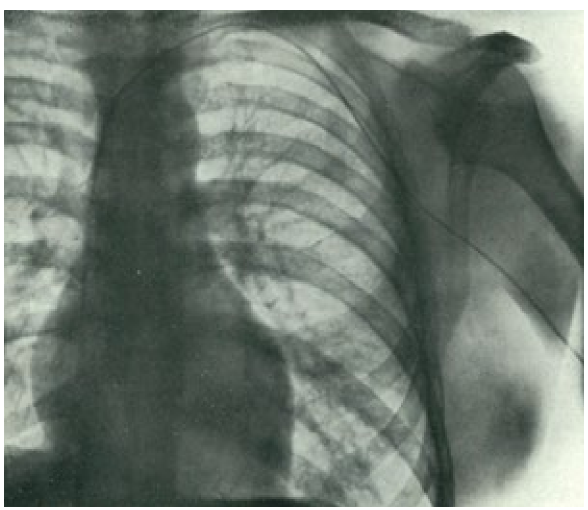


X-ray of the heart taken with the Blitzapparat
(Blitz is the German word for flash of lightning), c. 1909

Directly into the heart

For a long time, apart from X-ray images, cardiac diagnostics relied solely on percussing and listening to the heart, as well as on recording its electrical activity by electrocardiography – but these methods were not enough to make a comprehensive diagnosis. Conscious of these shortcomings in cardiology, Werner Forssmann began thinking about how to obtain greater access to the heart. He gradually arrived at the idea that a catheter could be used to investigate inside the organ and its vessels. Until that time, this procedure had never been tried on a living person.

In 1929, Forssmann was working as an intern at the hospital in Eberswalde, having recently acquired his medical license. Naturally, as a young and still very inexperienced physician, he was not permitted to put his ideas for cardiac examination into practice.

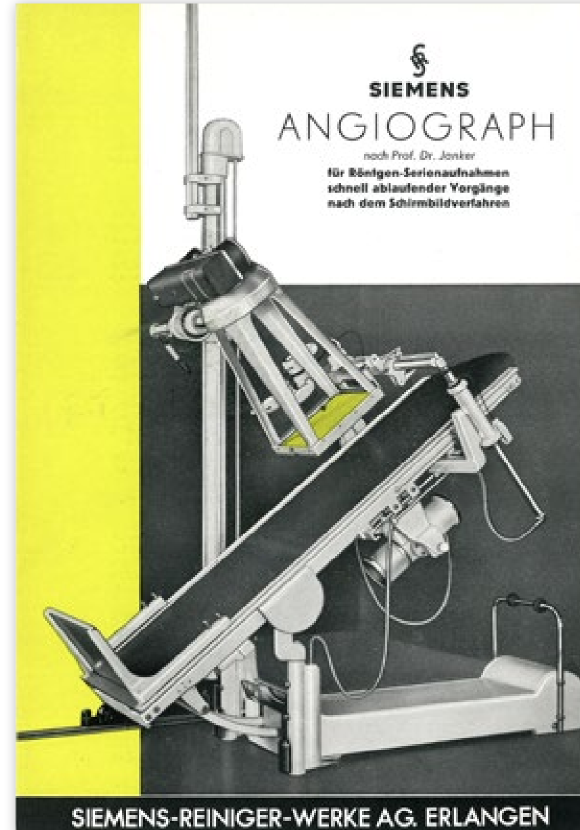


Source: Forssmann, Werner: Die Sondierung des rechten Herzens [Probing of the right heart], Klinische Wochenschrift, No. 45, 1929

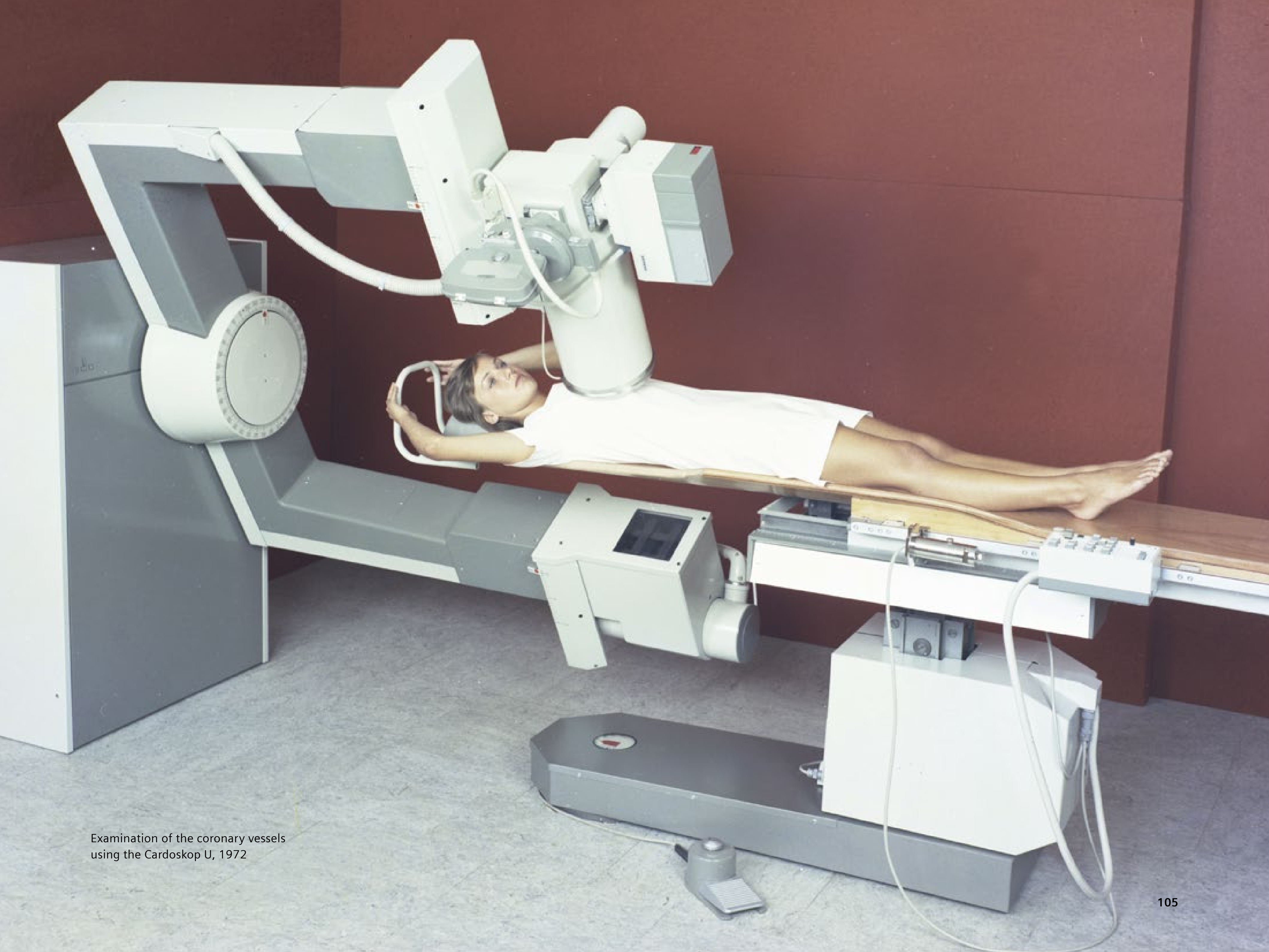
X-ray image to document cardiac catheterization, showing the catheter extending into the right atrium

However, Forssmann was so convinced of his hypothesis that he risked his life by attempting the procedure on his own heart. During his lunch break, he secretly locked himself in the hospital's small operating room. Undaunted, he punctured his left arm to gain access to the vein and threaded a well-oiled ureteral catheter into his heart. The procedure worked without a hitch. Now all he needed was proof, and so he asked the radiology nurse to X-ray his thorax. The resulting images clearly showed the rubber tube extending into his right atrium and were published, along with a description of his self-experiment, in the journal *Klinische Wochenschrift* in November 1929. At first, however, only Forssmann himself believed in the effectiveness of this examination technique.

It wasn't until the 1950s that cardiac catheterization was put to deliberate use – for example, to study arrhythmia or to take measurements of blood pressure and oxygen saturation in the chambers of the heart. A catheter could also be used to introduce contrast agents at specific locations in order to visualize the cardiac chambers and coronary vessels. Today, cardiac catheterization is a common practice and can be used not only to diagnose a multitude of cardiological diseases but also to treat them directly. X-ray monitoring has always been an essential part of this process. With the Angiograph in 1950, Siemens presented its first system that allowed physicians to observe the catheter on a fluorescent screen as it passed through the blood vessels and into the heart, and to document the flow of contrast agents through the vessels. This required the heart to be X-rayed from different positions, but there was one snag: The X-ray sources were mounted in a fixed position in the room – on the ceiling, for example. The initial solution was therefore to rotate the patient, even though they were supposed to be completely at rest during the procedure. In 1972, Siemens finally presented a solution in the form of the Cardoskop U, a special workstation for the cardiac catheterization lab that allowed the imaging system to pivot around the patient thanks to its special U-shaped arm.



Product brochure of the Angiograph from 1951

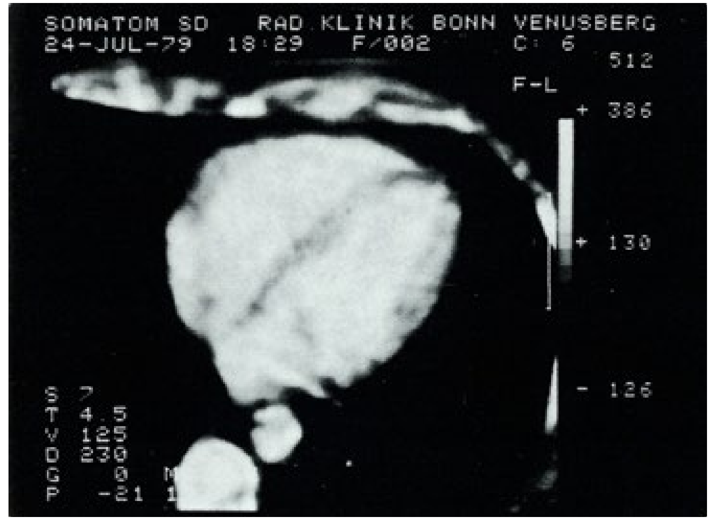


Examination of the coronary vessels
using the Cardoskop U, 1972

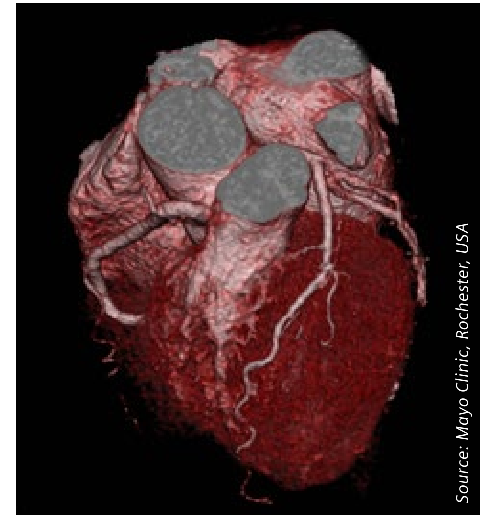
In constant motion

In the 1970s, the advent of computed tomography ushered in completely new ways of imaging the heart. Theoretically, the heart could now be visualized in detailed layers and slices without superimposition, but this new imaging technique faced a considerable hurdle. Indeed, the same challenge had plagued those researching classical X-ray technology around 1900: Our heart is in a state of constant motion. As the most important muscle in our body, it pumps blood continuously for the whole of our lives. In adults, the average heart rate is 70 beats per minute – resulting in over 100,000 beats per day.

SOMATOM, the first whole-body CT scanner from Siemens, could scan a 4 centimeter slice of the body in 2.5 seconds in its fast scanning mode, collecting over 92,000 measurements in the process. In the time it took the tube and detector to rotate around the patient once, the heart would beat three times and was therefore blurry in the resulting slice images.



ECG-triggered heart scan with SOMATOM 2, 1979



Visualization of the coronary arteries in end systole with SOMATOM Definition, 2006

In 1979, our developers successfully tackled the problem of the heart's motion by introducing a special cardio CT add-on for SOMATOM 2. An ECG measured heart function during the scan in order to synchronize the CT scanner with the patient's heartbeat. Accordingly, the scanner only emitted an X-ray pulse when the heart was not pumping, so that the slice image was largely free of interference. SOMATOM 2 took about 100 seconds to scan the whole heart.

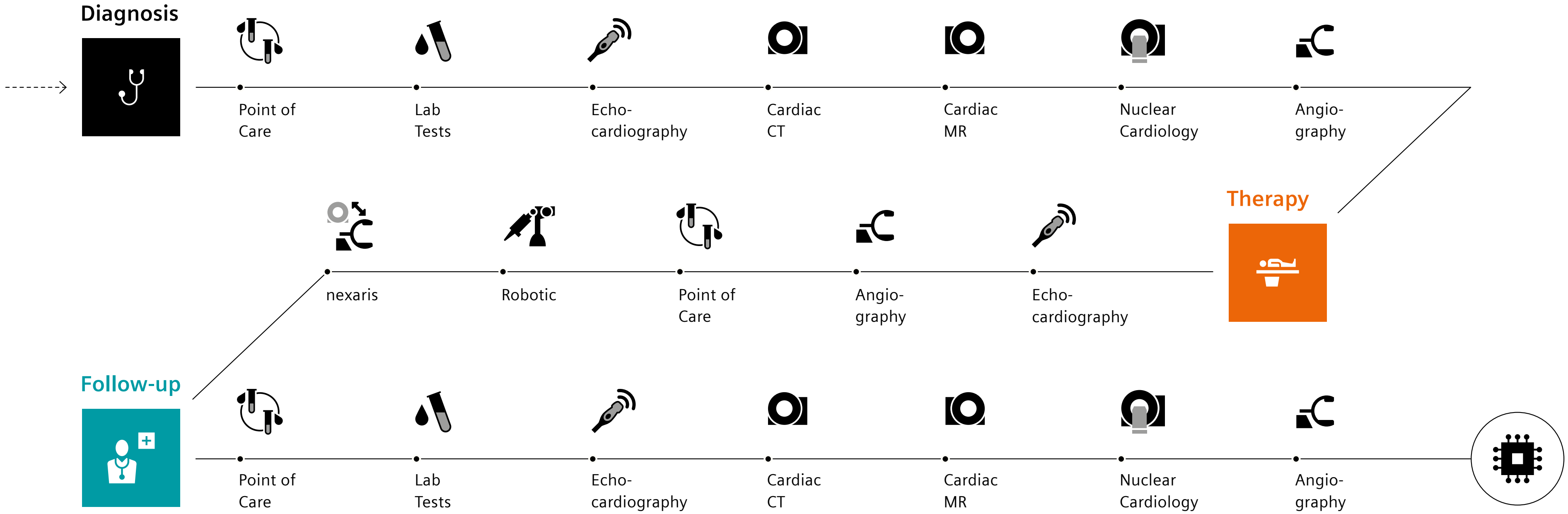
Yet, what if the CT scanner were faster than the movement of the heart? The answer to this question was provided by SOMATOM Definition in 2005. Equipped with Dual Source technology, the scanner featured two tubes and two detectors that rotated around the patient and was so fast that it could capture an entire image of the moving heart in just 0.083 seconds. This resulted in high-quality images with an excellent level of detail, and the device could be used to visualize not only the coronary vessels themselves but also details such as narrowing and fine calcareous deposits on the vessel walls.

The right combination is essential

Whereas the first X-ray images almost 125 years ago showed the heart as nothing more than a blurry shadow, modern CT scanners and angiography systems can visualize its anatomy in detail. Nevertheless, these images alone do not provide precise information about the function and performance of the heart. Cardiologists therefore have a range of other examination methods at their disposal in order to make more precise diagnoses and plan treatment accordingly.

Cardiological diagnosis usually begins with a review of both lab results and cardiac function, which involves recording the heart's electrical activity using electrocardiography. Echocardiography – that is, the use of ultrasound in cardiac diagnostics – is another basic examination used in cardiology and is easy to perform. This technique provides a quick way of obtaining information about the heart's anatomy or blood flow, for example, and is particularly good at visualizing the mobility and function of the heart valves.

Trial of SOMATOM Definition
with a test body, 2006



If cardiac ultrasound raises further questions, or if the findings are unclear, physicians can turn to magnetic resonance imaging (MRI) for much more accurate information. As well as purely anatomical imaging, MRI offers a way to assess factors such as the function of the heart muscle and heart valves. Moreover, this imaging technique can be used to distinguish scar tissue from the healthy tissue of the heart muscle. Where poor heart circulation is suspected, a nuclear medical examination is another potential source of information. In positron emission tomography (PET), the patient is injected with radioactively labeled substances in order to depict metabolic processes in the body. This allows physicians to visualize circulatory problems of the cardiac muscle, for example, or to obtain precise information about metabolic activity, albeit without an anatomical depiction. In 2001, Siemens therefore combined PET and computed tomography within a single device known as Biograph.

Each of these examination methods has its advantages when it comes to answering specific questions, but it is only through a combination of modern imaging techniques, software applications, and laboratory diagnostics that we can provide support at every stage of the patient's treatment – from the initial diagnosis to therapeutic planning, surgical inventions, and follow-up care.

The clinical solutions from Siemens Healthineers provide support at every stage of treatment – from the initial diagnosis to therapeutic planning, surgical interventions, and follow-up care.

Our digital heart twin

Although modern medicine offers many ways of diagnosing and treating heart diseases, the techniques always carry a certain degree of uncertainty. Will the drug work? Will the planned operation succeed in its objectives? As things stand, it is impossible to answer these questions in advance with sufficient certainty, as every patient is different and there are numerous factors that influence the effects of treatment.

Yet, what if we had a digital twin on which we could test procedures safely. It may sound like science fiction, but this technology is in the process of becoming a reality. A digital twin combines the real and digital worlds and is based on individual data obtained from investigations with imaging techniques, ECG, or laboratory diagnostics. The anatomy and function of the patient's heart are modelled from this huge volume of data with the help of artificial intelligence (AI). As the artificial neuronal networks are trained using individual patient data, the digital heart twin works and responds exactly as the patient's heart does.
Put simply, the digital twin of the heart is a virtual model of the patient that reproduces the structure and function of their heart as accurately as possible. For example, this model could be used to test whether a heart medication will work on the patient or not before they actually take it. Cardiac catheterization or heart surgery could also be simulated on the digital twin in advance of the planned procedure, allowing physicians to predict the chances of success. By running through different scenarios on the digital twin, they could ultimately select a treatment option that was perfectly tailored to the patient and their heart from the multitude of available options. It will still be some time before we have a digital twin of our entire body that accompanies us to doctor's visits throughout our lives, but the heart twin is currently being tested in research projects in collaboration with university hospitals.

Thanks to advances in medicine and technology, the heart has now been researched down to the last detail. It has largely lost its mystique but retains its vital importance. It is the engine of life, and we are more directly aware of the heart than of any other organ. It responds to our emotions. We notice that our heart is racing when we're stressed or under pressure. If we suffer a bitter setback or a painful loss, we feel tightness in our chest. There are also moments, however, that get our heart racing: When we fall in love, the heart flutters like a butterfly – and this intoxicating feeling may be the reason why the heart remains a symbol of love to this day.

At the Digital Summit held in Nuremberg in December 2018, Michael Sen, Chair of the Supervisory Board, and CEO Bernd Montag present the "Digital Twin" of the heart to German Chancellor Angela Merkel and Federal Minister for Economic Affairs and Energy, Peter Altmaier

Cover image of a campaign from 2014: "You can see more than meets the eye; Look closer..." Breast cancer screening relies on spotting every last detail

As early as possible

From bull-sized X-ray machines to special systems for mammography

All of the stories from the early days of medical X-ray technology feature brilliant and often even fascinating characters. Many of these pioneering radiologists devoted their careers to further exploiting the potential of X-rays for medical applications. Their research was sometimes triggered by an ingenious idea, sometimes by a groundbreaking discovery, and sometimes – as in the case of the radiologist Philip Strax – by a situation in the researcher's personal life. Strax was a general practitioner running a small practice in Manhattan when he and his family received some shocking news: His wife, Bertha Goldberg Strax, had developed breast cancer and died at the age of 39 in 1947. Philip Strax resolved to spend his life's work preventing that kind of shock from happening to anyone else, especially the patient.

Strax was passionately committed to his work and played a significant role in the development of breast cancer screening over the ensuing four decades. In his research partner Sam Shapiro and other scientists, Strax was said to have "provoked the urge to hug him and thank him for his inspiration." Many of his patients were so impressed by his humorous and sympathetic bedside manner that they were still talking about him 30 years after their examination. Indeed, in the numerous books and essays that Strax wrote on the subject of breast cancer, he repeatedly emphasized what he believed was the correct approach to diagnosis: "A good exam has three components: the mammogram, a clinical examination by a physician or trained nurse, and a lesson in breast self-examination." In the mid-1960s, Strax's self-founded screening clinics in New York therefore featured "machines the size of a full-grown bull." These bulky and awkward devices could be used to image breast tissue, which – in the words of a physician at the time – resembled "a spider's web" in the resulting X-ray images. In those days, the technique known as mammography (from the Latin mamma, "breast") was still in its infancy, but the equipment and knowledge available to Strax and his colleagues in the 1960s were the result of half a century of development. In terms of the broader history of X-rays, this development had been an unusual process in many respects.

A new method of diagnosis?

The history of mammography is unusual because the technique vanished into oblivion for over two decades in the very country where it was developed. What is also astonishing, however, is that the man who first used X-rays to examine diseases of the breast explained the diagnostic principles so comprehensively that subsequent researchers only needed to supplement his work with a small amount of theoretical knowledge. When the German surgeon Albert Salomon began his work in 1913, however, he still had to contend with the technological limitations of the time. As X-ray equipment was not designed for imaging breast tissue, or at least not without considerable effort, Salomon could only use excised breast tissue in his research. By comparing the tissue with the X-ray images, he identified how diseased tissue spread and how it could be distinguished from healthy tissue, among other observations. Given the laborious nature of the technique, Salomon did not envisage mammography becoming an important preoperative tool. In fact, he saw his work not as the basis for a new method of diagnosis, but simply as a scientific study of breast cancer. A further 14 years would pass before another German surgeon published the world's first clinical mammogram.

The first physician to use X-rays to examine breast tissue: Albert Salomon with his daughter, the artist Charlotte Salomon

It is impossible to say for certain when exactly Otto Kleinschmidt, a professor of surgery in Leipzig, produced the first known image of the breast tissue of a living patient. In the year of its publication, 1927, Kleinschmidt could already look back on several years of experience with mammography. He described the X-ray examination of the breast as “a diagnostic tool that, in some dubious cases, can be used in conjunction with other examination methods to make a correct diagnosis.” What can be said for certain is that the method was used in everyday clinical practice at the University of Leipzig Medical Center until at least 1934, after which it vanished altogether in Germany – lost, perhaps, in the turmoil of the Nazi era. Almost a quarter of a century later, however, the technique resurfaced with numerous refinements and new diagnostic capabilities.

Source: Zweifel, Paul/Payr, Erwin (Hg.): Die Klinik der bösartigen Geschwülste [Clinical assessment of malignant tumors], p. 58

The first known image of the breast tissue of a living patient, published in 1927

Philip Strax played a key role in helping mammography achieve its breakthrough into clinical practice

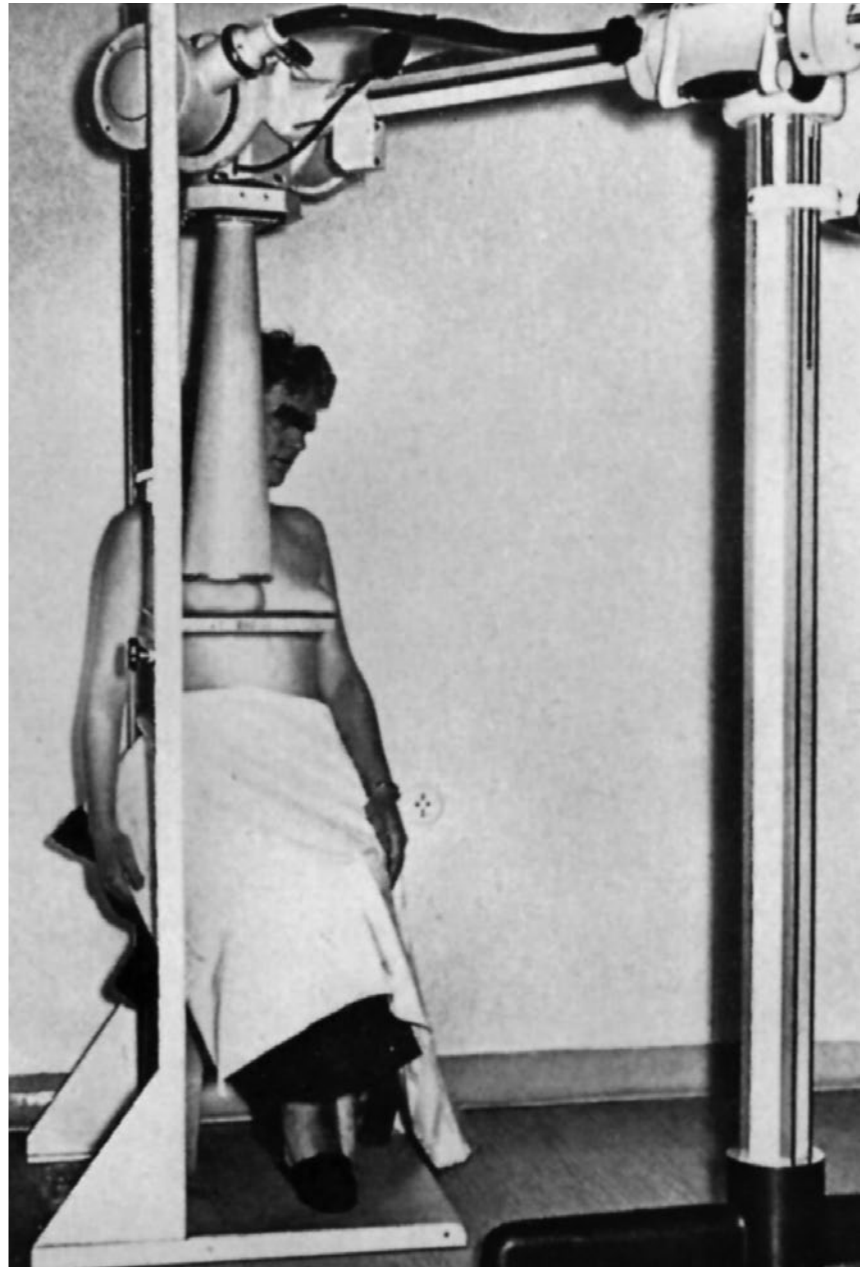
Mammography in your lunch break

Especially in Uruguay, France, and the USA, reports of reliable diagnoses of breast cancer using X-rays became increasingly common from the mid-1930s onward. In Montevideo, the radiologist Raoul Leborgne realized, among other observations, that breast tumors could spread over a large area without being detectable to the touch. In Strasbourg, Charles Gros improved the image quality by optimizing X-ray tubes for the visualization of soft tissue. In Pennsylvania, an American working group led by Jacob Gershon-Cohen and the pathologist Helen Ingleby demonstrated the importance of mammography in early detection and published the first standard work on the technique. Numerous other pioneers – and above all the nuclear medicine specialist Stafford L. Warren and the radiologist Robert Egan – laid the blueprint for today’s systems through their insights into and requirements for mammography equipment. In the early 1960s, however, mammography was still a laborious discipline practiced by only a few highly experienced specialists. One such specialist was Philip Strax, who, through sheer dedication to his work and the publication of a highly acclaimed study, helped mammography break through into clinical practice. In 1963, Strax teamed up with the statistician Sam Shapiro and the surgeon Louis Venet with a view to identifying the best way of detecting breast cancer as early as possible so that radical surgery could be avoided. Their research centered around a mass screening of some 62,000 New York women, which represented a huge logistical undertaking right from the outset. Most of the hospitals were in the north of the city in those days, and many women were not prepared to travel the long distances required. Undeterred, Strax began personally calling and writing the women to persuade them to take part. Venet and Strax eventually outfitted a van with an X-ray machine, parked it alongside the ice-cream trucks and sandwich vendors in Midtown Manhattan, and examined subjects in their lunch breaks. To allow participating hospitals to perform several thousand mammograms a day, the women were channeled through a carousel-like structure made up of multiple changing cubicles. This process went on all day and late into the evening, and was planned down to the last detail – from the stops on the route to the time that people entered the cubicles and even how much time they had to dress and undress. “To expedite turnover, the amenities of chairs and mirrors were omitted.” This was the largest study yet into the benefits of mammography, and it resulted in the timely detection and treatment of tumors in a number of women, with almost 40 percent fewer deaths from breast cancer among the screening participants than in the control group. An ecstatic Strax wrote: “The radiologist has become a potential savior of women – and their breasts.”

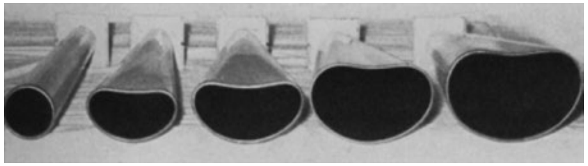
Recognition and more widespread use

In the meantime, mammography had reappeared in Germany. In 1957, Heidelberg University launched a major study that began by using the technology developed by Charles Gros in Strasbourg. "Using this as a basis, the researchers were able to develop their own technology over the next few years," explains Dietrich Buttenberg in the book *Die Mammographie* (Mammography), in which he published the results of the study after five years of research. "A number of technical improvements have paved the way for the more widespread use of mammography." The X-ray machine used at Heidelberg University Women's Hospital was the Siemens Tridoros IV. Although this equipment was not specifically developed for mammography, the physicians in Heidelberg worked with Siemens to optimize it to meet the exacting requirements of breast imaging with X-ray technology. For the first time, the X-ray tube was fitted with a cone that not only focused the X-rays but also compressed the breast in order to reduce the radiation load and improve detail recognition. "The results obtained using mammography at the hospitals of Heidelberg University are testament to the great value of the technique," wrote Hans Runge, director of Heidelberg University's Women Hospital, in his foreword to the book about the study. "This book is therefore likely to achieve a wide circulation and will result in the recognition and more widespread use of mammography."

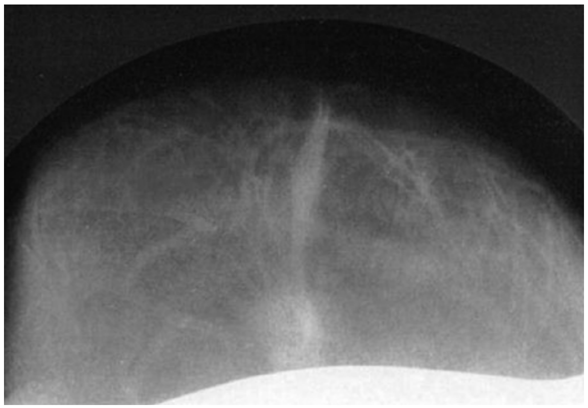
Like Strax's research in New York, the Heidelberg study was instrumental in helping mammography break through into clinical practice. It was then that the search for the optimum technique got underway in earnest. What was the best way of visualizing the fine details of breast tissue, which were so vital for the early detection of cancer? How should X-ray equipment be built so that it was not only



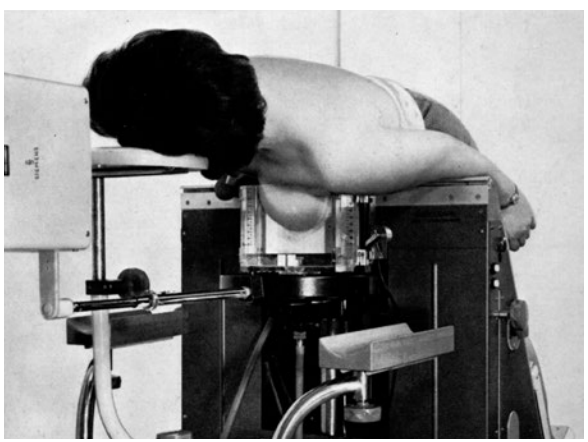
The Siemens Tridoros IV with a mammocone, the first X-ray machine in the history of Siemens Healthineers to be optimized for the requirements of mammography, 1962



Mammocones were developed in various breast sizes for the five-year study, 1957



In 1962, Heidelberg University presented the results of the study along with a number of clinical images



The FLUIDOGRAPH was based on what seems like an unusual concept from today's perspective, 1964

comfortable for the patient but also easy for physicians to operate? The 1960s saw the emergence of what seems like an unusual concept from today's perspective. The FLUIDOGRAPH, which was devised by the Austrian radiologist Walter Dobretsberger and realized in collaboration with Siemens, required the patient to kneel on the apparatus with their upper body lent forward and their breast immersed in a plexiglass container filled with alcohol. In 1967, Dobretsberger wrote: "In medical/diagnostic fields, the main advantage of this image is that the entire organ can be shown clearly – with its natural structure – in one image." Nevertheless, this approach was abandoned a short time later due to the discovery of a promising new basic structure.

The new unit

When Siemens presented the first special system for mammography to the public in 1971, the developers provided a summary of the current state of this fledgling diagnostic technique. They said that, until then, the equipment had required a great deal of skill and patience on the part of the operator and had to meet extraordinary requirements in order to image the female breast. At the same time, they added, the latest studies showed that breast examinations would become an increasingly important tool for cancer screening in the future. "With this in mind, we believe it is necessary to develop a special mammography device that allows quick and easy operation while also producing optimum image quality." The Siemens MAMMOMAT system eliminated the need for tedious configuration and adjustment of the X-ray equipment – indeed, everything was "optimized for a quick and straight-forward working process." In this "mammography unit," the X-ray tube, cone, and X-ray film were fixed to one another, and the cone could be adapted to each patient's anatomy quickly and easily using a hand crank. However, the developers emphasized that the key feature of a mammography unit was undoubtedly the quality of the images it could produce – and MAMMOMAT, with its X-ray tube optimized for breast diagnostics, could visualize tiny structures in the tissue down to a size of 0.1 millimeters. "With MAMMOMAT, a device is now available that, thanks to its easy operation and above all to the high image quality that it can achieve and the low radiation load for the patient, is suitable for the cancer screening examinations that are generally recognized as urgent."

By the early 1970s, medical research and the devices developed specially for mammography were sophisticated enough for it to become an accepted clinical technique rather than a laborious one-off examination. Arguably the most important step in overcoming the limitations of the early years dates back to Charles Gros's discovery in Strasbourg.
He found that the most efficient way of generating soft X-rays, which allow clear visualization of the soft tissue of the breast, was to use anodes made of the heavy metal molybdenum. The Siemens MAMMOMAT system used a highly advanced form of these X-ray tubes with a rotating molybdenum anode in order to reduce the amount of heat produced during an examination. As a result, the tube remained cooler, maintained its performance for longer, and generated reliably homogeneous X-rays. Moreover, the rays emerged from the tube via a thin, polished window, in what was a basic prerequisite for producing particularly soft X-rays. With this, the technical requirements were met, and the basic structure of the mammography systems was in place.

Taking this as the starting point, Siemens developed a number of often unique combinations of new technologies and comfort improvements over the course of the 1980s and 1990s. For example,

Mammogram of a carcinoma in the left breast, taken with a MAMMOMAT in 1972

Presented in 1971 and in clinical use from 1972: the first generation of the MAMMOMAT system

If necessary, MAMMOMAT B could powerfully magnify the structures of the breast, 1984

the grid technology in MAMMOMAT B improved image quality in various ways from 1981 onward, including by considerably reducing the amount of scattered radiation in the grid and by enabling further significant improvements in contrast and detail recognition in the X-ray images. If necessary, physicians could magnify fine details in the structures of the breast, and a special biopsy attachment allowed them to collect tissue samples during the mammogram itself. The increasing automation of the MAMMOMAT family extended to almost all of the systems' characteristics: From 1994 onward, MAMMOMAT 3000 featured a microprocessor that automatically determined the optimum parameters for capturing an X-ray image. For example, its compression system stopped automatically at the point where further compression would no longer improve the quality of the image. This spared the patient unnecessary pain while still offering the physician the best possible image quality.

In 1994, Siemens presented the next generation of mammography systems: MAMMOMAT 3000

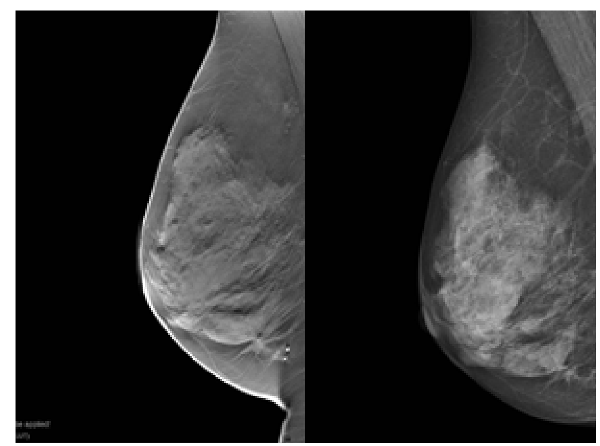
Turn your city pink!

After the turn of the millennium, the digitalization of mammography would bring about another significant increase in the quality of the resulting X-ray images. The new generation of digital systems – which began with MAMMOMAT Novation in 2003 – no longer recorded their images on traditional X-ray film. Instead, the X-rays were received by a detector that converted the measured values into electrical signals. Once the image was rendered, the physician could assess the results immediately on-screen while the patient was still present, and begin further examinations if necessary. The digitalization of mammography also paved the way for entirely new capabilities, such as the tomosynthesis functionality of MAMMOMAT Inspiration, which was launched in 2009. Tomosynthesis differs from conventional mammography in the same way as a three-dimensional CT scan differs from a traditional X-ray image. In systems from Siemens Healthineers, the X-ray tube and the detector rotate around the breast in a 50-degree arc, recording 25 individual images at a very low dose. From this raw data, MAMMOMAT Inspiration generates high-resolution 3D images of the breast that can even reveal tumors that were previously concealed by overlapping tissue. In the 2010s, studies showed that more tumors were detected when tomosynthesis was used as a supplement to mammography. Collaborations with partners and customers helped Siemens Healthineers develop new software applications in order to tailor the mammogram to the specific patient as closely as possible.

From 2012 onward, the MAMMOMAT Inspiration PRIME Edition featured a new image correction algorithm that reduced the radiation dose by up to 30 percent while maintaining the same image quality

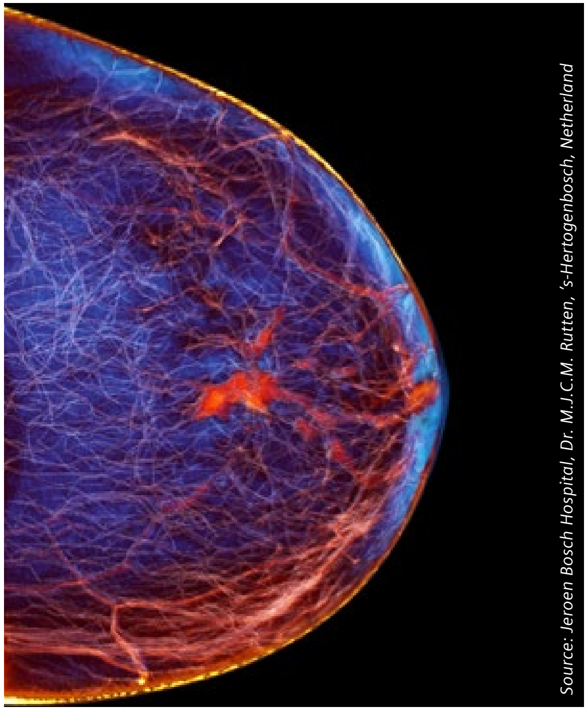
MAMMOMAT Novation in 2003 – the digitalization of mammography paved the way for a host of new capabilities

MAMMOMAT Inspiration (2009) was the first mammography system from Siemens to feature 3D tomosynthesis, 2009



The three-dimensional tomosynthesis image from 2009 (left) reveals structures that are concealed in the two-dimensional mammogram (right)

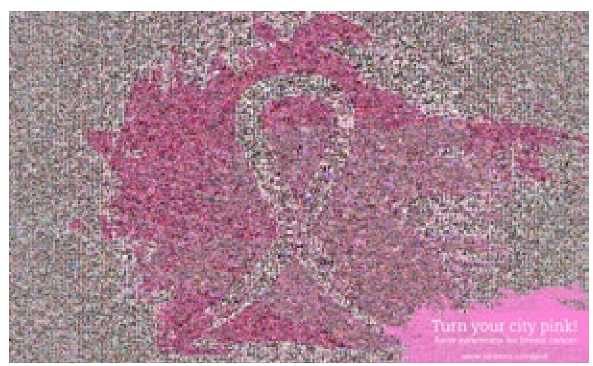
Released in 2017, MAMMOMAT Revelation from Siemens Healthineers was the first system to determine breast density automatically



Some 45 years after Philip Strax first screened women for breast cancer during their lunch breaks in a van in Manhattan, there are now "mammomobiles" out and about in several countries around the world. These mobile mammography units incorporate a small but fully functional examination room equipped with a MAMMOMAT Inspiration. With the introduction of the mammomobiles in 2008, Siemens hoped to give women in rural areas the opportunity to learn about breast cancer and to be examined there and then if they wished. The initiative was so successful that Siemens Healthineers still takes part in numerous information campaigns during the international Breast Cancer Awareness Month in October each year. In a year-long, global campaign launched in 2011, Siemens encouraged people to get involved in a series of public activities between October 2011 and October 2012. The motto of the campaign was "Turn your city pink! Raise awareness for breast cancer," as the color pink is a global symbol of solidarity with breast cancer patients. Those taking part in the initiative were encouraged to spread the campaign motto in their personal environments in the most creative and public ways possible. Over the course of the year, thousands of photos and videos were produced in 76 countries with a view to disseminating the central idea of the campaign – that is, to encourage people around the world to engage with the topic of early detection and to join the campaign themselves.

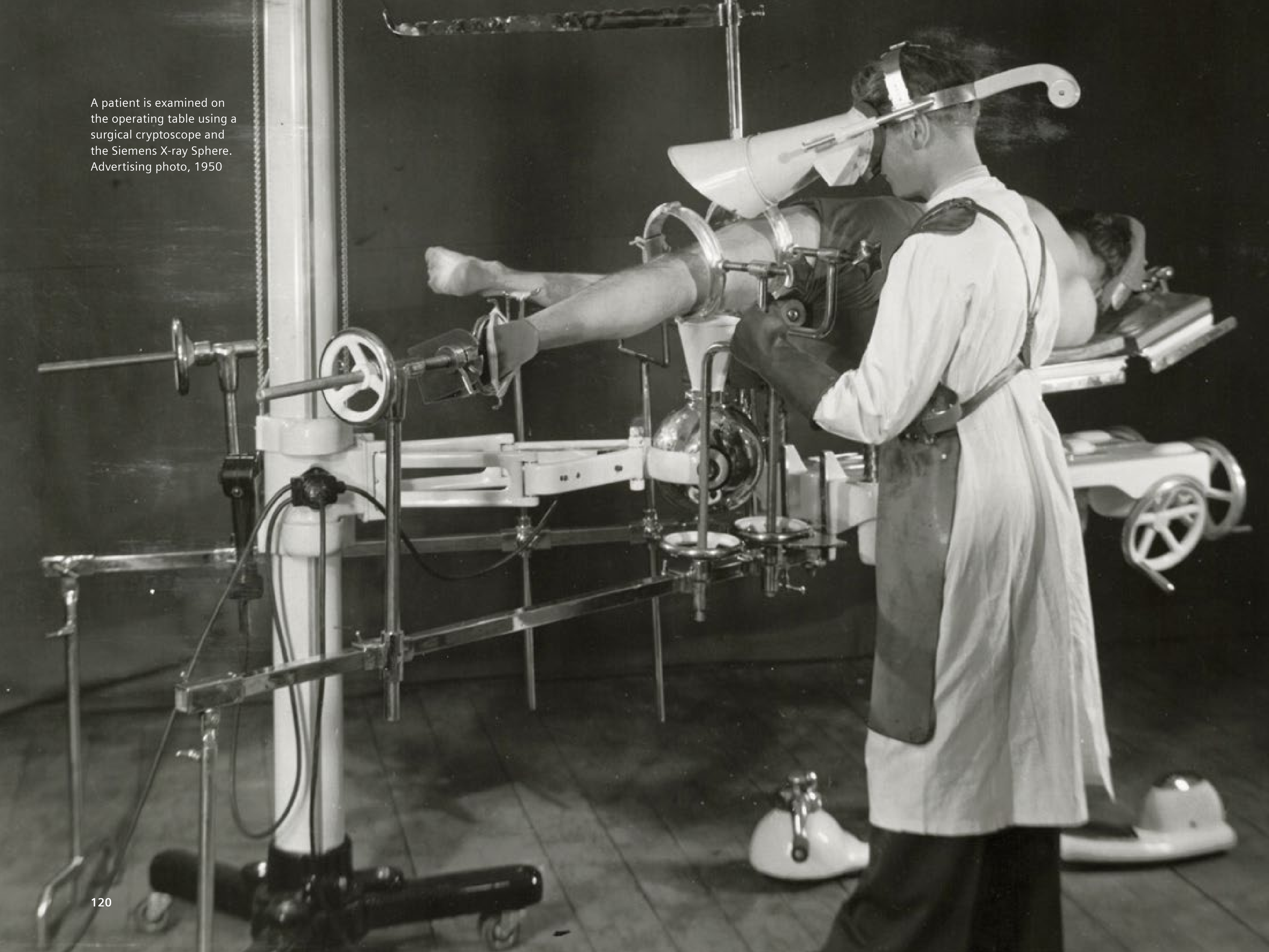
Cinematic Rendering image based on tomosynthesis data from 2016: A tumor in the breast tissue appears as a red spot in the middle of the image

In 2008, 34 "mammomobiles" were out and about around the world, including in Denmark, Poland, and Georgia



Collage of thousands of photos from participants in 76 countries following a year-long campaign

Raise awareness for breast cancer, 2011



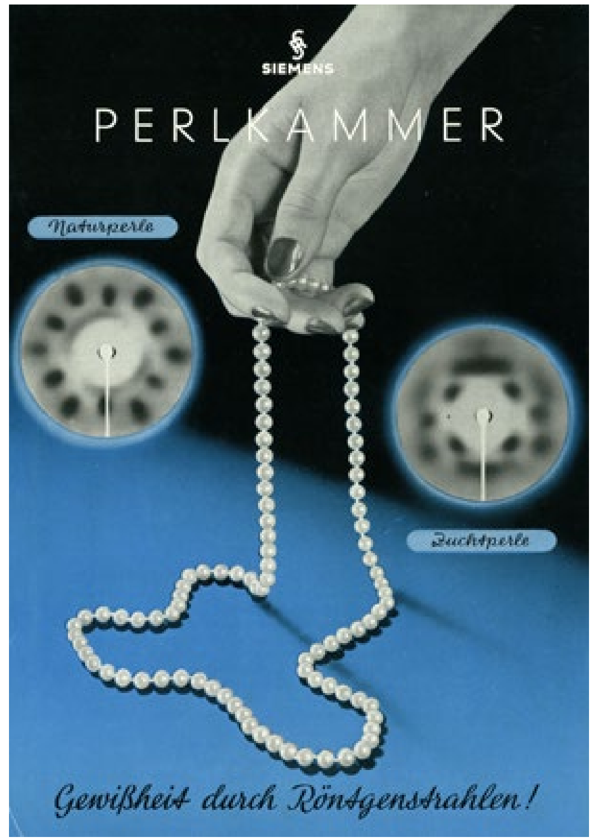
A patient is examined on the operating table using a surgical cryptoscope and the Siemens X-ray Sphere. Advertising photo, 1950

X-ray technology – the pearl of the operating room

A mysterious glow

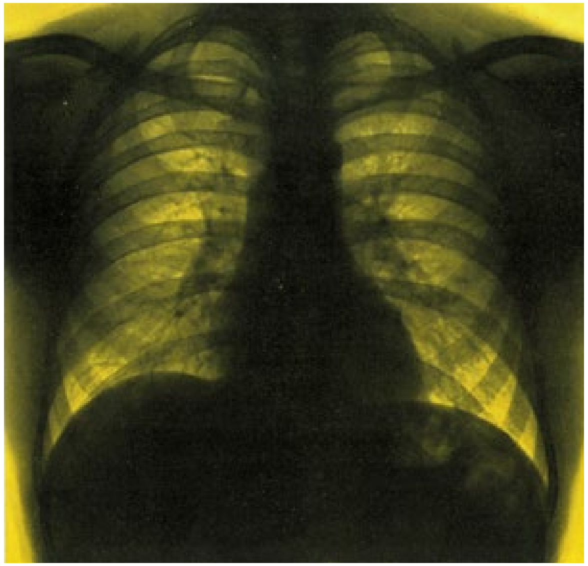
A cultured pearl and a broken fibula have more in common than one might initially suspect. It's fair to say that a broken fibula will be met with less enthusiasm by its "owner" than a cultured pearl, although the pearl can at least lead to a sense of disappointment, particularly if it was initially believed to be a real, natural pearl. What does link these two things, however, is that neither can be readily detected from the outside. In both cases, X-rays can provide the necessary certainty, and for both cases, Siemens-Reiniger-Werke (SRW), a predecessor company of Siemens Healthineers, launched suitable equipment. In addition to medical X-ray systems, SRW also manufactured materials-testing devices, such as the Siemens Perlkammer (Siemens pearl chamber). Presented in a 1953 marketing pamphlet, this device could be used to distinguish between natural and cultured pearls using two different techniques, one of which was known as the fluorescence method and used X-rays to excite the nucleus of the cultured pearls, causing them to emit a pale-green glow.

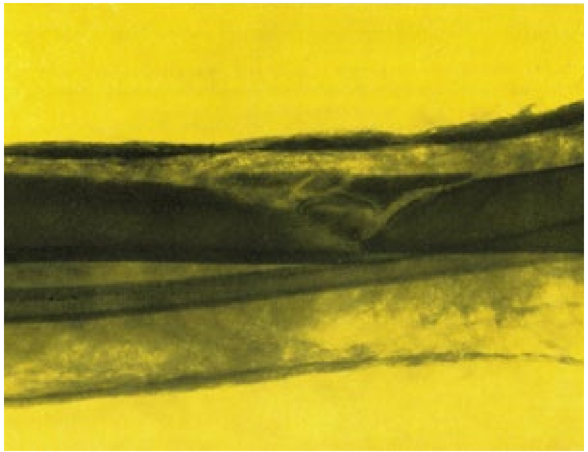
Fluorescence triggered by X-rays also had applications beyond the world of materials testing. Indeed, shortly after X-rays were discovered, physicians not only began recording X-ray images on photographic plates, but also using fluorescence to examine the human body in a process known as fluoroscopy. However, the first person to describe this method was not a physician but Wilhelm Conrad Röntgen himself, who might never have made his groundbreaking discovery had it not been for fluorescence. While conducting an experiment in a completely darkened room on November 8, 1895, he passed a current through a gas-discharge tube covered with black paper, causing a nearby piece of paper coated with barium platinocyanide to emit a yellow-green glow. When he studied this phenomenon in greater detail, Röntgen realized he was on the brink of a completely unprecedented discovery. As his research continued, he observed that if a hand was held between the tube and a fluorescent screen made of paper and barium platinocyanide, "the darker shadows of the hand bones can be seen within the slight shadow cast by the hand." Fluoroscopy became particularly important for one area of medicine: X-ray examinations in the operating room.



The Siemens Perlkammer provided two ways of distinguishing between natural and cultured pearls: One was based on the crystal structure (as seen in the image) and the other used the fluorescence method. Advertising brochure, 1953

"The miraculous discovery of X-rays aroused particular interest among physicians and, above all, surgeons," wrote one surgeon enthusiastically in February 1896. He believed that X-rays could be used primarily for localizing foreign bodies and diagnosing injuries and diseases of the bones. Indeed, the new technique replaced previous – extremely painful – examination methods, such as the palpation and mobilization of fractures or the use of a finger or probe to search for foreign bodies inside wounds. Nevertheless, both methods –radiography and fluoroscopy – had their fair share of advantages and disadvantages. For example,





These two examples give an impression of what fluoroscopic images looked like. Tissues that absorbed fewer X-rays appeared as brighter areas in the image. Bones, for example, which have a high X-ray absorptivity, appeared as dark areas on the fluorescent screen. Marketing brochure for the Siemens X-ray Sphere, 1951

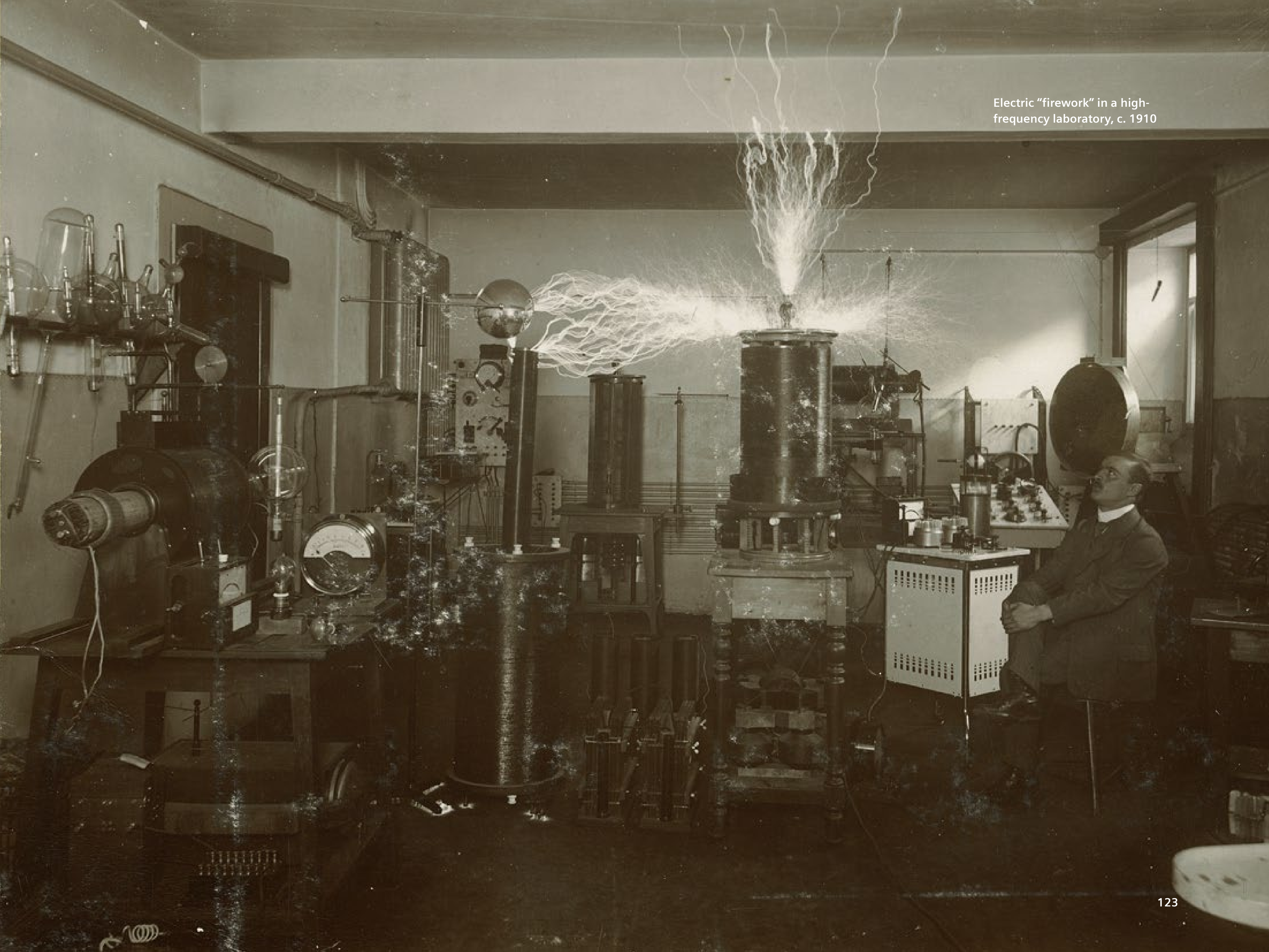
images captured on a photographic plate were more detailed than fluoroscopic images and were available in a permanent format for future reference. At the same time, the rudimentary equipment available in the early days of X-ray technology made it difficult to produce high-quality images. The exposure time could run to several minutes, during which the patient had to remain absolutely still, and the images then had to be developed. In the case of fluoroscopy, however, the image was available immediately, and physicians could examine the relevant body part from various angles and even observe sequences of movements. Would it not be ideal, therefore, if fluoroscopy could be used not only for preoperational planning but also during the operations themselves?

Cryptic darkness

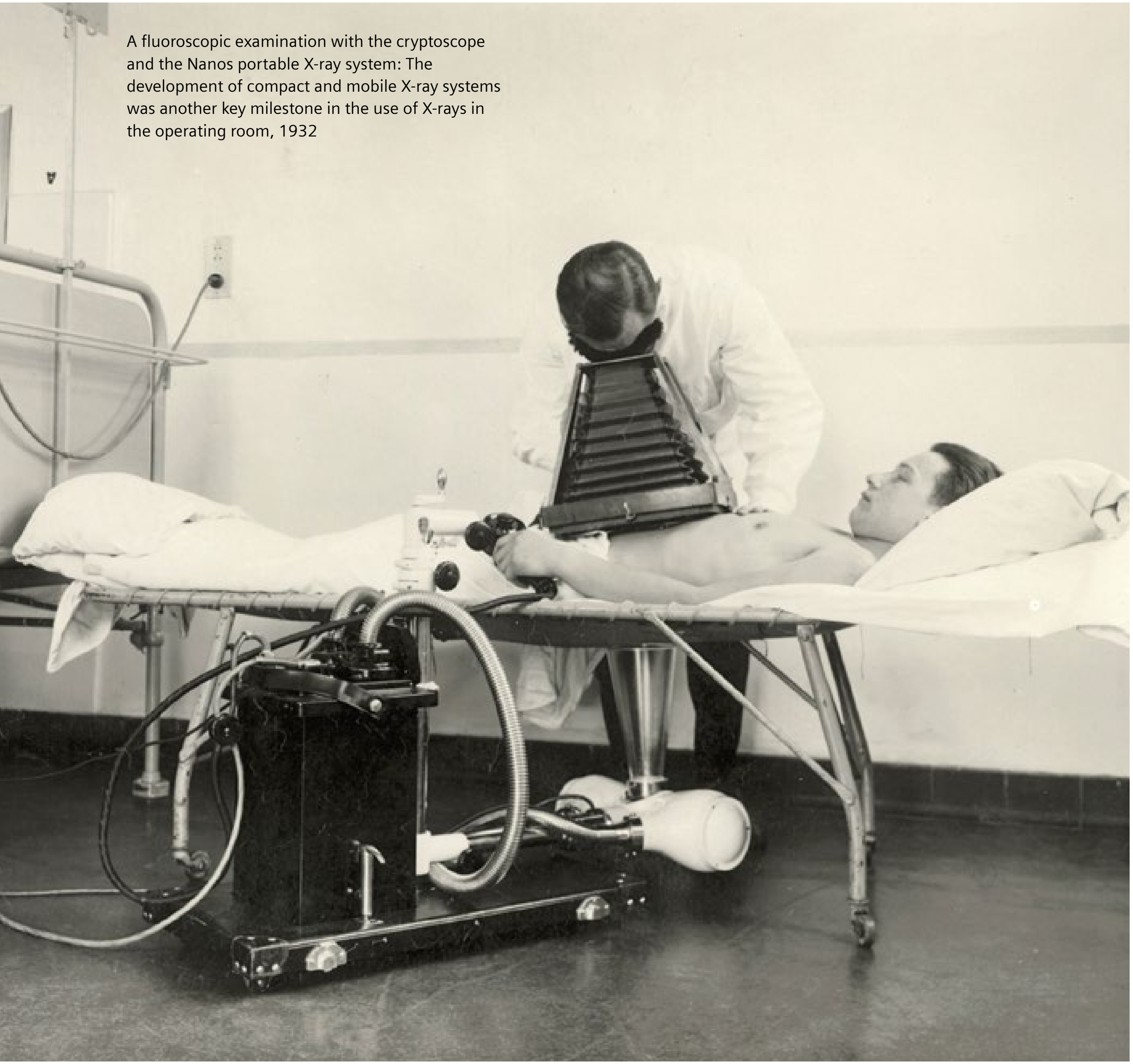
It wasn't long before surgeons began experimenting with the use of X-rays during operations. In 1897, for example, the Frankfurt physician Gustav Spiess described an operation in which he opened a patient's frontal sinus via their nose and tracked the movements of his drill "on the [fluorescent] screen at every moment." Nevertheless, these early experiments were only isolated examples, and it would be decades before X-rays became a fully established tool in the operating room. It was clear that the equipment needed to become more efficient, smaller, and – above all – safer. Moreover, if radiographic and fluoroscopic examinations were to be conducted at all, it would also be necessary to develop special operating tables that were transparent to X-rays. For these examinations, the X-ray tube was usually installed in a fixed position below the table, while the physician examined the patient from above using a fluorescent screen.

Nowadays, it is compulsory to explain operations to patients in advance, as every procedure carries certain risks – although a risk of explosions is presumably no longer one of them. In the early days of X-ray technology, things were quite different. The high-voltage cables of the X-ray equipment ran through the room exposed – that is, without insulation – in order to connect the high-voltage transformer to the X-ray tube. In combination with ether, one of the most common anesthetics at the time, this arrangement could result in undesired electrical discharges with potentially dramatic consequences. "Ether presents an extreme fire hazard, for its vapors can cause the most

The photo of this dental X-ray system from 1909 clearly shows how close the physician and patient came to the exposed high-voltage cables



Electric "firework" in a high-frequency laboratory, c. 1910



A fluoroscopic examination with the cryptoscope and the Nanos portable X-ray system: The development of compact and mobile X-ray systems was another key milestone in the use of X-rays in the operating room, 1932

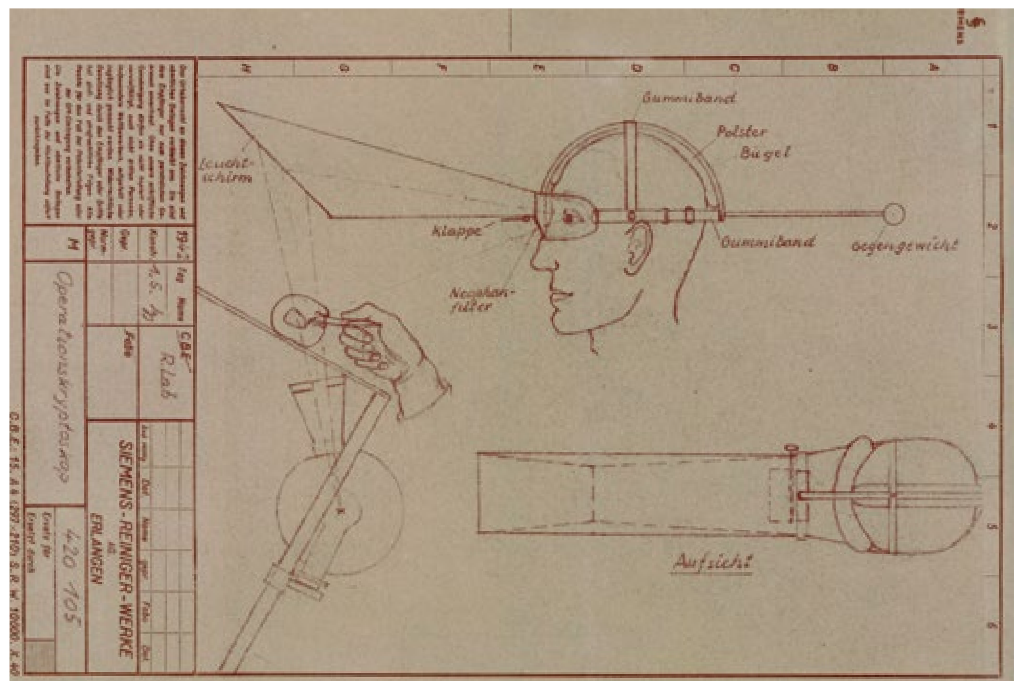
almighty explosions when mixed with air," readers were warned in the 1922 *Ratgeber für die Vorbereitung chirurgischer Operationen und das Instrumentieren für Schwestern, Ärzte und Studierende* (Guide for the preparation of surgical operations and the provision of instruments for nurses, physicians, and students). For this reason, operations were to be performed as far as possible from the open fireplace, and "no burning matches are to be thrown on the floor." Accordingly, X-ray equipment could not be used when patients were anesthetized using ether. Of course, medical staff in particular were also at serious risk of coming into contact with the high-voltage cables – especially in the darkened operating room. This hazard was only eliminated with the introduction of reliable insulation in the early 1930s.

However, readers may be wondering why it was necessary to darken the operating room in the first place. The answer is simple: One fundamental problem in the early days of fluoroscopy was that the luminance of the screens was too low for the images to be visible in bright rooms. Indeed, the brightness of the first fluorescent screens made of barium platinocyanide was often likened to that of a moonlit landscape. By comparison, the display of an average smartphone is approximately 180 times as bright as a fluorescent screen of this kind. The examination room therefore had to be completely dark, and the physicians had to adapt to the darkness for between 15 and 45 minutes (in what was known as the adaptation time) prior to each fluoroscopic examination so that they could make out the finer structures in the fluoroscopic image.

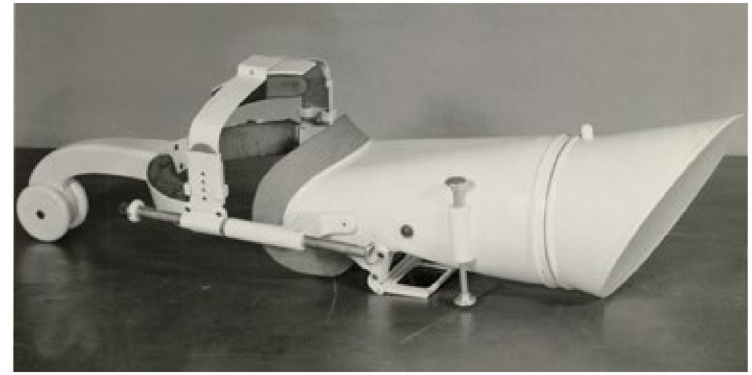
It wasn't long before a device was invented to remedy this situation: "The purpose of the cryptoscope is to be able to perform X-ray fluoroscopy examinations even outside of a darkroom. The device consists of a pyramid-shaped box [...] that is cut open at the top and upholstered with soft fur in such a way that it fits closely around the viewer's eye area during use and prevents daylight from entering the eye. On the underside, the cryptoscope is sealed with a barium platinocyanide screen." The cryptoscope provided physicians with greater versatility than a fixed fluorescent screen, and it was no longer strictly necessary to darken the room for fluoroscopic examinations. However, fluoroscopy also carried a number of risks. For example, long screening times exposed patients and medical staff alike to high doses of radiation. Writing in Siemens's own journal, *Electromedica*, in 1980, one author described examinations using the cryptoscope as "a working method that would make today's radiation protection officers' hair stand on end." Although it was a relatively simple tool, and despite the risks associated with it, the cryptoscope played an important role in X-ray examinations in the operating room until the mid-1950s. It was only then that physicians received reinforcements in the form of a device that could intensify X-ray images.


Cryptoscope, 1897


An examination using stereoscopic apparatus. The exposed high-voltage cables passed directly behind the patient, 1908



Design drawing for a surgical cryptoscope, 1942



Surgical cryptoscope, 1942

Some readers may remember similar devices known as shoe-fitting fluoroscopes. Here, a housing containing a transformer and X-ray tube was fitted with a viewing box that fulfilled the same purpose as a cryptoscope: Regardless of the ambient illumination, the image on the fluorescent screen could be used to determine the correct shoe fit – and it could even be viewed by several people at once. The devices were still found in German shoe shops until the 1970s.

The “mole-like existence of radiologists”

Despite continual attempts to improve fluoroscopy, including by using different fluorescent substances to produce the screens, radiologists still found themselves condemned to perform the technique in the dark. By the 1930s, people were already coming up with suggestions for how the fluoroscopic image could be intensified electronically, but these electronic X-ray image intensifiers weren’t ready for the market until the 1950s. In simple terms, the image intensifier was, “from a purely external perspective, a large vacuum flask, previously made of glass, which has now […] largely been replaced with metal,” as explained by Friedrich Gudden, head of Siemens X-ray diagnostics development, in an interview in 1981. The X-rays would strike the input fluorescent screen and produce a fluoroscopic image, just as in a normal fluoroscopic examination. The difference here, however, was that the input screen was connected to a photocathode that emitted electrons when struck by light from the fluorescent screen – the brighter the light, the more electrons were emitted. In the image intensifier, the electrons were then accelerated by an electric field and focused onto the output fluorescent screen by electrodes in the electron-optical system. Although the image produced on the output screen was smaller, it was crucially several times brighter and could either be viewed through a lens system or captured using a camera. By the 1950s, the output image was about 800 to 1,000 times brighter than the image on the input fluorescent screen, and it was about 20,000 times brighter by the early 2000s. At first, these brighter images meant that the operating room only had to be darkened slightly, and eventually no darkening was needed at all. Moreover, the images also provided a far greater level of detail, which considerably reduced exposure times – and the examinations only required about a third of the previous radiation dose. Faster examinations and the omission of the adaptation time led to general improvements in surgical procedures, such that the introduction of the image intensifier reduced operating times by about half.

Despite all the advantages of the electronic image intensifier, the developers were initially unsure whether it would be a success. “There were any number of setbacks, and they keep on coming,” said Gudden in the interview. In particular, the viewing screens turned out to be difficult to manufacture. “Time and time again, for whatever reason – no one knows whether it is because of the position of the moon or the weather – the output of the screens falls to zero. It then takes a great deal of effort to work out what caused this – perhaps, for example, a bicycle chain had been cleaned in a cleaning bath, which contaminated the bath with oil. But it can take many months to work something like that out.” The businesspeople also had to wait with bated breath: “In total, it took ten years for the turnover to cover development costs for the first time, and fifteen years for […] the development of the image intensifier to turn a profit.”

Looking back, it is clear that “the introduction of the image intensifier marked a turning point in X-ray technology, which put an end to,” as Gudden’s interviewer puts it, “the mole-like existence of radiologists, working in darkened rooms, with lengthy adaptation periods before beginning their work, and so on.” The aforementioned author in *Electromedica* also stated that the invention of the image intensifier led to a breakthrough for X-ray technology in the operating room, because it took “a tool that, however useful it may have been, tended to be seen as unavoidable and unwieldy,” and transformed it “into a valuable and fully integrated instrument for the operating surgeon.”

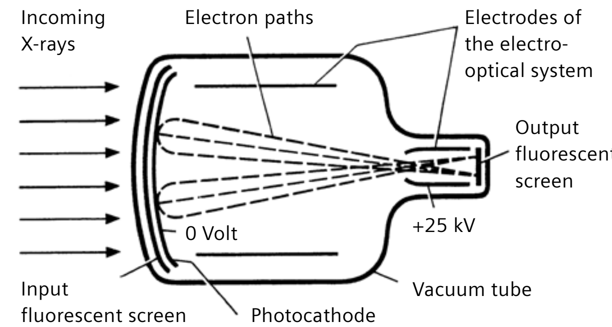
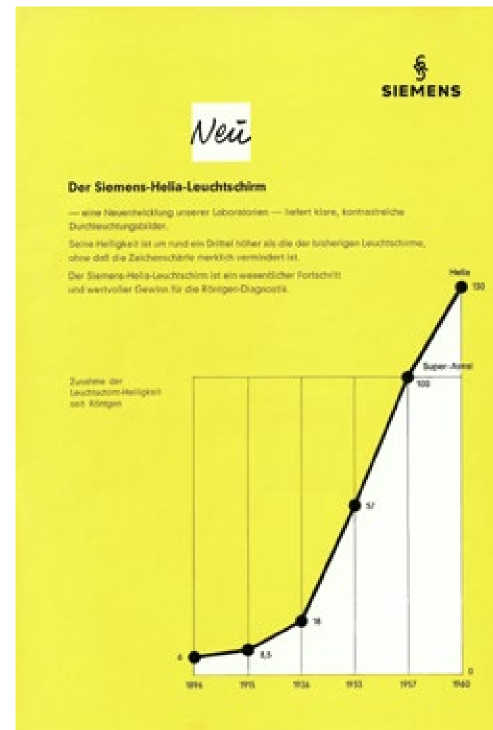


Diagram of the structure of an electronic image intensifier



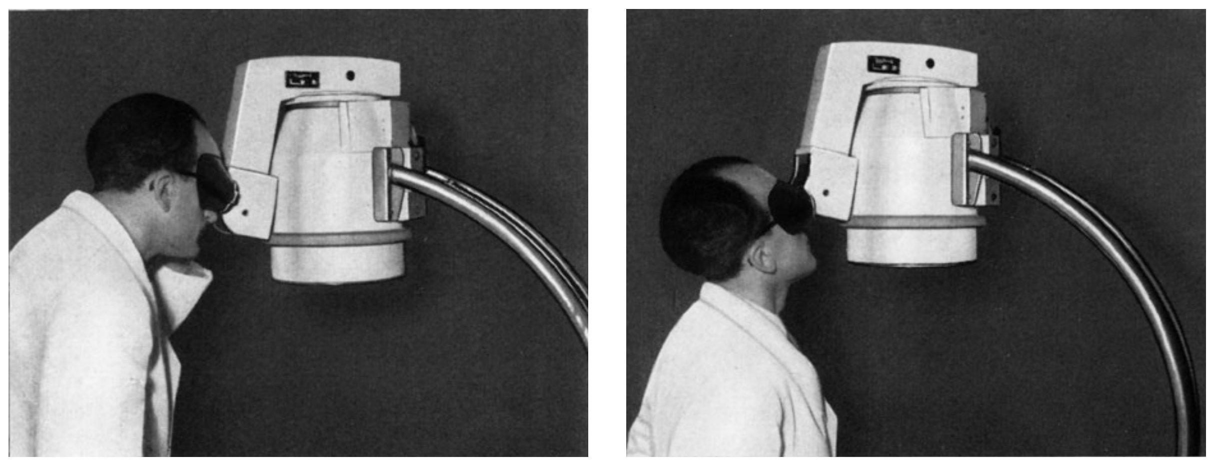
Change in fluorescent screen brightness from 1896 to 1960: Advertising brochure for the Siemens Helia fluorescent screen, 1961

TV makes viewing easier

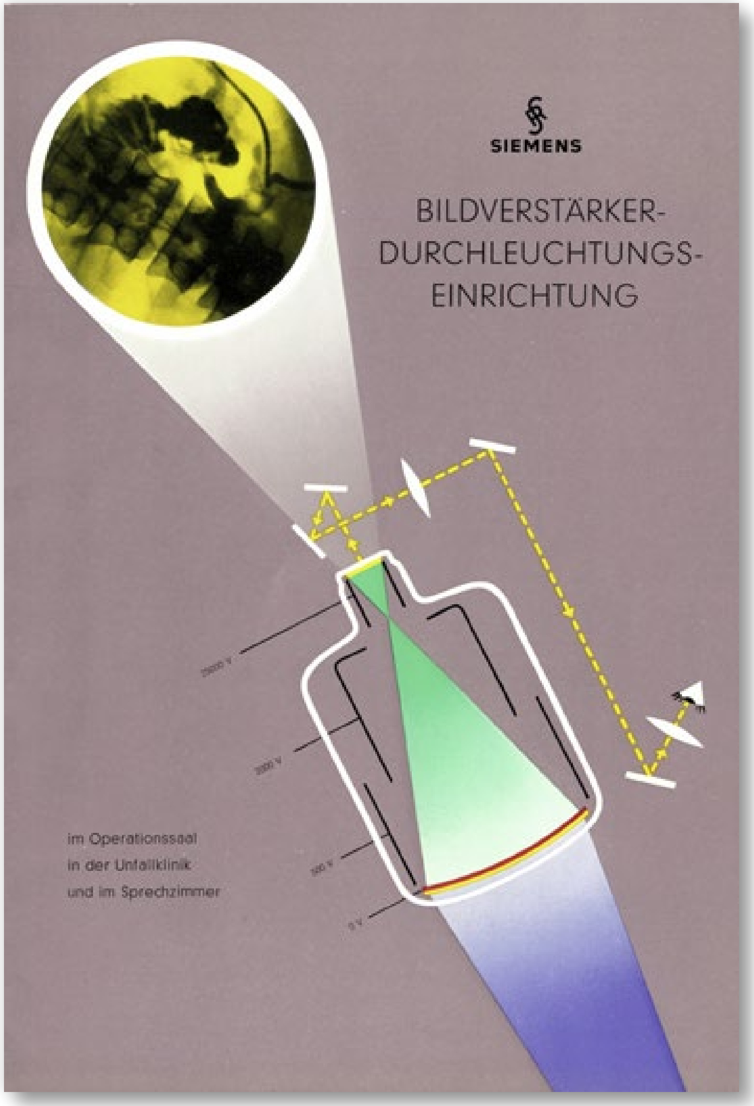
The advantages of electronic image intensification were clear from the outset, but the image intensifier could be made even more useful by connecting it to another piece of technology – namely, a television camera. The camera could convert the output from the image intensifier into an electronic video signal that could then be displayed on a TV screen, so that physicians were no longer tied to the position of the optical viewing system and could instead view the image wherever was most convenient for them. In addition, all of the experts present in the operating room could now interpret the X-ray image at the same time, so that they could immediately discuss how to proceed with the operation, for example. The image could also be relayed to any number of devices, including to other experts at the hospital or to a lecture hall. One of the key advantages of X-ray television, however, was that the electronic video signal from the camera could also be manipulated electronically. This allowed physicians to adjust the brightness and contrast of the TV signal in order to highlight or fade out certain areas of the fluoroscopic image with a view to making the overall image even more diagnostically relevant. The possibility of storing the TV image represented another key advantage – especially in terms of radiation protection. It was now possible to display the X-ray image for as long as necessary without having to expose the patient to radiation throughout, thereby improving the level of X-ray protection for medical staff and patients. Moreover, the technology could even be used to display sequences of movement. "I'm convinced that the stored image – especially that stored in digital memory – will play a huge role in the future," said Gudden in 1981. "The image appears immediately and in excellent quality, and there's no need for a lengthy detour via film, developers, darkrooms, transport, etcetera."

The C-arm reigns supreme in the OR

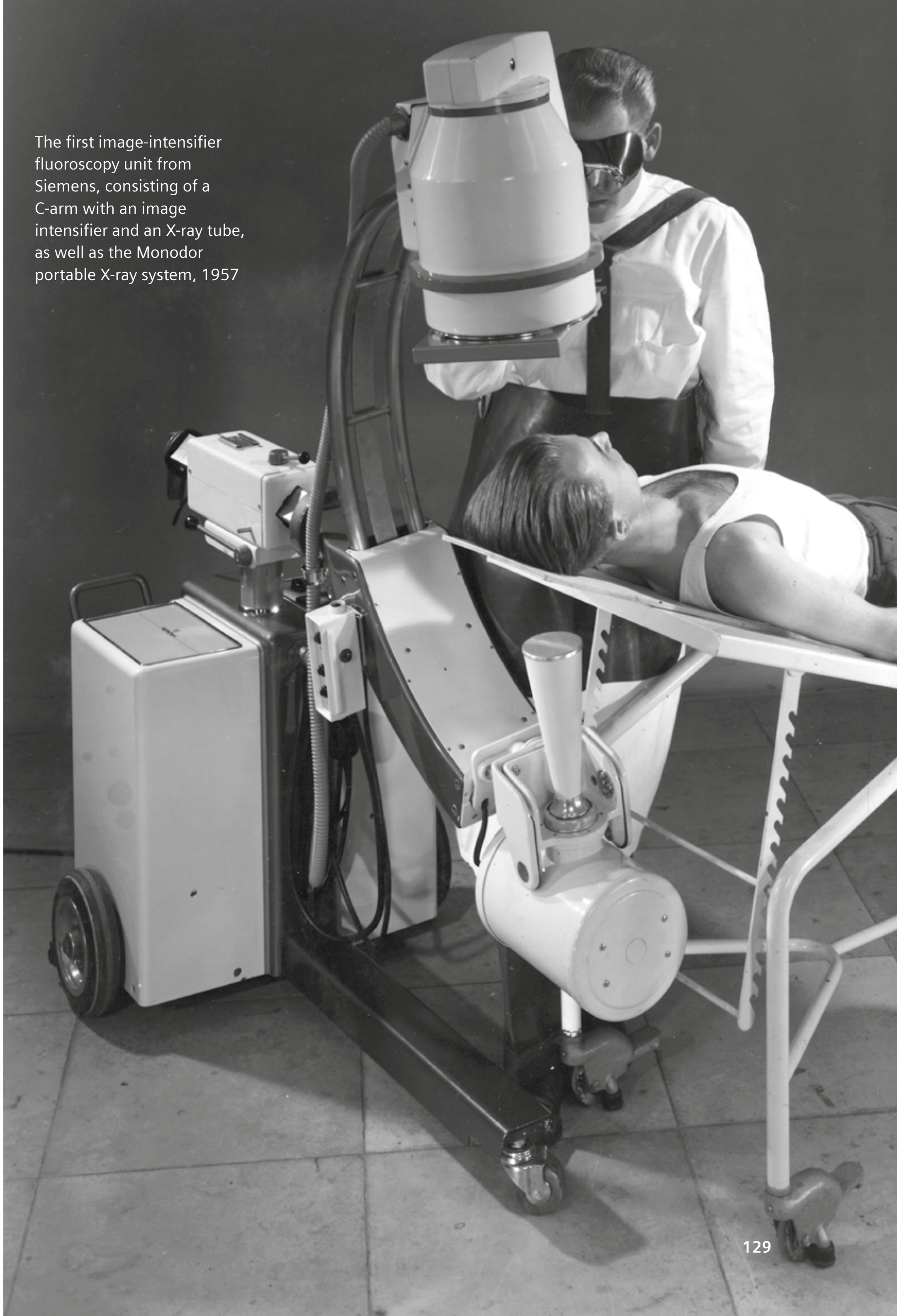
To facilitate the work of physicians in the operating room, portable fluoroscopy units were also developed. Here, the image intensifier was permanently attached to the X-ray tube in a construction that, because of its shape, was referred to as the C-arm. The advantage of this construction was that the image intensifier and the X-ray tube were always in the ideal position relative to one another. By rotating and pivoting the C-arm in numerous directions, physicians could select the best position for the examination at all times. Siemens launched its first image-intensifier fluoroscopy unit with a C-arm in 1957. Initially, the optical viewing system was still attached to the image intensifier, so the physician was always tied to the position of the image intensifier when it came to viewing the image. Accordingly, the lens system had to be designed to make viewing as comfortable and effective as possible. "The optical viewing system is designed so that glasses-wearers can view the images without removing their glasses, and there is a large anatomical eye mask to keep out interfering light." To take account of physicians' different heights, the viewing system could be tilted up and down and – according to the advertising brochure – was therefore equally suited to both shorter and taller physicians.



SRW marketing pamphlet, 1957



Schematic diagram of the mode of operation of an image intensifier with an optical viewing system: SRW marketing pamphlet, 1958

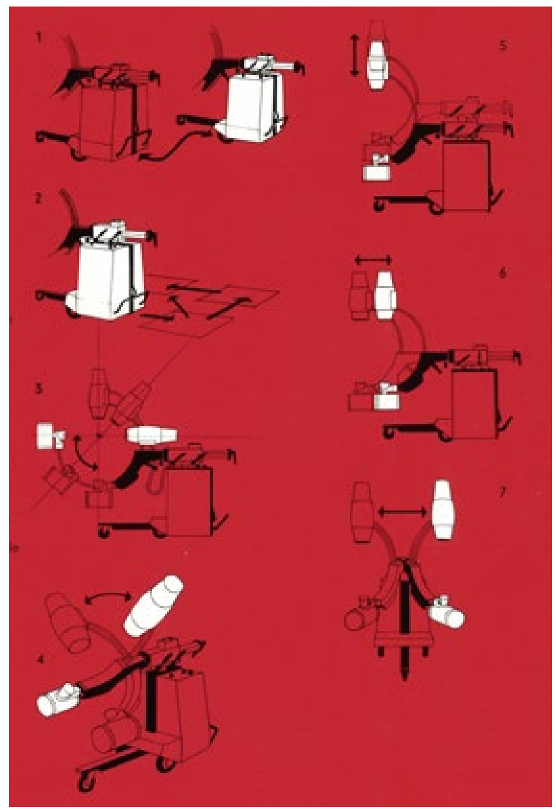


The first image-intensifier fluoroscopy unit from Siemens, consisting of a C-arm with an image intensifier and an X-ray tube, as well as the Monodor portable X-ray system, 1957

Although the advantage of mobile C-arm devices was that they could be used in various different rooms, transport actually placed a considerable burden on the fluoroscopy units. This quickly led to the development of C-arm devices that were mounted on the ceiling – initially on a rail system and later by being suspended at fixed points. These devices provided a number of advantages, including that they were available for use immediately at all times, and took up less space at the operating table. Moreover, mounting the units on the ceiling eliminated the need for cable connections on the floor between the various components of the mobile devices, which could get in the way during operations.

The basic shape of the C-arm – regardless of whether it was mobile or ceiling-mounted – was so suited to applications in the OR that cutting-edge devices still use this construction today, although the technology inside is constantly being refined. In 1965, Siemens-Reiniger-Werke launched the Siremobil as a successor to the first image-intensifier fluoroscopy unit – and, in doing so, established a family of devices that would remain part of the product portfolio for upward of 40 years. Even in those days, the Siremobil featured automatic dose regulation, whereby the X-ray dose required for the examination was adjusted automatically to maintain constant image brightness.

This led to a considerable reduction in exposure times without compromising on image quality, which improved at a steady rate overall. Larger image intensifier tubes allowed physicians to visualize larger regions of interest, and there was also a continual improvement in image resolution – and therefore in detail recognition. The year 1981 saw the launch of the Siremobil 3, which featured Siretron technology and was Siemens's first mobile C-arm device for the operating room to provide an instant digital image. On the Siremobil 4, aids such as a laser light cross allowed the accurate positioning of equipment such as drills, even without the use of X-rays. Despite all



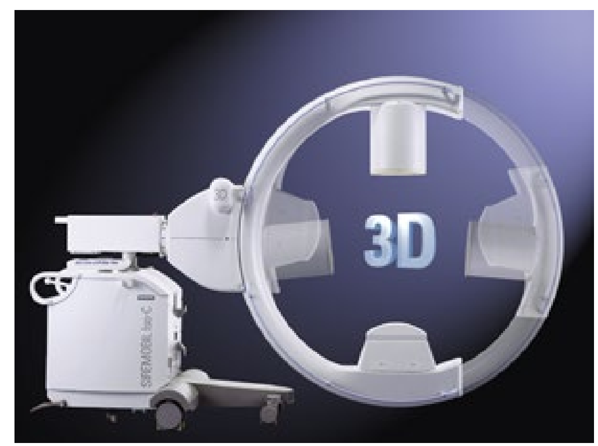
Left: The ceiling-mounted Arcoskop 100-OP, which was specially designed for the operating room, 1980

Right: Illustration from a 1965 advertising brochure showing the Siremobil's maneuverability

The Siremobil 4, 1987

of these technical advances, the C-arm suffered from a persistent limitation for many years: It could only be used to produce conventional two-dimensional images, which did not provide enough information for many surgical interventions – for example, when operations called for the precise insertion of screws. In order to remedy this situation, Siemens launched the Siremobil Iso-C 3D, whose laser light cross allowed physicians to position the part of the body they wanted to visualize in what was known as the “isocenter” of the C-arm. During the scan itself, the C-arm rotated 190° around the isocenter and captured 2D images – either 50 images in one minute or 100 images in two minutes. These images were then used to generate a 3D image that was available immediately after the scan.

Siremobil Iso-C 3D, 2002



From their introduction in the mid-1950s until the turn of the millennium, there was no alternative to electronic image intensifiers when it came to imaging with C-arm systems. It was only in the early 2000s that digital detectors could rival the image quality of conventional image intensifiers. In 2002, Siemens presented the AXIOM Artis *d*FC, the company's first C-arm device to be equipped with a dynamic flat panel detector, which converted the X-rays into digital data so that the imaging system could generate a digital image. Although the AXIOM Artis *d*FC was primarily developed for applications in cardiology, it represented a turning point in development: Since its introduction, digital detectors have also increasingly featured in C-arm devices that are specifically designed for surgery. Nevertheless, the tried-and-tested technology of the image intensifier can still be found in many operating rooms today.

Siemens Healthineers is continuing to break new ground with ARTIS pheno – at the time of its introduction the only robotics-equipped C-arm system on the market. It recognizes the position of the tabletop at all times and aligns itself to the tabletop with every movement. Thanks to memory positions, the system can move the C-arm out of the operating area quickly if necessary, giving the surgeon and the operating team free access to the patient. The C-arm can then be moved back to exactly the same position again for further imaging. This means results can be checked directly, even while the operation is still in progress.

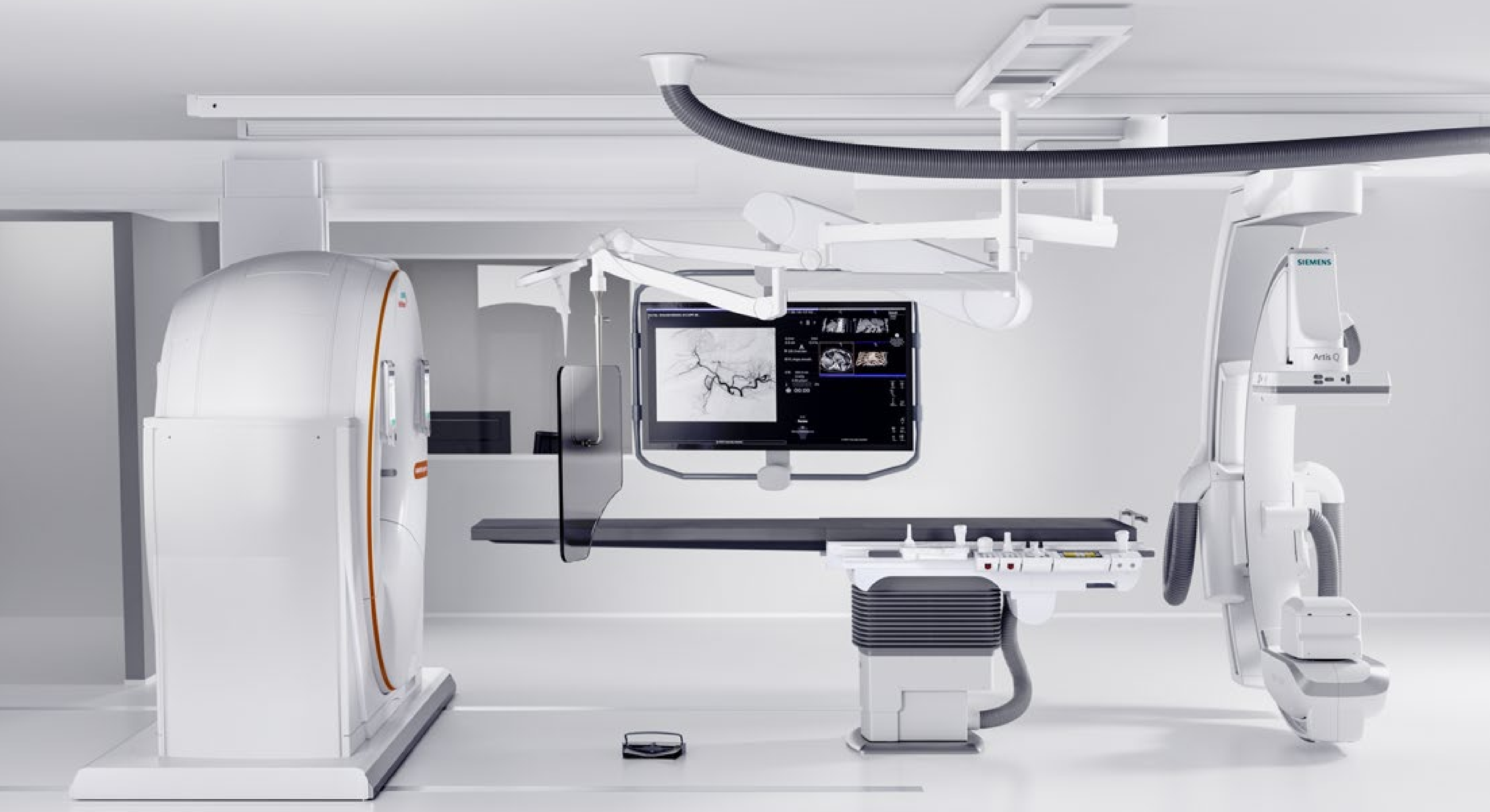
Accurate and detailed imaging not only helps physicians with their work, but also provides direct benefits for the patient. It is a vital part of minimally invasive surgery – that is, surgery that has the least possible impact on the patient. For a long time, this type of procedure was used primarily in cardiovascular surgery and neurosurgery – for example, to insert "stents" (supports used to treat the narrowing of blood vessels). Modern hybrid ORs equipped with high-tech equipment, such as ARTIS pheno systems or SOMATOM computed tomography (CT) scanners, are helping other disciplines – such as orthopedics and trauma surgery – to perform more and more minimally invasive operations as well. This type of intervention is gentler than open surgery and, as such, is particularly important for treating older patients or patients with preexisting conditions. Moreover, minimally invasive surgery can significantly shorten the recovery period and the length of hospital stay. For instance, pelvic fracture patients who receive a minimally invasive screw fixation procedure can walk with full weight-bearing just one day after the operation. Nowadays, it is impossible to imagine medical imaging without software solutions. For example, *syngo* DynaCT captures hundreds of individual images and takes just a few seconds to convert them into 3D images that resemble those from CT scanners. Particularly important information from the generated images can be superimposed on fluoroscopic images during the examination to allow physicians to navigate the procedure even more precisely.

ARTIS pheno in use in the operating room, 2016

Slices on rails

As head of Siemens X-ray development at the time, Friedrich Gudden was also asked about the relatively new field of computed tomography (CT) in 1981. Among other things, he reported that "many of the physicians known to us say that the devices can increasingly also be used for the detection of small tumors in the region of the lungs and, in the future, may also be suitable for cardiac examinations." It was still unthinkable in those days that the new technology might one day be used not only to prepare for operations, but also to perform examinations in the operating room itself. In the meantime, this too has become a reality. In 2014, Siemens installed a CT scanner on rails at University Hospital Frankfurt. The rail system allowed the scanner to be brought to the patient, so that physicians could examine trauma patients in the resuscitation area, for example, without having to move them. Today, this principle is also applied in CT systems within the operating room, where the gantry – that is, the part commonly referred to as the "donut" – slides over the patient on rails without requiring them to be moved or repositioned for the scan. When the system is not in use, it can slide back to its parking position. The rails themselves are set into the floor so that they do not present an obstacle for equipment trolleys or beds.

Electronic image intensification, robot-assisted C-arm systems, and CT scanners – in the early days of X-ray technology, surgeons presumably couldn't even have imagined the benefits of these accomplishments. However, it is thanks to innovations such as these that X-ray imaging is no longer simply a useful tool when preparing for an operation, but now also plays a key role in the surgeon's work inside the OR.



SOMATOM CT Sliding Gantry systems are mounted on rails up to 12 meters long, which can be used to take them up close to the patient when required, 2017

The Sensis Vibe documentation system (2011) captures all events, decisions, measurements, and data during a catheter intervention

Learning for the future

From Polaroid photos of screens to digital twins

If you took all of the digital data generated in the healthcare industry up to 2020 and loaded it onto tablets, would the stack of tablets be shorter or taller than the Empire State Building? The tablets would certainly have to store an almost unimaginable quantity of data. While a typical DVD has a capacity of 4.7 gigabytes, the volume of data generated in healthcare is counted in exabytes. The prefix exa- refers to a one followed by 18 zeros – meaning that an exabyte is equal to one billion gigabytes. It is estimated that, if written down, all the words spoken in the history of humankind would take up approximately 5 exabytes. The quantity of data generated in healthcare by mid-2020 was approximately 2,300 exabytes – meaning the stacked tablets would reach a third of the way to the moon.

Every year, the quantity of data in medicine grows by 48 percent, faster than in any other digital setting. Around 240,000 patients an hour come into contact with systems from Siemens Healthineers alone. The digital transformation will be accompanied by enormous changes in diagnostics and therapy. Indeed, digital assistants are already not only relieving the burden on radiologists when it comes to assessing computed tomography (CT) and magnetic resonance imaging (MRI) images, but also helping physicians to make decisions. In the future, increasingly powerful software applications, such as those based on artificial intelligence, will process this deluge of medical data quickly and accurately in order to support both clinical and surgical decision-making. Digitalization could be as transformational for medicine as the discovery of X-rays was in its day. Yet the history of digital medical and X-ray technology is every bit as fascinating as the predictions for its future. What were the inventions that marked the beginning of its development? What is so special about digital radiology compared with other technologies of the information age? How did it come to pass that we can now produce almost photorealistic images of the inside of the body?

Packets of zeros and ones

The history of digitalization in medical technology does not begin with one specific idea or invention. However, the digital image can be described as the root of all subsequent developments and was made possible by a combination of numerous achievements from various areas of technology. In space travel, for example, methods developed in the 1960s allowed images to be transmitted quickly and losslessly over large distances. The picture information was divided up into pixels and gray scales before being encoded and transmitted as a multitude of individual data packets. This "image matrix" contained all of the information in the image in the form of binary code – in other words, it was made up of two symbols, such as 0 and 1 or Hi and Lo – and could be used to reconstruct the original image after it had been saved or transmitted.

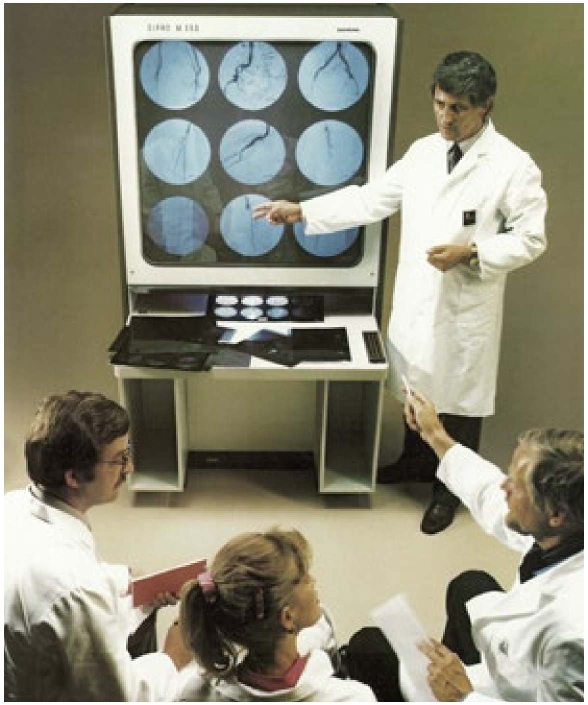
By the end of the 1950s, digital images were being produced in the fields of nuclear medicine and ultrasound diagnostics – but they had to be converted back into analog signals in order to be viewed on screens that resembled televisions. In this context, digital refers to the processing of values measured in the patient's body. For example, an ultrasound probe converts the (analog) echo from the body into electrical impulses for digital processing. The first digital technique in radiography was computed tomography (CT), which caused great

The prototype of SIRETOM with a magnetic tape storage device and a Polaroid attachment on the control desk, 1974 excitement in the medical community in the early 1970s. In those days, however, the only way to digitally store the images produced by CT scanners, such as the SIRETOM system from Siemens, was on magnetic tapes – and the easiest way of recording the image was still to take a Polaroid photo of the screen.

First steps into the digital age

For a number of years, computed tomography was referred to as "digital X-ray" or "digital radiography," because traditional X-ray images were initially still produced on film. As the first two-dimensional digital radiographic techniques became established over the course of the 1980s, computed tomography ultimately broke away from the term "the digital X-ray" in colloquial usage. The first computer-assisted two-dimensional X-ray technique was known as digital subtraction angiography (DSA). This form of angiography – that is, the visualization of blood vessels using contrast agents – could remove (subtract) "interfering" content from the X-ray image. The first step was to take an X-ray of the vessels without a contrast agent in order to produce what was known as the mask image. A computer then subtracted this digital mask from the ensuing X-ray images, which showed the contrast agent spreading through the vessels. This meant that any structures that differed from the mask image could be largely hidden in the X-ray images, so that the DSA images primarily showed vessels that were supplied with blood.

It was the cardiologist Paul Heintzen and his working group at University Children's Hospital in Kiel who carried out the initial work on digital subtraction angiography in 1976. Thanks to further pioneering work by Sol Nudelman, M. Paul Capp, and their teams at the Universities of Arizona and Wisconsin, the first medically usable DSA images of the heart were one of the key topics at radiology conferences in 1980. Just a year later, Siemens presented the Angiotron, its first digital image-processing system for DSA. The Angiotron generated images so quickly that physicians could watch the contrast agent spread through their patient's blood vessels on a monitor at a rate of 50 frames per second. This form of angiography was used at many hospitals from 1982 onward and remained the most widely used digital technique in classical X-ray technology for many years.



Advertising photo for one of the DSA solutions from Siemens, 1982

X-ray images through the laundry chute

Digital imaging as a whole increasingly took center stage in research from 1982 onward, in particular thanks to three major advantages of DSA: Firstly, the X-ray image did not have to be developed and appeared on the screen immediately after it was taken. Secondly, image-processing software could be used to obtain information from a digital X-ray image that could not be visualized on X-ray film. Thirdly, in the words of one internal Siemens analysis at the time, "the easy transferability via data cables ensures rapid image availability."

Recording and assessing a digital subtraction angiogram in 1984

One of the first installations of the Siemens PACS connected several Berlin hospitals in 1988

This was only theoretically true in those days, as there was still no standardized network that could record the digital images or, for instance, relay them to several specialists at a hospital for assessment. The deluge of images was growing by the day and required hospitals to invest considerable time and human resources in managing, archiving, and transporting the images from department to department by mail or internal mail. Diagnoses were frequently delayed because images were still in transit. However, research was already underway – especially at American universities – into methods that could bring medical images together within a digital network. As well as searching for suitable standards, scientists were working to network screens and install cables throughout radiology departments. At Cornell University in New York, for example, broadband TV cables were run through laundry chutes to connect the various floors of the radiology department to one another.

Recording diagnostic images on X-ray film involved laborious development and archiving, as shown in this image from 1960

In 1982, at an international conference in Los Angeles, the medical technology manufacturers finally reached an agreement with hundreds of radiologists and academic researchers on a common standard for the medical networks of the future: All images from medical imaging instruments would be compatible with a picture archiving and communication system (PACS) – and the Digital Imaging and Communications in Medicine (DICOM) standard, which was established slightly later, would allow the images to be exchanged with systems from various manufacturers. Later that year, Siemens began developing a PACS that could be used across an entire hospital or region – or even worldwide. Although it would be several years before this system was ready for series production, the first tests at Victoria General Hospital on Vancouver Island paved the way for continually expanding the Siemens PACS and upgrading it with new technologies. In 1988, long before PACS solutions became generally established in clinical practice, the system developed by Siemens was already in use at numerous hospitals in North America, Japan, and five European countries.

The future begins

In May 1992, the world's first fully digital and networked radiology department began operating at the Donauspital in Vienna. Under the product name SIENET, Siemens brought together the hospital's full complement of imaging systems, including X-ray units, CT and MRI scanners, and ultrasound systems, via fiber-optic cables to create one large, integrated PACS that could process 13 gigabytes of data per day – this was an enormous volume of data at the time and is roughly equivalent to the contents of 13,000 books, each with 500 pages. Radiologists enjoyed immediate access to the diagnostic images from any terminal in the hospital, and even in 1992, SIENET provided a network speed of 100 MBit/s, which is over four times faster than the average download speed of German Internet connections in 2019.

Following the pilot project in Vienna, Siemens installed further SIENET systems, including at Hammersmith Hospital in London and Viborg Regional Hospital in Denmark, where 500,000 digital images were produced by January 1993 alone. Together with the American company Loral, Siemens set up what was then the world's largest PACS: a network of several American military hospitals that began in Texas and was progressively extended. From that point onward, digital images and networks would play an increasingly important role – and this growing digitalization would affect not only physicians' work but also the patients themselves. For example, up to 15 percent of images had previously been lost due to incorrect filing, and this could have a critical impact on potential follow-up treatment. When X-ray images on film were underexposed, they were useless for diagnosis and had to be taken again, whereas digital images could be enhanced and corrected. During the trial of SIENET at the Donauspital in Vienna between September 1991 and the final report in May 1992, not a single X-ray had to be repeated due to loss or unsatisfactory image quality.

X-ray images using a laser

By the early 1990s, the Siemens product range already featured numerous hardware and software developments that could take advantage of the benefits of digitalization. At that time, SIENET could connect equipment including CT, MRI, and ultrasound scanners to digital radiography systems,

The SIENET MagicView workstation in 1996

The POLYTRON 1000 system could be used to assess all digital X-ray images from 1988 onward.

such as the POLYTRON 1000, as well as devices optimized for digital subtraction angiography, such as the MULTISKOP. Workstations with up to eight monitors allowed physicians to perform a variety of tasks, such as magnifying important details or hiding unimportant ones, accentuating contours, or adjusting the image contrast.

One of the key milestones of this era was a radiographic technique that allowed conventional X-ray equipment to be upgraded to digital systems. In the Siemens DIGISCAN imaging plate system, the cassette of the X-ray unit contained a special phosphor-coated film instead of the usual X-ray film. A laser beam scanned the X-ray image on the imaging plate point by point, converted it into light signals, and transferred the information to the image processor in the form of digital data. This imaging plate was significantly more photosensitive than

The DIGISCAN workstation in 1992

Among other things, the DIGISCAN system allowed the operator to magnify important details of the X-ray image and accentuate contours

In the Siemens DIGISCAN imaging plate system (1992), the cassette of the X-ray unit contained a special phosphor-coated film instead of the usual X-ray film

the X-ray film, and the details of the image were clearly visible even in poorly exposed areas. Whereas traditional X-ray images each required their own film, one DIGISCAN imaging plate was enough for several thousand images. With a few clicks of the mouse, which was still a rare thing in those days, the radiologist could assess the X-ray images, manipulate them on the high-resolution monitor, and store the examination results in the PACS.

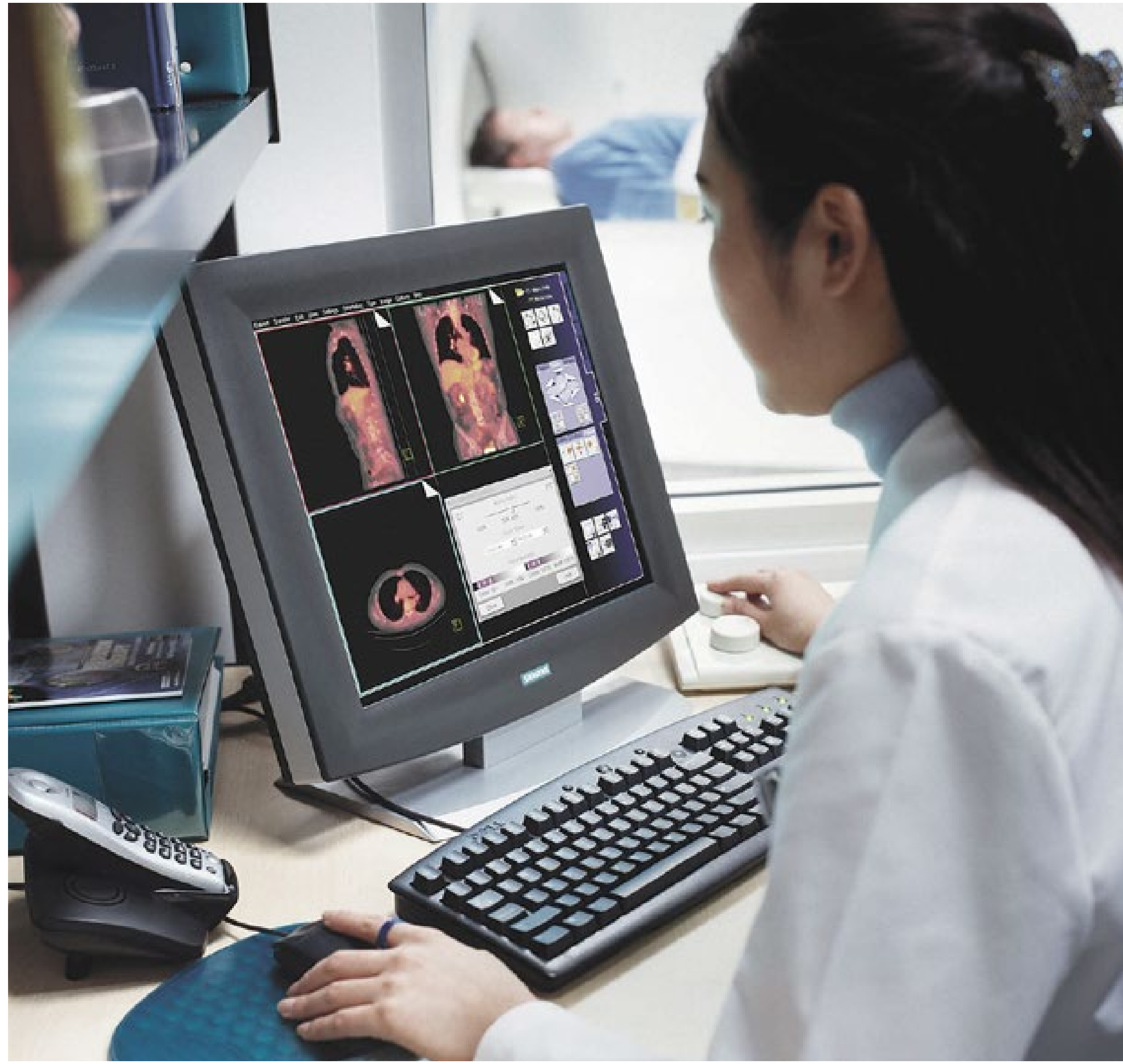
An advert for the CARE software, 1994

One for all

The digitalization of medical technology affected more than just the form in which the data was present. Indeed, development work attached equal importance to how data and systems could be used in the most sensible way for physicians and patients alike, with software playing a key role in obtaining the best possible results from the hardware. Over the course of the 1990s, engineers at Siemens developed numerous applications that continue to underpin the digitalization of modern systems from Siemens Healthineers. These applications ranged from programs to optimize the radiation dose to multimedia systems that were intended to make the examination as comfortable as possible for the patient. From 1994 onward, for example, the Combined Applications to Reduce Exposure (CARE) software calculated, for each individual patient, the lowest possible dose for a CT scan while maintaining the best possible image quality. Depending on the patient's anatomy, CARE could reduce the radiation dose by over 50 percent, with reductions of up to 75 percent for pediatric examinations.

The 1990s saw such huge advances in software that Siemens systems at the turn of the millennium were barely comparable with those at the start of the decade. With the launch of its *syngo* software in 1999, Siemens became the first medical technology manufacturer to standardize operation across all of its systems. In the past, CT and MRI scanners or other imaging systems from the same manufacturer had used different software interfaces, meaning the operating personnel first had to acquaint themselves with each and every one of them. With *syngo*, Siemens standardized device operation, resulting in a much shorter training period for staff when a hospital or medical practice bought a new Siemens system. The graphical user interface used simple and self-explanatory symbols throughout, and *syngo* offered numerous features under the hood that were optimized for workflows at hospitals and medical practices. For example, all of a patient's data could be brought together within the electronic patient record so that physicians always had an overview of previous examinations, such as findings from CT scans, lab results, or surgical reports. Moreover, interdepartmental networking accelerated workflows, giving physicians more time to spend with patients.

With the launch of its *syngo* software in 1999, Siemens became the first medical technology manufacturer to standardize operation across all of its systems



By 2003, *syngo* had already significantly refined its user interface

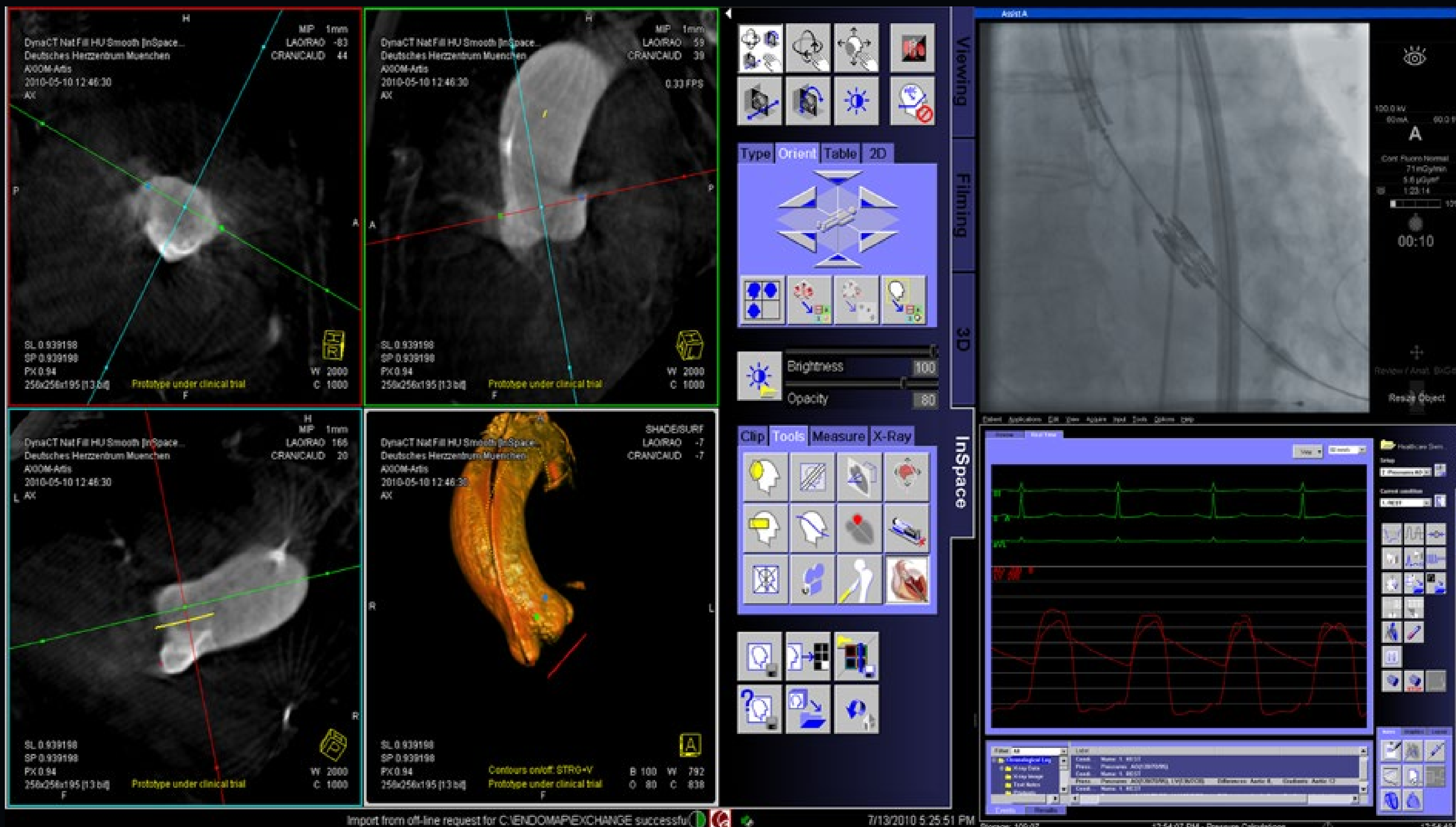
Direct imaging

The imaging plate systems of the 1990s represented a compromise and, to some extent, a workaround. Although they allowed physicians to benefit from digitalization even when using traditional X-ray technology, they didn’t deliver images instantly, as the plate still had to be scanned point by point with the laser. At the turn of the millennium, the technology had reached the stage where the X-ray converters known as solid-state or flat-panel detectors were at least on a par with analog X-ray film in terms of radiographic quality. In this “FD technology,” the X-rays reaching the detector struck a scintillator, which converted the signals into visible light. Photodiodes then converted this light into electric currents, and a converter turned these analog signals into digital data before relaying them to the computer for analysis. Once the images were captured, the physician could view them on the monitor immediately and store them in SIENET.

In the year 2000, Siemens launched the Thorax FD, Vertix FD, and Multix FD X-ray systems, which were primarily used to diagnose problems with the lungs and skeleton. These were quickly followed by other fully digital X-ray systems, such as the AXIOM Aristos universal X-ray system with a 9 million-pixel resolution – more than that of a typical cinema screen in 2020. Since the turn of the millennium, flat-panel detectors have also increasingly been used in angiography and cardiology, which place far greater requirements on the detector as the system must display moving images of the blood vessels or the beating heart. To confound matters, the detector had to be both big enough to visualize whole regions of the body, such as the thorax, and compact enough to provide the physician with optimum access to the patient during an intervention. For the AXIOM Artis *d*FC cardiology system, the engineers at Siemens therefore developed a special version of FD technology: AXIOM FDi was a flat-panel detector measuring just 30 x 40 centimeters. As the detector was pivot-mounted and insensitive to magnetic fields, it allowed physicians to use AXIOM Artis *d*FC in conjunction with special magnets in order to guide the catheter through the coronary vessels during an intervention. In combination with new software, the flat-panel detectors of angiographic C-arm systems paved the way for numerous new applications. From 2005 onward, for example, *syngo* DynaCT made it possible to generate slice images resembling three-dimensional CT scans directly at the operating table.

The FD technology of AXIOM Aristos FX (2002) reduced the radiation dose for patients and clinical staff alike

In combination with new software, the flat-panel detector of AXIOM Artis paved the way for numerous new applications, 2004



syngo DynaCT allows slice images to be generated and assessed directly at the operating table

Cinematic images of the body

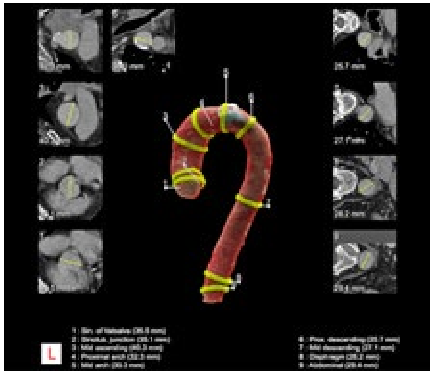
Cinematic Rendering* images impressively demonstrate the results that sophisticated software can obtain from the right hardware. Klaus Engel and Robert Schneider, two of the leading visualization experts at Siemens Healthineers, based the underlying concept for their invention on – as the name of the technology suggests – the computer-generated effects seen in the movie industry. The algorithm in the software uses three-dimensional patient data to generate photorealistic images of anatomy by simulating the physical properties of light in datasets obtained from the patient's body. However, whereas effect rendering in the movie industry only considers light reflected by the surfaces of animated characters' bodies, the algorithm for Cinematic Rendering technology takes account of much more complex factors, such as photon scattering in the tissue. The light propagates through the three-dimensional datasets naturally and casts realistic shadows, and it is this realistic shadowing that makes the images so lifelike – because our eyes are trained to identify the structure of objects based on minute differences in shading.

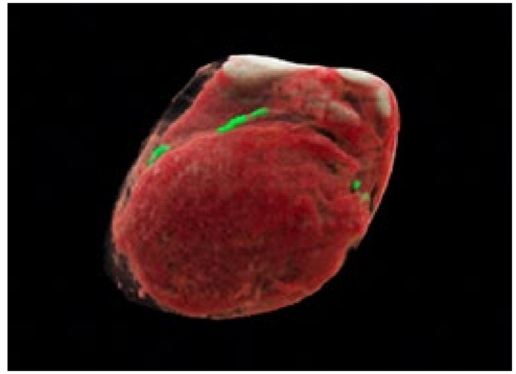
Since 2017, the *syngo*.via software has allowed Cinematic Rendering images to be generated using CT or MRI scans with a few clicks of the mouse. It also has a filter function that allows the operator to hide different types of tissue – for example, in order to leave only the bones visible in an image used to examine the skeleton. Cinematic Rendering has enormous potential, and several studies are currently investigating the added value that the technology offers in various medical disciplines, including forensics. The photorealistic images can, for instance, facilitate communication between physician and patient, or help surgeons to plan operations better. Cinematic Rendering has also found successful applications in teaching: Franz Fellner, head of the Central Radiology Institute at Kepler University Hospital Linz, worked with Engel and Schneider to further refine the technology and, since 2015, has used the innovative images to teach anatomy to medical students on a huge projection screen. In 2017, Engel, Schneider, and Fellner were one of three teams of scientists to be nominated for the German Future Prize, one of Germany's most prestigious awards for technology and innovation.

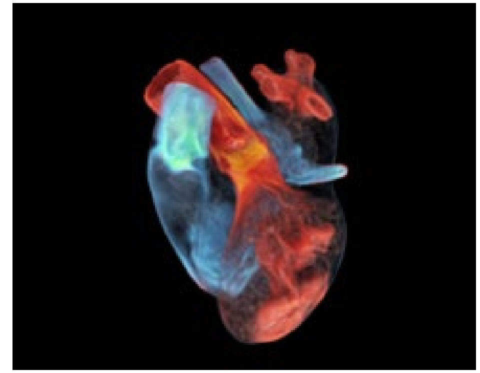
The thyroid gland and bones of the head and neck region, visualized using Cinematic Rendering in 2015

The white cables on this Cinematic Rendering image belong to an ECG unit that was connected to the patient during the CT scan

*Cinematic Reality is for education and communication. Not for diagnostic use. The application is still under development. Its future availability cannot be guaranteed.







Left: Among other things, the intelligent software assistant AI-Rad Companion Chest CT measures deviations and compares them with reference values

Middle: AI-Rad Companion Chest CT automatically marks abnormalities

Right: The digital twin of a real patient simulates the processes taking place in their heart

Smart companions

Today, 125 years after the discovery of X-rays, software is playing an increasingly significant role when it comes to further improving diagnosis and therapy. In order to make constructive and helpful use of the enormous quantities of digital data, the engineers at Siemens Healthineers are currently developing a whole host of new tools. It is imperative that big data becomes smart data. Intelligent imaging means using the opportunities of digitalization to help users obtain the best possible results from their equipment. Today, in Siemens Healthineers Digital Ecosystem, applications such as teamplay myCare Companion support the networking of patients and healthcare teams, allowing care to be provided remotely to patients with chronic diseases, such as cardiac insufficiency. Using *syngo* Virtual Cockpit, specialists from one hospital can connect with scanners from Siemens Healthineers at hospitals elsewhere in order to provide their colleagues with expert assistance. For example, this allows healthcare providers to conduct specialized examinations that rely on specific user expertise across all of its locations without requiring patients to travel long distances. Help is also available in the form of myExam Companion, which provides smart user guidance based on artificial intelligence (AI). As a smart assistant, myExam Companion helps users find the correct configuration for CT scans in order to obtain the best possible clinical image and the correct dose for each individual patient.

AI systems of this kind are quite literally learning for the future. They can spot patterns in enormous, complex volumes of data quickly and accurately – provided that high-quality training data have taught the algorithm what to look for. Today, specially trained AI systems from Siemens Healthineers are already providing support for clinical decision-making. AI-Rad Companion Chest CT is an intelligent software assistant for radiologists that can recognize organs and potentially pathological changes in tissue. The software discerns and highlights structures in CT scans of the thorax and marks abnormalities. Rather than replacing radiologists, however, AI-Rad Companion Chest CT will relieve them of routine activities so that they have more time to deal with complicated diagnoses. In 2019, Siemens Healthineers successfully used intelligent algorithms to simulate the heart of a real patient. In a joint research project with University Hospital Heidelberg, cardiologists used imaging data, laboratory diagnostics, and ECG measurements to create a digital twin of a real patient's heart in order to tailor the treatment of heart diseases specifically to the individual patient. The digital twin can be used to conduct preliminary tests of certain medications or surgeries in a digital environment in order to gauge the chances of success. With digital twins of other organs already in development, algorithms are set to take on an increasingly important role in imaging. However, despite all of the technical advances since the discovery of X-rays by Wilhelm Conrad Röntgen, we should see artificial intelligence as a way of supplementing human abilities in order to improve decision-making. The aim is to support sounder and more accurate decision-making while also reducing the workload and the potential for human error.

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