Siemens Healthineers Historical Institute

The history of magnetic resonance imaging at Siemens Healthineers

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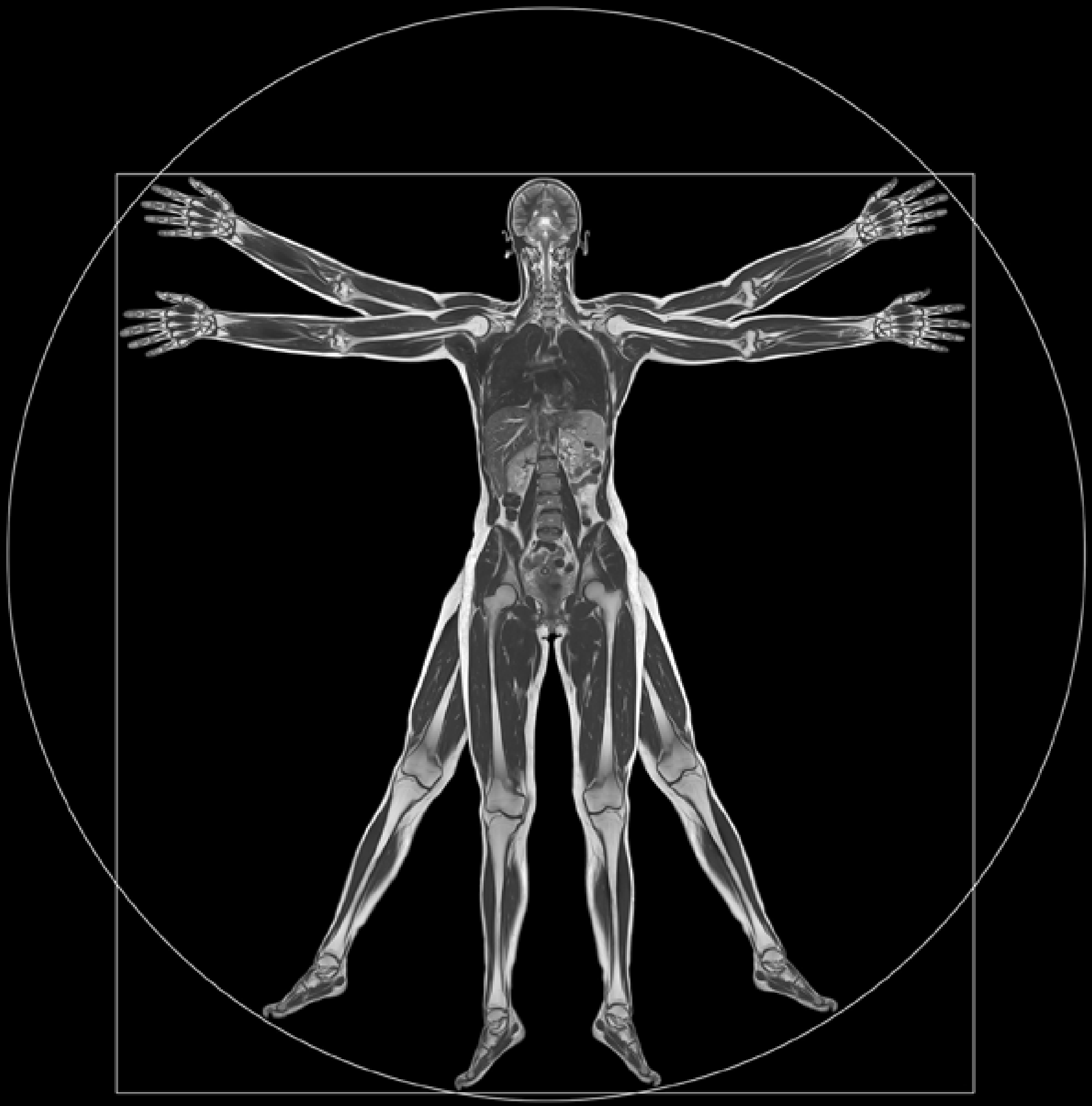


The underlying principle

Magnetism is part of our daily life. Even as children, we are fascinated by the invisible force, for instance, when we try to connect the cars of our wooden toy train set. Why do the cars repel each other when they are the wrong way round? What attracts them to each other when they are the right way round? As adults, we use objects in our daily lives that could not function without the force of magnetism. All electric motors – whether in our power drills or electric toothbrushes – are driven using magnets. Everyday objects such as computers, loudspeakers, telephones, microwave ovens, parking lot barriers, or ATMs, would not exist in their present form without magnet technology. The most impressive examples of magnets at work are magnetic levitation train systems, the *Large Hadron Collider* at the CERN European Organization for Nuclear Research, and the most flexible imaging method used in medicine: magnetic resonance imaging (MRI).

Magnetic resonance imaging – previously called nuclear magnetic resonance – stands out from other medical imaging systems for a number of reasons. Even the basic principle behind MRI sounds both weird and fascinating at the same time:

The properties of certain atomic nuclei can be used to generate detailed images of inside the human body.

While they were developing this basic idea in the 1970s and 1980s, the pioneers of magnetic resonance imaging were faced with entirely new challenges. Experience gained from the development of X-ray machines, ultrasound systems, computed tomography or molecular imaging scanners offered little to no help in the early days of MRI. Entirely new questions arose: What did people working in the vicinity of magnetic fields have to consider? Were air hoses with membranes the only way of communicating with patients while they were inside the bore? And what did streetcars and elevators have to do with MRI exams?

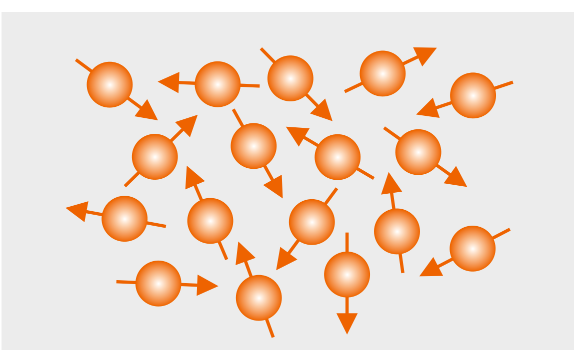
Pioneers working on the development of new ideas often have to resort to unconventional means to overcome challenges. The story of magnetic resonance imaging at Siemens Healthineers is one of many unusual ideas. Every MRI system has been the subject of some exciting, often informative, and even amusing anecdotes. This book tells the story of the people behind this impressive technology, its rapid progress, and defining innovations. In the time between the initial work on the prototype of the first MAGNETOM in a small wooden hut in Erlangen and the latest new generation systems, many significant milestones were reached. First of all, however, let us take a look at the basic technology behind magnetic resonance imaging. How is it possible to look inside our body using magnets?

The compass within

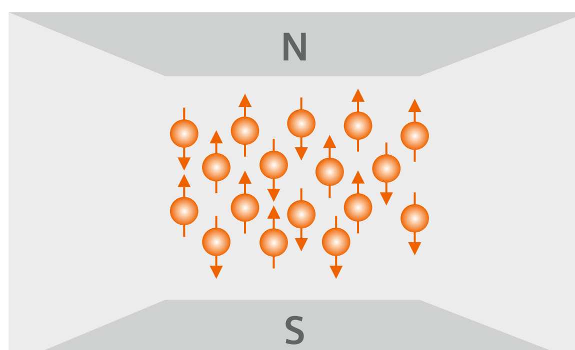
A brief introduction to the basic principles of magnetic resonance imaging

About 65 percent of our body consists of water, which itself is made up of minute particles: hydrogen and oxygen atoms. The nucleus of the hydrogen atom usually consists of one positively charged proton. The proton has spin, so, like a planet, it is permanently rotating around its own axis. Moving electrical charges produce a magnetic field around themselves. Nuclear spin is therefore the physics behind magnetic resonance imaging. In material, the axes of rotation of the hydrogen nuclei generally point in equal proportions in all directions and cancel out each other's magnetic effect. That is why the human body, like almost all materials, is not magnetic. If our body is near to a strong magnetic field, however, the hydrogen nuclei inside it align with this field, much like a compass needle does in Earth's magnetic field – and this phenomenon can be put to good use in medicine with magnetic resonance imaging.

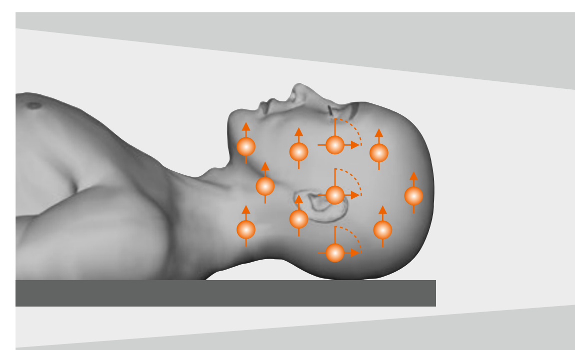
So, for example, when a patient is moved into the bore of the magnetic resonance imaging scanner, the hydrogen atoms inside the patient's body align with the external magnetic field. In this state, the hydrogen atoms inside the patient spin identically in the magnetic field and thereby generate constant magnetization of the body. The basic principle behind magnetic resonance imaging is deliberately to introduce disturbance into the equilibrium of the spins. To do this, the MRI scanner transmits short radio-frequency waves, called RF pulses, which have the same frequency as the spins. The RF pulses must enter into resonance with the protons. In other words, the radio waves must resonate at the same frequency as the spin of the protons in order to interact with them. That is where the *resonance* in magnetic resonance imaging comes from. After each disturbance by an RF pulse, the spins return to their original state relatively quickly. This process, which is termed *relaxation* in physics, can be measured using highly sensitive receiver coils and allocated to a position in three-dimensional space. A computer converts the measured values and generates a tomogram, or slice image, from them. These tomograms map the inside of the body in thin slices, which can be viewed by clinicians in two or three dimensions on the screen.



The axes of the hydrogen atoms inside the body point in all directions and cancel out each other's magnetic effect



Nuclear spin is what gives the hydrogen atoms their magnetic properties



In MRI, the hydrogen nuclei align with the direction of the magnetic field

The main components of a magnetic resonance imaging system

The heart of the system: the magnet

In principle, magnetic resonance can also be used in Earth's magnetic field, for instance to find underground oilfields. This is because the orientation of spins in every spatial direction is only fully random in the complete absence of a magnetic field. For clinical imaging, ten thousand-fold stronger magnetic fields are needed. For example, the magnet of an MRI system with a strength of 3 tesla generates a magnetic field that is approximately 66,000 times stronger than that of Earth. Strictly speaking, the unit *tesla* refers to the magnetic flux density. However, in everyday language, it has come to mean "field strength", i.e., the strength of the magnetic field – although this is not correct usage in physics. The stronger the magnetic field, the better the so-called *signal-to-noise ratio*. This means that the signal measured by the MRI scanner is more easily discernible against the background noise. This noise consists of unwanted image pixels, whose brightness deviates from the actual image content. Due to its correlation with the signal-to-noise ratio, the field strength affects the potential image resolution, examination duration, and image contrast, that is, the difference between dark and bright image pixels.

Besides the desirable field strength, the magnet also produces an unwanted stray field: A magnetic field occurs in the space around the MRI scanner that is not required for the generation of the image. This stray field affects magnetic objects in and around the examination room. Both the magnet and the examination room must therefore be shielded. In the past, iron shielding was used and the magnet could weigh up to 38 metric tons. Modern MRI systems are shielded with special coils and usually weigh between 4 and 7 metric tons. Not only the field strength but also the distribution of the forces exerted in the magnetic field have a considerable influence on the quality of the image produced by the MRI system. The force distribution can be shown as magnetic field lines. A magnetic field that has the same field strength everywhere is called *homogeneous*. The field lines of a homogeneous magnetic field run parallel.

The strong magnetic fields that are needed for magnetic resonance imaging are usually produced with so-called superconducting magnets. Superconducting means that the niobium-titanium wires of the magnet coils do not exhibit any electrical resistance at temperatures below minus 269 degrees Celsius. To maintain this low temperature, the coils of almost all systems must be surrounded by several hundred liters of liquid helium. Helium is a non-toxic noble gas and the only substance that under normal pressure does not solidify even at an absolute zero point of minus 273.15 degrees Celsius. When used in an MRI scanner, helium has a similar effect to a vacuum flask. The heat transfer between the content and the surroundings is reduced. Yet, like a vacuum flask, the helium jacket does not provide complete insulation. Over time, the noble gas evaporates due to the heat from its surroundings. Older MRI systems used up to 0.5 liters of helium an hour. After about six weeks, the noble gas had to be replenished. On modern systems, however, very little or no helium evaporates during normal operation. In most cases, less than one refill per year is required (zero boil-off technology). Superconducting magnets have many advantages over conventional electromagnets: For instance, no more electricity is required once the coils have been charged. No heat is generated that needs to be removed. The magnetic field of a superconducting magnet is stable 24/7 without consuming electrical power. The more powerful magnetic field of this magnet means that more protons align parallel with the field, resulting in an improved signal-to-noise ratio and therefore a higher resolution of the examination images.

From the signal to the image: gradient technology

The signals emanating from the body in the magnetic field must be precisely allocated to their original location. To achieve this, a so-called gradient system generates further magnetic fields in three directions in space, which are superimposed on the main magnetic field. A gradient is therefore a change in the magnetic field in a particular direction. The coils that generate the gradients can be switched on and off thousands of times per second. This generates a slice in three-dimensional space that corresponds to the section of the body to be examined. The nuclear spins outside this slice are not affected by the RF pulse. This measurement step produces the raw data that provide the spatial coordinates required to calculate the image.

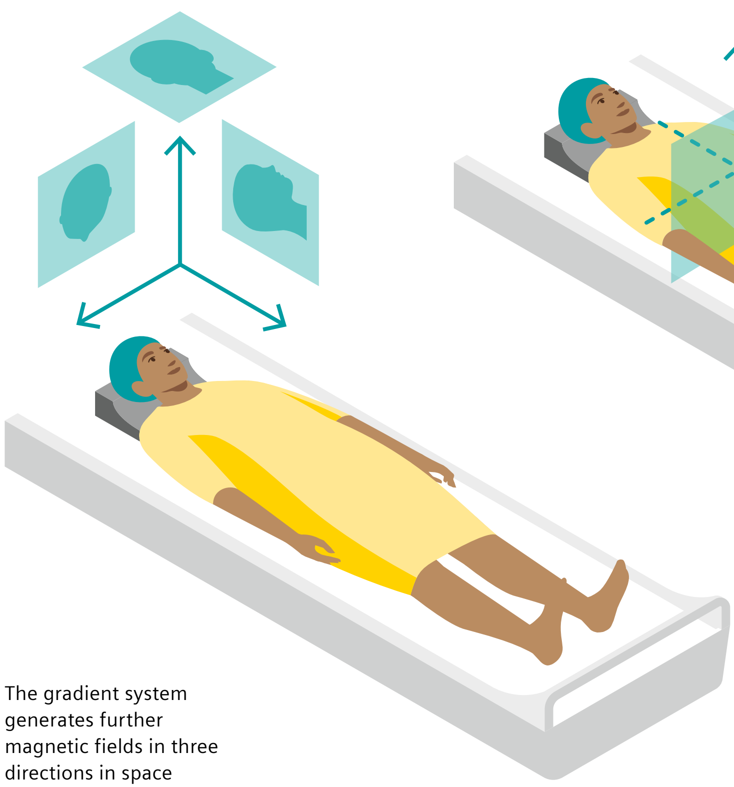
The fast switching of the gradient coils is what causes the very loud noises that are produced by the magnetic resonance imaging scanner. The coils are contained within plastic structures that are arranged inside the magnet tunnel directly around the patient. Since the gradient fields must be stronger than the main magnetic field, the coils are switched on and off within microseconds with very high electric current. This means that huge forces are exerted on the plastic structures and the coils. The gradient system vibrates, which, depending on the frequency, sounds like hammering, knocking, or humming.

Transmitting and receiving: the radio-frequency system and the sequences

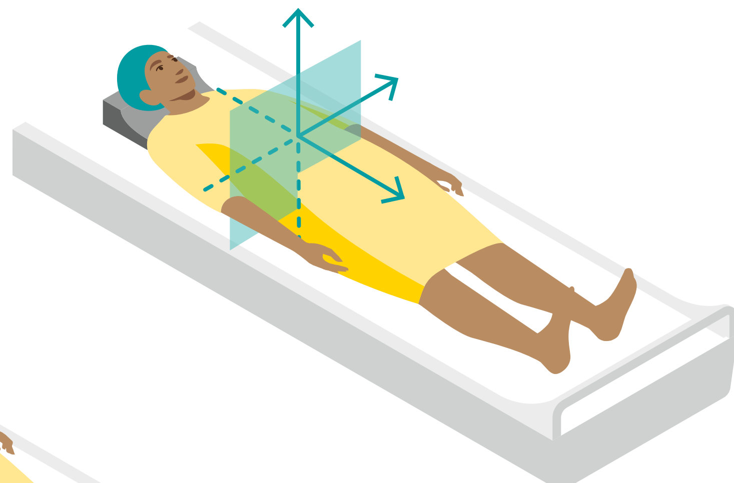
Nuclear spins are excited in the patient's body by pulsed magnetic radio-frequency fields. First, the RF coil transmits the signal to excite the spins, then, within just a few microseconds, it switches over to receive the "reply" from the atoms. One microsecond corresponds to 0.000001 seconds. A body coil with a large measurement field is integrated in the magnetic resonance imaging scanner. Depending on the region of the body to be examined, additional special coils are used whose shape is adapted to the region in question. Today, so-called array coils are used to examine larger body regions. These are coils with several smaller coil elements that can be combined as required for the examination.

The magnetic resonance imaging scanner excites the spins with so-called pulse sequences. Put simply: The system activates the various gradient coils at different points in time during the measurement, transmits the RF pulse to excite the nuclear spin, and receives the "echo" of the resonance. Depending on the required image quality, these steps must be repeated several times. The more resonance signals the MRI scanner receives from the body, the better the image quality. The choice of pulse sequence influences the amount of useful information in the images as the settings have a direct influence on the contrast and resolution of the images. Many different software-controlled pulse sequences can be generated with the same hardware.

Depending on the pulse sequence, different tissue types transmit different signals, which appear as different gray scales on the resulting image. Some sequences are excellent for imaging the heart, while others are designed to show the brain or the muscles. The exceptional flexibility of magnetic resonance imaging is due in no small part to the many different pulse sequences that have been developed over the years.



The gradient system generates further magnetic fields in three directions in space



The switching of the gradient coils generates a slice that corresponds to the section of the body to be examined

What happens during an examination?

An MRI examination including preparation of the patient usually lasts about 20 to 60 minutes. Since magnetic resonance imaging operates with strong magnetic fields, the patient is asked to remove metal objects such as jewelry, piercings, wristwatches, and eyeglasses. Some implants[1], such as, for example, pacemakers[2], stents, or artificial joints, are affected by the magnetic field and must be made known to the personnel before the examination. As some cosmetic substances contain metal particles, which can affect image quality, patients should attend examinations, particularly of the head, without make-up. Large-area tattoos may feel slightly warm during the examination because the metal particles of some colors are set into slight motion by the magnetic fields. For some examinations, contrast agent is administered to the patient, which makes certain structures in the body more visible, for example, blood vessels or tumor tissue.

Depending on the body region to be examined, the patient lies in a head-first or feet-first position on the patient table. The radiology technologist then places the coils on the parts of the body to be examined. Most examinations are performed in the supine position, but some are performed in the prone or lateral position. Patients are given a soft rubber ball to hold, called a squeeze bulb, which, when pressed, calls the staff via an intercom system. To protect the patient from the acoustic noise produced by the gradient system, which can be louder or less loud depending on the pulse sequence, earplugs, or headphones can be worn. As soon as the patient is ready for the examination, the patient table is moved into the bore of the MRI scanner. When all preparations are complete, the staff leave the examination room but continue to monitor the patient during the exam and can contact the patient over the intercom and give instructions, if necessary. During the examination, the patient must keep still – much like when having a photo taken – so that the images are not fuzzy or blurred. When the examination is over, the patient is moved out of the system and the radiologist can evaluate the MR images.

Additional special coils may be used depending on the body region to be examined

A science in harmony

The discovery of nuclear magnetic resonance and early developments at Siemens

In 1952, holding the Nobel Prize for Physics in his hands, Felix Bloch began his speech with the reverential words: "It is a tribute to the inherent harmony and the organic growth of our branch of science that every advance in physics is largely due to the developments that preceded it." He views his discovery of nuclear magnetic resonance as a typical example of this harmony. Thousands of people have contributed toward understanding the structure of atoms and the effect of magnetism. The story of magnetic resonance imaging – unlike that of X-ray technology – does not start with a specific event, but rather consists of a huge network of fascinating ideas and experiments, which at various times have made significant breakthroughs and advances possible. Felix Bloch's Nobel laureate speech provides an overview of the most important milestones in the early years of this technology, offering us "an outline of its long and distinguished background", which finally led to his discovery of nuclear magnetic resonance.

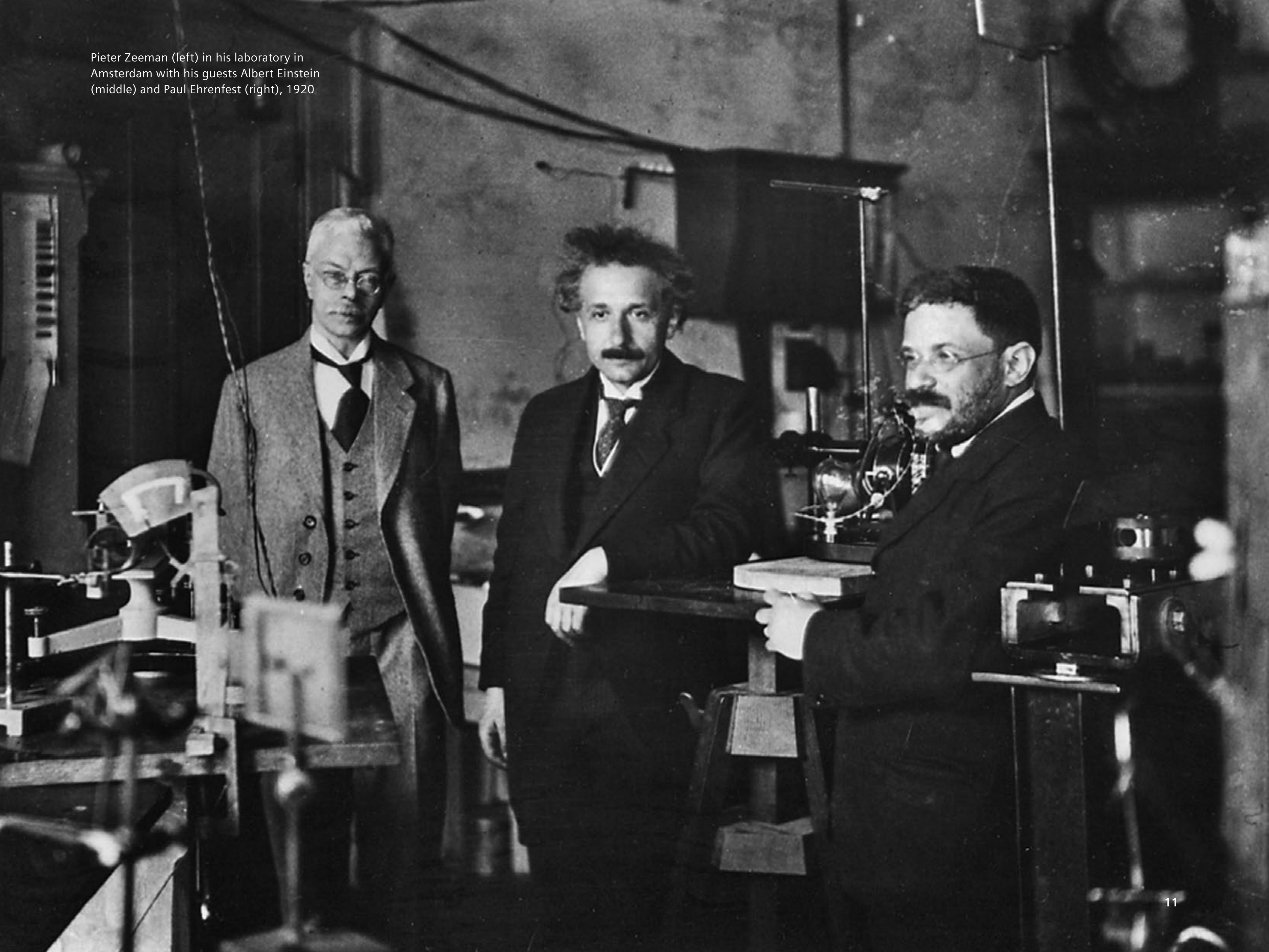
Brilliant investigations

Bloch begins by emphasizing that his research on nuclear magnetic resonance is in fact rooted in spectroscopy, "a field to which modern physics owes so much in other respects." A spectrum (from the Latin meaning specter or apparition) originally defined something that is visible but intangible, like the colors of a rainbow, for instance. Spectroscopy covers a group of physical methods with which the

Felix Bloch in his laboratory at Stanford University, 1952

properties of radiation and its interaction with matter can be analyzed. Every substance has its own characteristic spectra. Properties such as wavelength or number of waves allow precise conclusions to be drawn about the matter being examined. Regardless of which spectra we are analyzing – light, heat, X-rays, or radio waves – all electromagnetic waves can be broken down into their constituent parts by means of spectroscopy just like a particle beam made up of atoms and molecules. In astronomy, for example, this method can be used to determine the brightness of a star from its spectrum and, from that, derive its distance from Earth.

For Felix Bloch's own nuclear magnetic experiments, one effect, which the Dutch physicist Pieter Zeeman observed for the first time in 1896 with his spectroscope, was of particular importance: The light spectrum changes in a characteristic way when it is subjected to a strong magnetic field. Instead of one single wavelength, several wavelengths can be observed. Zeeman's teacher Hendrik Antoon Lorentz, one of the most influential figures in the history of physics, had already predicted this effect in his theories. When Lorentz learned of Zeeman's observations on Saturday, October 31, 1896, he asked his pupil to come to his office on the following Monday so that he could explain to him the theory behind his observation. In atomic physics, this phenomenon is now known as the Zeeman effect. Zeeman and Lorentz received the Nobel Prize for Physics in 1902 for their joint research into the influence of magnetism on radiation, making them the second laureates in the history of this prize after Wilhelm Conrad Röntgen.



Pieter Zeeman (left) in his laboratory in Amsterdam with his guests Albert Einstein (middle) and Paul Ehrenfest (right), 1920

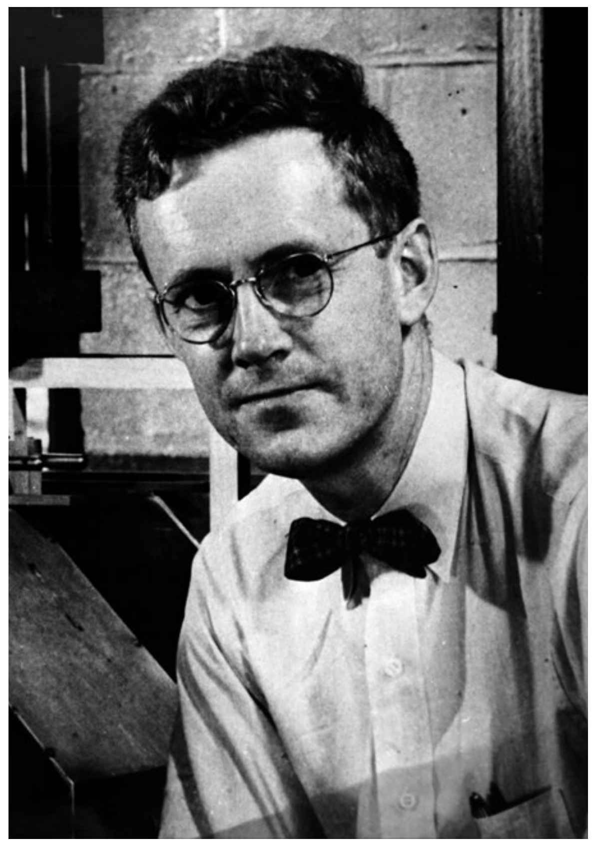
From now on, several more Nobel Prizes would be awarded for research connected directly or indirectly with the history of magnetic resonance imaging. In his speech, Felix Bloch gave special recognition to three of his predecessors: Wolfgang Pauli, Otto Stern, and Isidor Isaac Rabi. The Austrian physicist Wolfgang Pauli, who in 1924 was the first to describe the structure of the electron shell of atoms in an understandable way, called the Pauli Principle, assumed the existence of a spinning atomic nucleus. A further decisive step forward can be attributed to the German physicist Otto Stern and his experiments with protons. Protons, like neutrons and electrons, are constituent parts of atoms. In 1933, Stern was able to prove that the proton of the element hydrogen has magnetic properties. It therefore has a north pole and a south pole and consequently reacts to other magnetic fields. The U.S. American physicist Isidor Isaac Rabi built on Stern's work and invented the so-called molecular beam magnetic resonance detection method, the precursor to magnetic resonance spectroscopy. In a "brilliant series of investigations," as Bloch says, Rabi's team was the first to examine the magnetic properties of atomic nuclei using the resonance method. In 1944, Rabi was awarded the Nobel Prize for Physics for inventing this method, Otto Stern was laureate in 1943, and Wolfgang Pauli was awarded the Nobel Prize in 1945.

Misunderstandings

"The idea that a neutral elementary particle should possess an intrinsic magnetic moment had a particular fascination to me," Bloch continued in his speech, referring to Otto Stern's discovery. But could nuclear spin also be measured in solid or liquid matter? Was the discovery that protons have a magnetic moment only of academic interest or could it be put to practical use? Shortly after the end of World War II, two research groups set out to answer these questions with experiments: one team at Stanford University led by Felix Bloch and another team under the U.S. physicist Edward M. Purcell at Massachusetts Institute of Technology (MIT) and Harvard University. Both groups, Bloch's and Purcell's, knew nothing of the work of the other; both developed novel methods of nuclear magnetic precision measurement and were jointly awarded the Nobel Prize in 1952 for their work. Felix Bloch's team

Otto Stern's successful measurement of the magnetic moment of the proton was an important milestone in the development of magnetic resonance spectroscopy called its method and the discoveries made with it *nuclear induction* while Edward M. Purcell's group summarized its discoveries under the term *nuclear magnetic resonance* (NMR for short). However, when the papers were published in 1946, no one initially recognized that both methods had been exploring the same phenomenon.

When the science community finally began to realize that both groups were describing the same physical properties of atomic nuclei, the reason for the initial misunderstanding soon became apparent: The teams were using different scientific terms to describe their new findings. The terminology used initially differed so much that Bloch and Purcell had difficulty exchanging details about their discoveries when they first met. A simple explanation of their respective research work can be given as follows: Bloch and Purcell had both discovered the principle of nuclear magnetic resonance. Among other things, they were able to prove that atomic nuclei flip in a magnetic field when excited by an electromagnetic high-frequency field. If this high-frequency field is switched off, the atoms release the energy that they have absorbed and return to their initial state. In this process, for which the scientific term is *relaxation*, all atomic nuclei show the same characteristic properties. In other words: Bloch and Purcell had discovered how the phenomenon of nuclear magnetic resonance could be precisely measured. At this stage, no one realized that they had also discovered the technological basis for magnetic resonance imaging. Even the enormous potential for research into matter was not yet obvious shortly after Bloch's and Purcell's discoveries. The only known NMR signal was the nuclear magnetic resonance of water. So it was even more surprising that U.S. American inventor Russell Harrison Varian should immediately recognize the future significance of NMR spectroscopy.



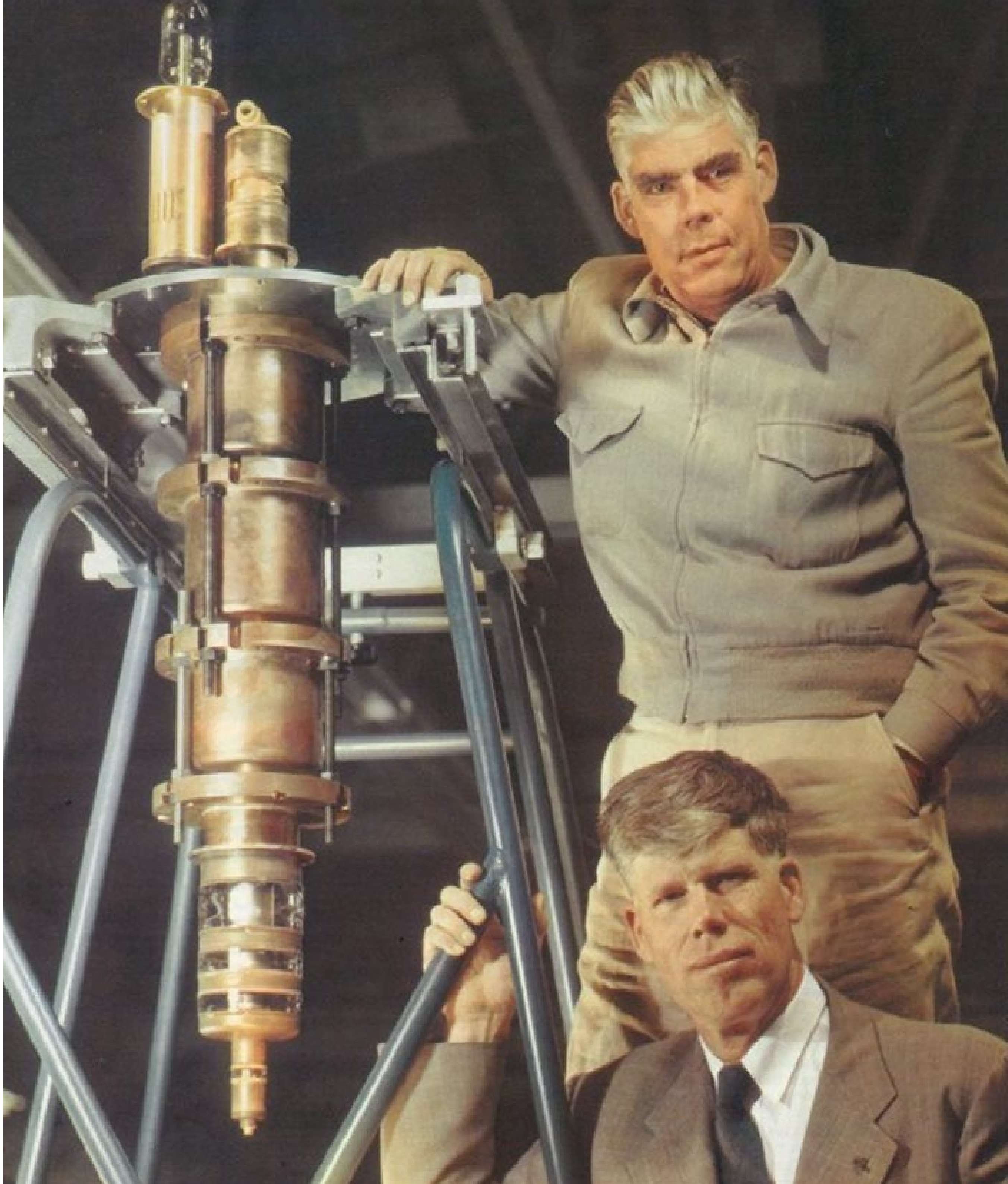
Magnetic resonance in Silicon Valley

Russell Varian had already made a name for himself in the 1930s. The first klystron – a high-performance electron tube for generating microwaves – was based on an idea by Russell Varian, which he realized together with his brother Sigurd and U.S. American physicist William Webster Hansen at Stanford University in California. In 1947, less than a year after Bloch's discovery of nuclear magnetic resonance at Stanford, Russell Varian was working with scientists at the university to improve the klystron. When he learnt of Bloch's work and saw the potential of NMR, he suggested to Bloch and Hansen that they patent the technology. However, Bloch showed little interest. He believed that NMR spectroscopy would only be of interest to a small circle of physicists. Instead, Russell and Sigurd Varian obtained the exclusive license to develop a *method and means for chemical analysis by nuclear induction*.

In 1948, the Varian brothers together with William Webster Hansen and Stanford physicist Edward Ginzton, founded the company *Varian Associates,* one of the first high-tech companies in what is today Silicon Valley. The declared purpose of Varian Associates was defined in the articles of incorporation: "to conduct general research in the fields of physical science of every kind or nature."

Edward M. Purcell's team first coined the term *nuclear magnetic resonance* to describe their methods of nuclear magnetic precision measurement

Initially, the founders assumed that NMR technology would form a cornerstone of the company. However, the trade with klystron tubes was immediately so lucrative that the profits could be used to finance the development of NMR spectroscopy. In 1949, Varian introduced the world's first commercial NMR instrument to the market; three years later, the much-improved Varian NMR spectrometer made the first high-resolution investigations of matter possible. In the decades that followed, Varian continued to lead NMR technology and research into magnetism with numerous inventions. One of the best known was Russell Varian's *magnetometer*, with which the magnetic field of the Earth could be measured precisely for the first time in the mid-1950s.



Russell and Sigurd Varian with their first major invention, the klystron tube

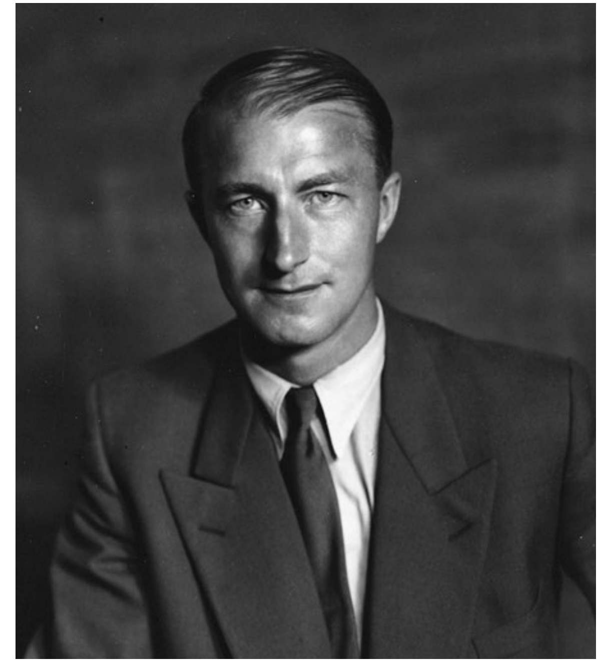
The beginnings at Siemens

Without Varian, the story of NMR technology would no doubt have run a very different course. But in the mid-twentieth century, the focus of the research – both at Varian and in the general scientific field – was almost entirely on the chemical analysis of matter. Only very few researchers thought in terms of medical applications. But even in the early days, curiosity may well have inspired some researchers to examine living subjects using an NMR spectroscope. Felix Bloch, for example, stuck his finger inside the coil of his spectrometer and got a very strong signal. In 1948, Edward M. Purcell even went so far as to place his head, surrounded by a coil, in the 2-tesla magnetic field of a cyclotron belonging to Harvard University. However, the only measurable signal he could identify was the electromagnetic field from his dental fillings. These initially rather lighthearted investigations soon developed into targeted experiments. In the mid-1950s, several laboratories around the world started initial biological research on living cells. Several findings from this era led to a promising yet initially hesitant hypothesis: The phenomenon of nuclear magnetic resonance could also be used in medical diagnostics. One of the few researchers who was entirely convinced of the potential was German physicist Alexander Ganssen.

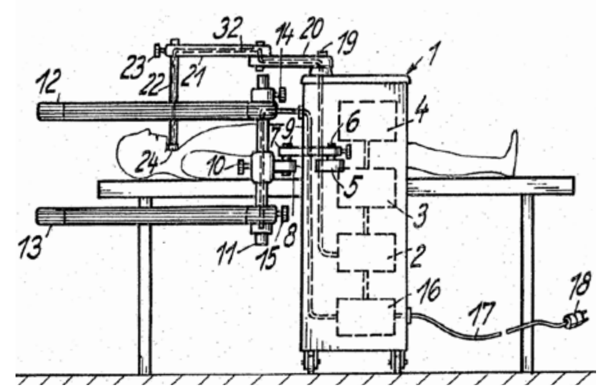
Even as a student, Alexander Ganssen was interested in nuclear magnetic resonance, and he would remain loyal to this field throughout his life. Ganssen referred to Bloch's and Purcell's discoveries in his doctoral thesis of 1949 and from them developed, as the title of his work indicated, a "new method for determining the magnetic atomic relaxation times in liquids." After earning his doctorate, Alexander Ganssen took up a position as a research assistant at the Technical University of Munich in 1953. He then moved to the U.S. for ten years where he also worked with the nuclear magnetic resonance laboratories at MIT and Harvard University until finally joining Siemens in 1965. Ganssen became head of the newly created *Electron Spin and Nuclear Resonance Laboratory* in Erlangen, where he was instructed to research whether and how nuclear magnetic resonance could be applied to medical diagnostics. The title "laboratory head" sounds very grand indeed but in reality Ganssen was the laboratory's sole employee. Still, he received a great deal of support from his colleagues in basic research in Erlangen and other Siemens laboratories.

At Siemens, Alexander Ganssen initially worked in the special area of magnetic resonance, which had already provided the subject of his doctoral thesis: the analysis of liquids. As early as 1965, Ganssen suggested measuring the viscosity of blood *in vivo*– Latin for "within the living." Jay Singer, an electrical engineer at the University of California, had already carried out pioneering work on measuring blood flow on living mice a few years before. In 1967, Ganssen's approach resulted in the world's first patent for a whole-body NMR device that measured blood flow in a patient's carotid artery or arm. To some extent, the concept already anticipated angiography as applied in magnetic resonance imaging of the 1980s. Ganssen was ahead of his time both with this proposal and with the patent that he registered in 1972 describing the concept of contrast medium, which would be introduced 15 years later.

Another NMR device conceived by Alexander Ganssen for analyzing blood, other body fluids, and tissue *in vitro* – that is, in the test tube – was tested by Siemens after 1969 in collaboration with several hospitals and universities. However, the device would never go into series production. The market for such a specialized device was too small; the interest in nuclear magnetic resonance experiments



Alexander Ganssen headed the newly founded *Electron Spin and Nuclear Resonance Laboratory* at Siemens in Erlangen from 1965



Sketch from Alexander Ganssen's patent specification for a whole-body NMR device that measured blood flow in the carotid artery or the arm

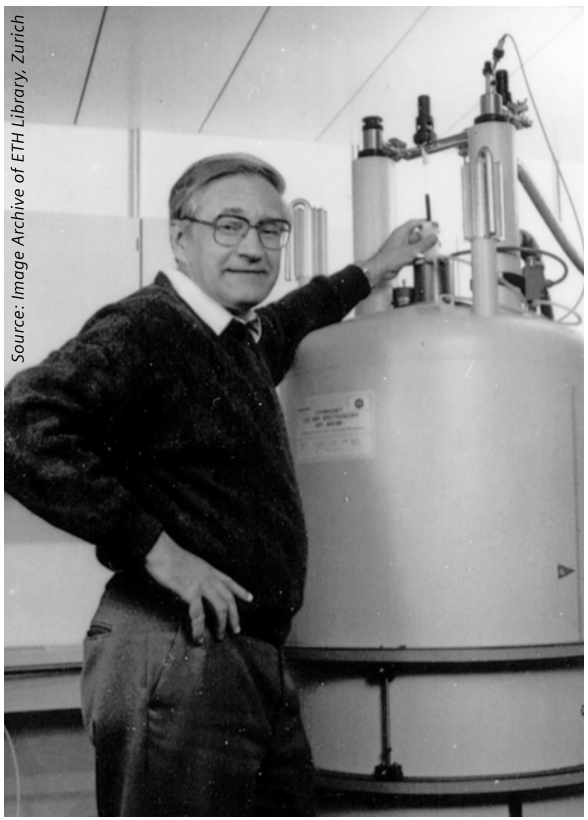
From 1969, Siemens began testing an NMR device for analyzing blood, other body fluids, and tissue in collaboration with several hospitals and universities

in biology is initially largely academic. "We can assume with some certainty," Ganssen stated in his prediction about the long-term development of the nuclear resonance laboratory at Siemens, "that sooner or later, medical applications will be found." The magnetic resonance methods were not so much to be regarded as an alternative to technologies such as ultrasound or X-ray, "but more as an enhancement, which when combined with the methods referred to, can deliver additional information." In this respect, Ganssen would again be proved right, as with so many of his hypotheses in the late 1960s, the most striking being the prediction he made in 1968: "In the field of nuclear magnetic resonance, early detection of cancer currently seems to be especially promising."

It is in no small part due to Alexander Ganssen's tenacity that Siemens started research into the medical possibilities of magnetic resonance so early. At the beginning of the 1970s, there were few signs that magnetic resonance would one day indeed play a significant role in diagnostics. Ganssen was regularly forced to justify his determination. In a report in June 1973, he answers the rhetorical question of why the Siemens Medical Technology Division should continue to engage in nuclear magnetic resonance as follows: "We are concerned with the construction of devices whose task it is to deliver information about the human system. The system elements with which our technology interacts are essentially the atoms from which we are made." This endurance would pay off four years later as we are about to find out. At this time, medical NMR was being developed at various universities from a spectroscopic method into an imaging method. Elements of this story recall Felix Bloch's Nobel Prize speech – because this progress, too, was founded on the harmonious growth of this science.

Wheel of fortune with a pulse

In the late 1960s and early 1970s, it looked as though NMR technology had reached the peak of its possibilities. Many older physicists were of the opinion that the exciting era of magnetic resonance had passed, that the next generation would do better to seek "greener pastures." At the time, it was very difficult to imagine the significance of some discoveries for later magnetic resonance imaging.

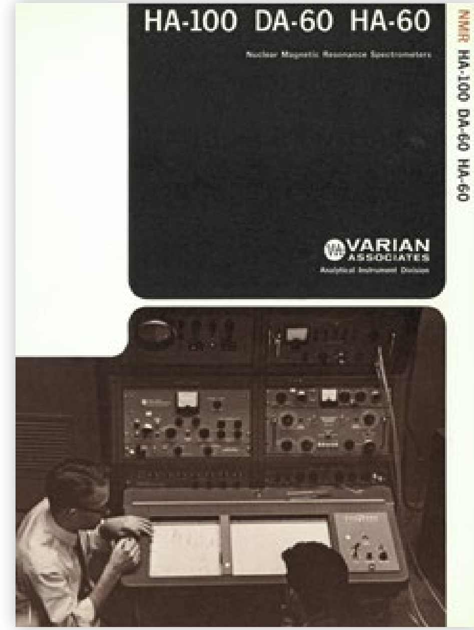


Source: Image Archive of ETH Library, Zurich

Richard Ernst accelerated magnetic resonance data acquisition thousandfold

Erwin Hahn's spin-echo technology, for example, was hailed as "beautiful" and "elegant" but was barely used until the introduction of MRI. Put simply, Hahn's theory posits that the spins in atomic nuclei produce an echo when they are excited with two high-frequency pulses – one of the basic techniques of magnetic resonance imaging.

Another prerequisite for modern magnetic resonance imaging, which was just as significant, was the work of Richard Ernst, for which he was awarded the Nobel Prize for Chemistry 30 years later. When Richard Ernst took up his post at Varian Associates in 1963, the methods for exciting nuclear magnetic resonance were still very ineffective and slow.
In 1964, Wes Anderson, a colleague of Ernst's and NMR specialist at Varian, further developed an idea of Russell Varian's and invented a new method for exciting nuclei: The technology, coined "Wheel of Fortune," in its second, improved version used high-power RF pulses to excite nuclear magnetic resonance and converted the measured signal using so-called Fourier transform. Fourier transform is a mathematical analysis method without which none of the modern tomography imaging techniques would be possible. Richard Ernst implemented Wes Anderson's concept by constructing a pulse spectrometer together with a few Varian engineers in just two months. The idea of exciting an entire spectrum using pulse technology accelerated data acquisition thousandfold. Richard Ernst refined this method together with Kurt Wüthrich at ETH Zurich, where he became a lecturer in 1968 and later a professor. Today, pulse technology combined with Fourier transform is one of the most important basic principles of magnetic resonance imaging.

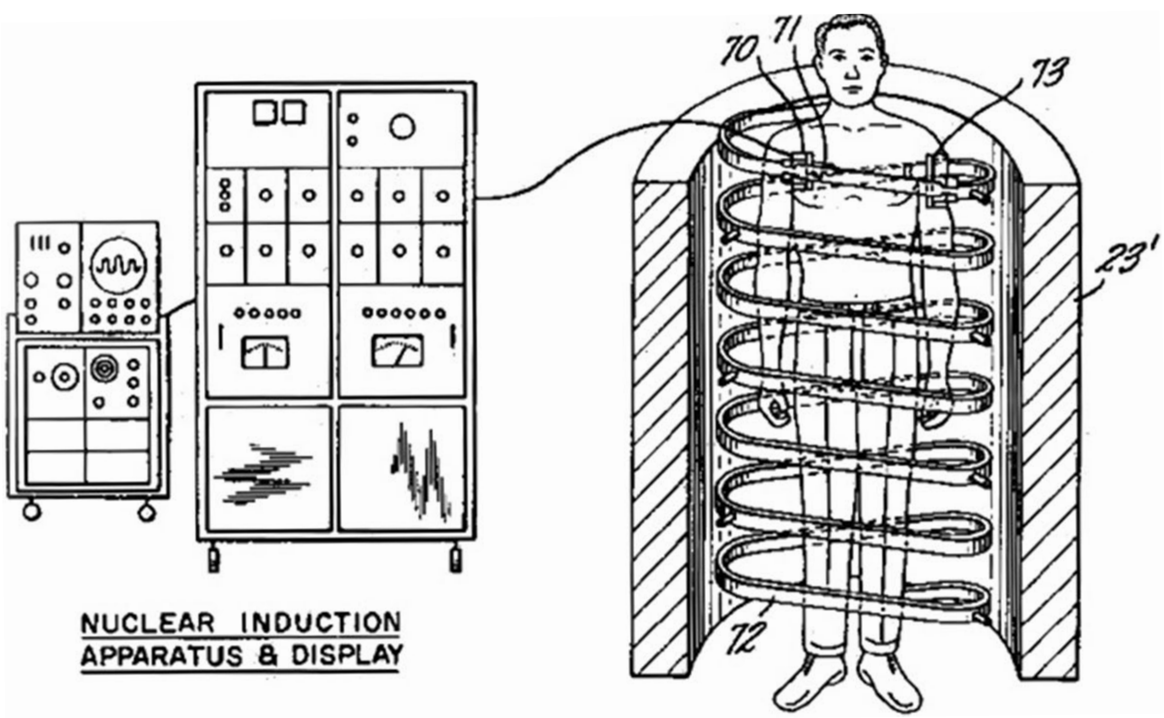


Cover of a Varian Associates product catalog for NMR spectrometers from the 1960s

From the spectrum to the image

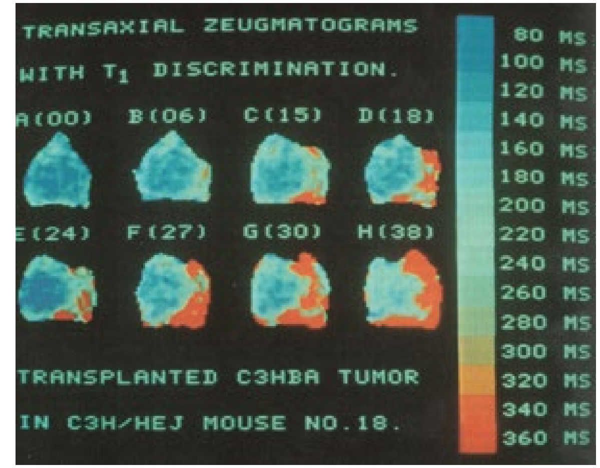
Despite all the excitement surrounding the huge technical advances, the great potential of NMR technology for medicine was still very much undiscovered in the late 1960s. Measuring blood flow velocity seemed to be the only possible application that could exploit the magnetic properties of the human body diagnostically – until a series of ideas and observations heralded a development that around seven years later resulted in the first NMR image of inside the human body. In 1970, U.S. physician Raymond Damadian hypothesized that cancer cells and healthy tissue could be distinguished from one another by measuring the NMR relaxation times. In his experiments on rats, he observed that removed tumor tissue really did have longer relaxation times than normal tissue. Damadian published his research results in 1971 in the magazine *Science*, thereby arousing the interest of other scientists. Further publications led readers to assume that the method was not reliable because the absolute measured relaxation times fluctuated too much to reach a reliable conclusion. Yet, although no absolute relaxation times could be measured, the relative differences were very stable. Damadian's work represented a significant contribution toward highlighting the medical possibilities of magnetic resonance.

In the summer of 1971, U.S. American chemist Paul Christian Lauterbur was given the opportunity to observe such cancer experiments on tissue samples from rats. Fascinated by the rich diversity of information that an NMR analysis of tissue uncovered, Lauterbur asked himself: "Might there be a way of locating the precise origins of NMR signals in complex objects?" That same evening, while eating a hamburger in a Big Boy restaurant, Lauterbur had a sudden brainwave that would eventually earn him a Nobel Prize: If an homogeneous magnetic field was overlaid with three gradient magnetic fields, could the spatial coordinates be measured and images calculated from them? "I was so sure of this that I immediately went out and bought a notebook and had the idea witnessed."

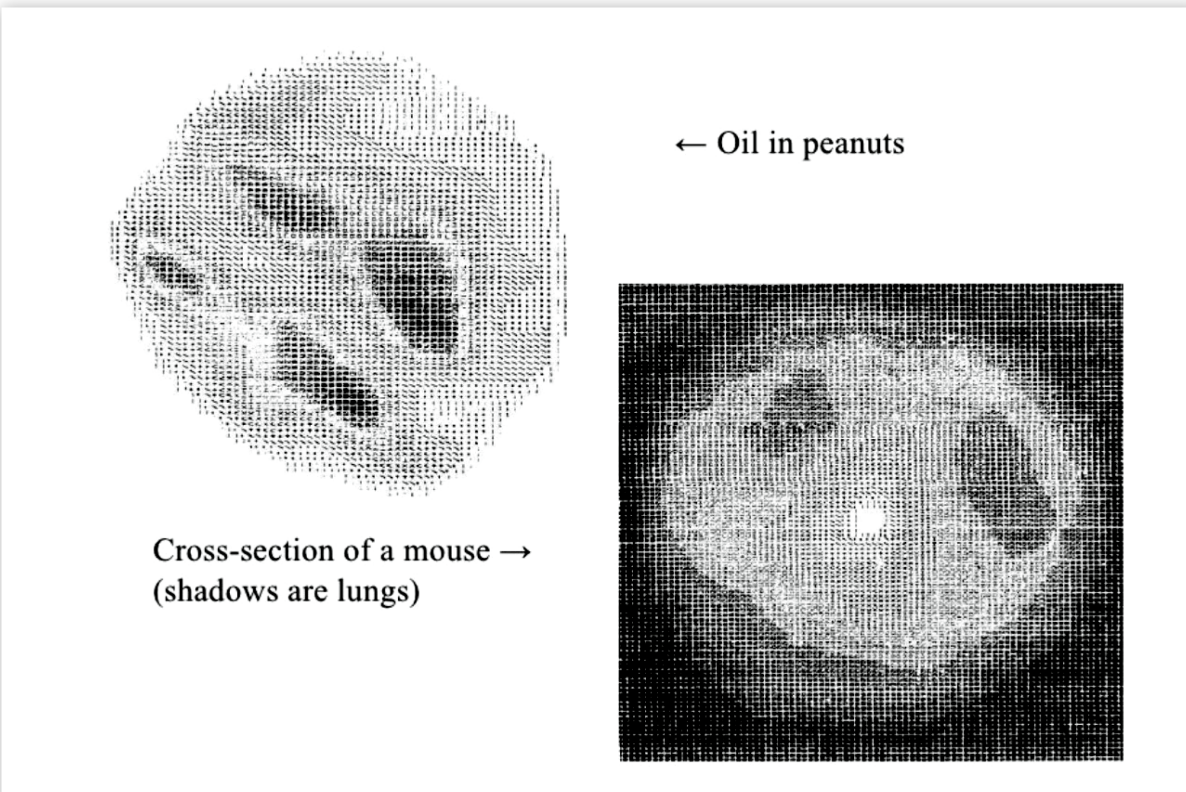


Concept for a whole-body NMR scanner from Raymond Damadian's patent submitted in 1972

Still, initially, Lauterbur could not convince anyone of his idea. For many months, he experimented with a Varian A-60 spectrometer and arranged the gradients at different locations in the magnetic field, until he finally succeeded in acquiring the first image in the history of magnetic resonance imaging: the image of water in a test tube. He called his method *zeugmatography*, derived from the Greek word *zeugma*: "that which joins". In October 1972, Lauterbur submitted his final draft for publication in the magazine *Nature* but had difficulty convincing the editors that his work really was relevant. After a protracted correspondence, Lauterbur's gradient method finally appeared in the March edition of 1973. A short time later, when the first images of live animals were acquired, it was the tiny magnets used at the time that placed limits on the method. First, Lauterbur acquired images of the soft tissue on the inside of a four-millimeter clam placed inside a test tube five millimeters in diameter. The famous images with which Lauterbur observed the growth of a tumor in a live mouse over several weeks were produced in 1974 using an optimized Varian DA-60 spectrometer with a magnet five centimeters in diameter. "Thus, it was beginning to seem plausible that at least some cancers should be detectable by NMR imaging techniques in human patients."



In 1974, Lauterbur observed the growth of a tumor in a live mouse over several weeks using an optimized Varian DA-60 spectrometer

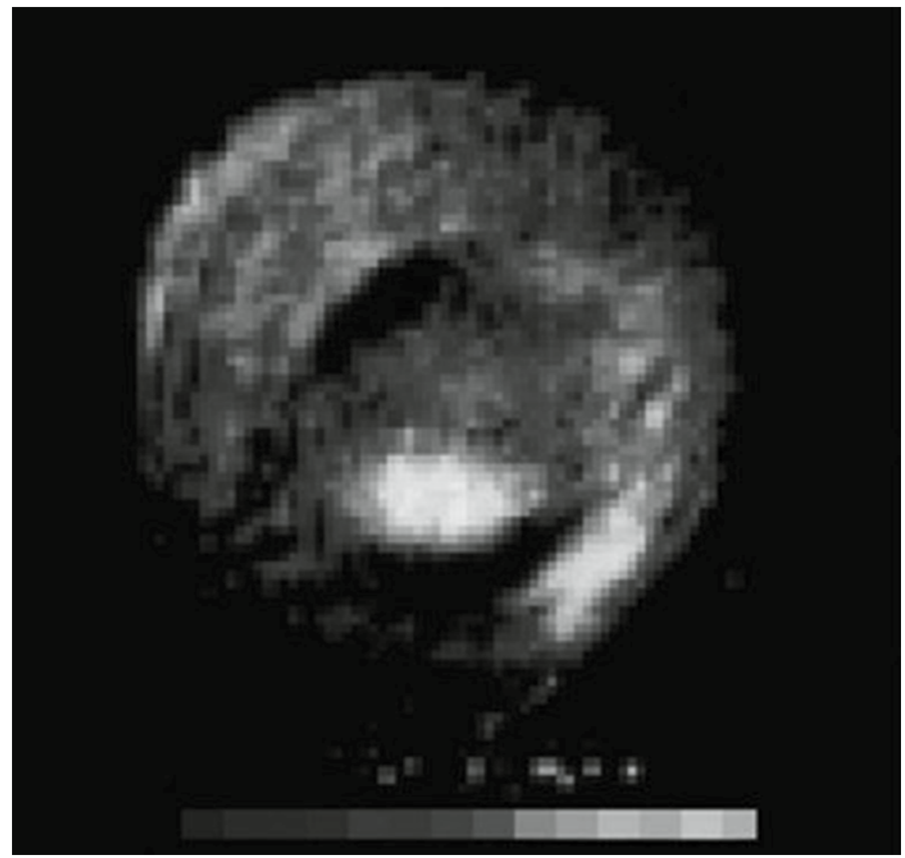


On March 16, 1973, the magazine *Nature* published the first images in the history of magnetic resonance tomography that were produced by Paul C. Lauterbur

A similar approach to that of Paul C. Lauterbur was being followed at the same time by the British physicist Peter Mansfield. Mansfield, like Lauterbur, had the idea of imposing gradient magnetic fields on the main magnetic field. When Mansfield heard of Lauterbur's work in 1974, he combined both approaches with a technique of his own, which is still one of the fastest measuring methods in magnetic resonance imaging today: *Echo-planar imaging* excites nuclear magnetic resonance by rapid switching of the gradients. Assuming that powerful computers were available, an image could be acquired in this way in just a few milliseconds with a single excitation. With four kilobytes of RAM, Mansfield's computer could produce nothing like this measuring speed, but he nevertheless managed to acquire a spectacular image in 1976: the finger of Mansfield's student Andrew Maudsley was the first magnetic resonance image of a living person.

In 1977, Andrew Maudsley used a slightly larger magnet and was able to make the nerves, arteries, and other tissue of a human hand visible. The potential of magnetic resonance technology was becoming ever more apparent. Meanwhile, at Siemens in Erlangen, plans were underway to build a magnetic resonance scanner. Andrew Maudsley will cross our path again during this story, as will Paul C. Lauterbur, Sir Peter Mansfield, and, of course, Alexander Ganssen.

The first magnetic resonance image of a living person: the finger of Peter Mansfield's student Andrew Maudsley



Peter Mansfield further developed Paul C. Lauterbur's gradient technique and significantly accelerated the measurement method with his invention of echo-planar imaging. In 2003, both scientists were awarded the Nobel Prize for Medicine.

“Ping, the magnet just switched itself off”

The “patient” from the fruit and veg shop and the prototype of the first MAGNETOM

Erlangen, February 2, 1978: On his second day at Siemens, physicist Arnulf Oppelt was sitting behind his desk when suddenly the head of imaging development, Friedrich Gudden, walked into his office. Gudden, who knew Oppelt from their days together at TU Darmstadt, noticed his new colleague and asked: “What are you doing here?” Oppelt, somewhat surprised, replied: “Well, I’m supposed to be looking into zeugmatography.” Gudden retorted: “Well, you can forget that! We’ve got no time for that sort of nonsense here.” That was, Oppelt recalled around 40 years later, just Gudden having a joke – the plan to develop the first magnetic resonance imaging scanner in the history of Siemens Healthineers was already a done deal.

About 18 months earlier, in the summer of 1976, the plan to build a magnetic resonance imaging system had started to take shape. Alexander Ganssen used his connections and reached out to subsequent Nobel Prize laureates, Paul C. Lauterbur and Peter Mansfield. First, Ganssen visited Lauterbur in New York; six months later, Lauterbur came to Siemens in Erlangen and, among other things, showed his famous images of living mice. “From these images produced over the last two years in Professor Lauterbur’s lab,” Ganssen concluded in his report that “we are still in the relatively early stages of development of this technology, but it opens up new possibilities for imaging living organisms, which until now could not be achieved by any other method.”

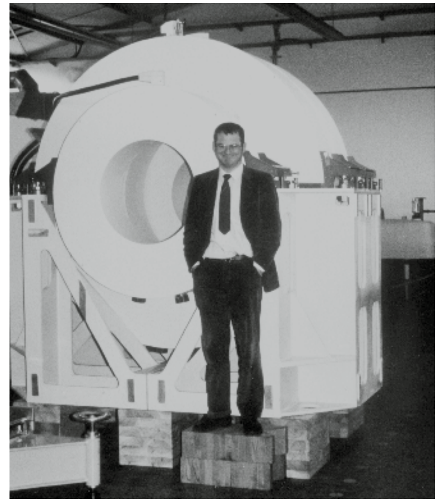
A trip to Nottingham to Peter Mansfield’s laboratory gave Ganssen further cause for optimism. Mansfield showed him sectional images of a rabbit’s head, which had been scanned in 20 minutes and already revealed significant tissue detail. “The men I spoke to there were in no doubt that this method could also be used to visualize larger body regions with good spatial resolution,” Ganssen reported on his return in June 1977. At a meeting in Erlangen on November 17, Mansfield recommended using a magnet from Oxford Instruments, which he also used in his laboratory. The meeting was also attended by Oppelt, Ganssen, Ganssen’s boss Rudolf Schittenhelm, Schmitt, and Kuckuck from the Siemens research laboratory – and Mansfield’s former PhD student: Andrew Maudsley. After gaining his doctorate under Mansfield, Maudsley worked with subsequent Nobel Prize laureate Richard Ernst on two-dimensional spectroscopy for a year in Zurich and is arguably one of the most experienced pioneers of magnetic resonance imaging. Ganssen persuaded Maudsley to leave ETH Zurich and join the Siemens Medical Technology Division in Erlangen. Paul C. Lauterbur and Peter Mansfield also worked together with Siemens as advisers over the next few years.

The first MRI measuring system at Siemens in 1978

Transfer to the wooden hut

“Dr. Ganssen was our resident nuclear magnetic resonance expert who time and again pointed us to the experiments being performed around the world,” Friedrich Gudden later wrote in his memoir about his time as head of development at Siemens Medical Systems. “He found an ally in Dr. Schittenhelm, who recruited Dr. Oppelt from Darmstadt in 1978 to work on foundational developments in magnetic resonance imaging – a real stroke of luck.” Friedrich Gudden and Rudolf Schittenhelm initially had to stave off some strong opposition. Some colleagues would have preferred to invest the two million German marks (DM) development costs in computed tomography. Once Oppelt and Maudsley joined the company on February 1, 1978, however, practical development of the first prototype could finally begin. Ganssen had overall responsibility for the project, Oppelt was in charge of hardware development, while Maudsley wrote the software

The first MRI research laboratory made of wood, photographed in 1979



Arnulf Oppelt next to a 0.2-tesla whole-body magnet that the Siemens research lab constructed for the first clinical installation in Hannover

The pilot system with Faraday cage for shielding radio-frequency waves

for image reconstruction and component control. The core team – Oppelt and Maudsley – was backed by physicists, engineers, and electronics engineers from the Siemens research center.

When Arnulf Oppelt embarked on his work, the large 0.1-tesla magnet from Oxford had already been ordered but would not arrive for another several months. He initially had to resort to the components used by Alexander Ganssen in his earlier experiments. In Ganssen's laboratory, Oppelt found a pulse generator and a small electromagnet weighing around one metric ton that was just large enough to insert a test tube or a finger. "I connected it all together, pestered an electronics engineer until he had built me a preamplifier, and two months later I was able to demonstrate the first NMR-pulsed signal."

Ganssen's laboratory magnet was the temporary equipment used by Oppelt and Maudsley to test the other components until the magnet arrived from Oxford. The engineers from the central research laboratory designed the gradient coils and power supply, while colleagues from the Siemens Medical Technology Division developed the radio-frequency equipment, the control, and the software. The entire process required a great deal of persuasive effort throughout, Oppelt recalled, because in those early days everyone had their own ideas about how results could best be achieved. Everyone agreed on where the first prototype should be built: In order to avoid interference with the magnetic field, Siemens built a wooden hut devoid of magnetic parts on the grounds of the central research laboratory. Not one single iron nail was used in its construction!

After the move to the wooden hut, Peter Mansfield again paid a visit to the team in Erlangen, bringing with him the first thorax images captured by Raymond Damadian in 1977. In order to be able to visualize large regions of the human body accurately, the magnetic field must be extremely uniform, in other words, homogeneous. And this homogeneity must be measurable. In the search for a measuring technique, many ideas, which would now be deemed impractical, were considered. Probably the most unusual suggestion: A robot, for which a basic design was already available in the Siemens research lab, equipped with a long rod and a probe was to scan the magnetic field point by point. Oppelt and Maudsley, however, agreed to build upon a method that Maudsley had learned during his time with Richard Ernst in Zurich. They developed a two-dimensional imaging technique where the magnetic field is analyzed by means of NMR spectroscopy. This pioneering feat was largely ignored when it was first described in a German scientific publication but is known today as *spectroscopic imaging*.

Practical solution

Andrew Maudsley also developed an imaging technique that scanned objects row by row rather than point by point. In a later, improved version, Maudsley's program was even able to measure several rows at once. "He even got it to run on the laboratory magnet," Oppelt recalls. But in early 1979, Maudsley left Siemens to head superconducting magnet development at Columbia University in New York. "It was left to me to take all our electronics, including the computer and the rest, into the wooden hut at the central research laboratory and install it." Once there, however, Maudsley's program would not run for some unknown reason. Oppelt did not have much experience of programming computers. Even a mathematician brought in especially to find the bug could not help. Together with Maudsley's successor, physicist Wilfried Loeffler, Oppelt found a solution to the problem: "We'll put it to one side for now and look again at the method for measuring the magnetic field." An extremely practical solution as it would turn out, because this technique offered an option that they could build on: It not only measured homogeneity but also the spatial distribution of the spins in the magnetic field.

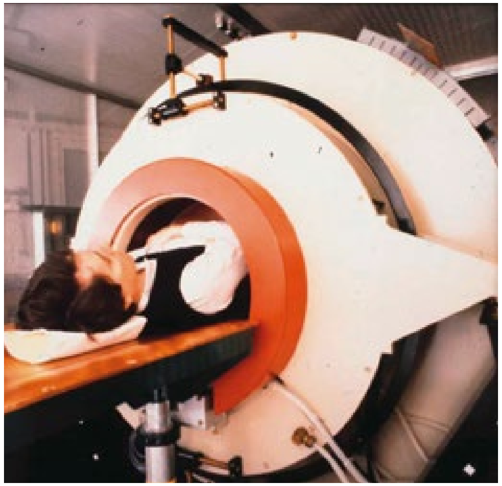
Loeffler, who had two years' experience working in computed tomography at Siemens, first had to familiarize himself with Maudsley's software and then modify and improve it. By mid-1979, the first pilot system had been assembled in the wooden hut and was operational, "but we didn't get any images."

Since the frequency of nuclear resonance is in the same range as radio waves, Oppelt and Loeffler also picked up signals, for example, from Australian shortwave radio stations. So they built a Faraday cage, an enclosure made of electrically conductive material that electrically shields the interior. Yet, according to Loeffler, "this thing that we'd cobbled together" had two weaknesses: The cage was made of aluminum, a material that we now know is not at all suitable for the task. Even worse than that, "we had put a hole in it to lay the cables to the magnet. And that was practically like an antenna for picking up interference." The problem could in fact have been easily solved with a filter, which the Siemens Energy division had in its portfolio; but weeks, even months would pass before one could be delivered.

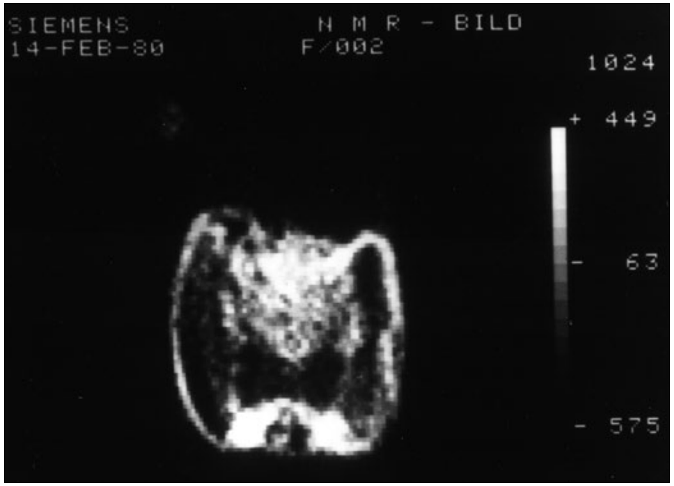
The "patient" from the fruit and veg shop

"We didn't want to just sit back and wait," explained Oppelt, "so we continued programming and thought up new pulse sequences, for example." The noise was still in the images – and November 1979 was steadily approaching. Oppelt and Loeffler were expected to provide reproducible results before the budget review the following year. And this meant: an image. Arguing that they were still waiting for a filter would not have been accepted. It was up to Oppelt to think of something. "So, I said to Wilfried Loeffler: No problem. We'll just scan for a very long time, again and again, and then average out the disturbance." For an acquisition time of several hours, the two of them needed a measurement object that remained still, that had a structure, and that could be cut open to show that the image really does visualize the internal structure. "We needed something that contains water," Loeffler recalls.

So, they drove Mrs. Loeffler's VW Beetle down to the local fruit and vegetable shop and purchased a large, juicy green bell pepper. "We placed it in the prototype and said: OK, now let's set the thing to scan for



Wilfried Loeffler inside the pilot system, 1980



The reconstruction of the bell pepper dated February 14, 1980 two hours." Scanning lasted from the late afternoon into the evening. Of course, Oppelt would reminisce later, it was fairly boring just sitting there watching while the machine rattled away. Whenever the gradients switch, magnetic resonance imaging produces that characteristic knocking noise. "Why not get a couple of beers from the local supermarket," Oppelt suggested. The six-pack of beer helped while away the time until the measurement was completed and "lifted our spirits considerably." When Ganssen, who was Oppelt's and Loeffler's immediate boss, rang to inquire how things were going, they both told him that he would have to wait a little longer. Shortly after, Ganssen's boss Schittenhelm and then Schittenhelm's boss Professor Gudden also rang, "but he, too, was told to wait". By the evening, all the data had been collected. Oppelt and Loeffler planned to calculate the images the next morning and went home.

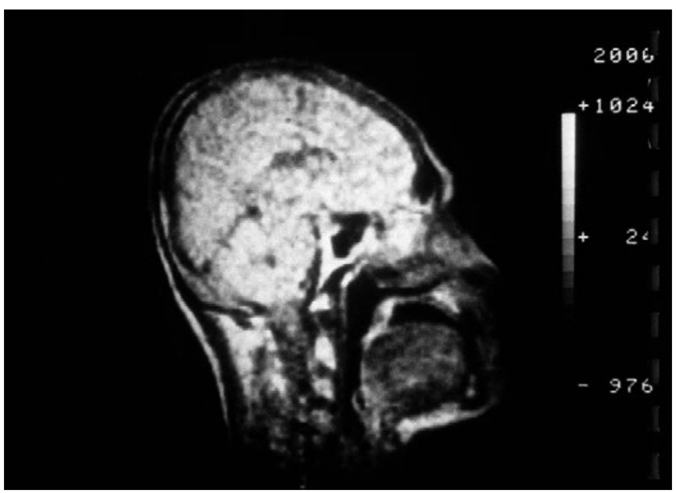
"The next day we reconstructed the image and got quite excited. We showed it to our bosses and they were even more excited. The bell pepper had got everyone excited!" It became immediately obvious that Oppelt and Loeffler had to continue with their work. The MR image of the bell pepper has since been reproduced in numerous publications, most of them showing the date February 14, 1980. In fact, the image was taken in November 1979; however, the first reconstruction showed a small image error. "A band ran across the image," Oppelt explained. "We eliminated the error and then reconstructed the data. That's why you see 1980 in the image."

Uncomfortable head images

After the successful image of the bell pepper, the pilot system was used to perform the first scan of a part of the human body was performed on March 14, 1980.

Against this general mood of excitement, the team had no difficulty in finding a willing volunteer. "Dr. Ganssen was extremely eager and nimbly crawled into the prototype and placed his head inside," Oppelt recalled. But Ganssen could not be subjected to two hours of scanning – like the bell pepper – and certainly not in this uncomfortable position. The data for the first image of a head were collected in twenty minutes and then reconstructed. However, without a filter, the results were rather disappointing. "So we designed a patient table," Oppelt explains, "on which the volunteer could lie and remain still." At last, in spring 1980, the long-awaited filter arrived in Erlangen. In the weeks that followed, multiple head images, which could be evaluated clinically, were captured and then presented by Oppelt at the annual conference of the German Society for Neuroradiology in the summer of 1980.

"Of course, the image quality was not that great," Oppelt remembers about his presentation. "The neuroradiologists were very 'wait and see'." They were familiar with computed tomography images – but this was something new." The huge advantage of magnetic resonance imaging had not yet been recognized. Just six months later, however, the extraordinarily high contrast in the head images was becoming more and more apparent. When Wilfried Loeffler presented magnetic resonance imaging as a new technique at the German X-ray Congress in October 1980, the latest images attracted considerable attention. "In 1979, there was probably still a lot of skepticism surrounding magnetic resonance imaging," Loeffler recalls. "However, during the course of 1980, it became increasingly clear that a new diagnostic method would evolve from it."



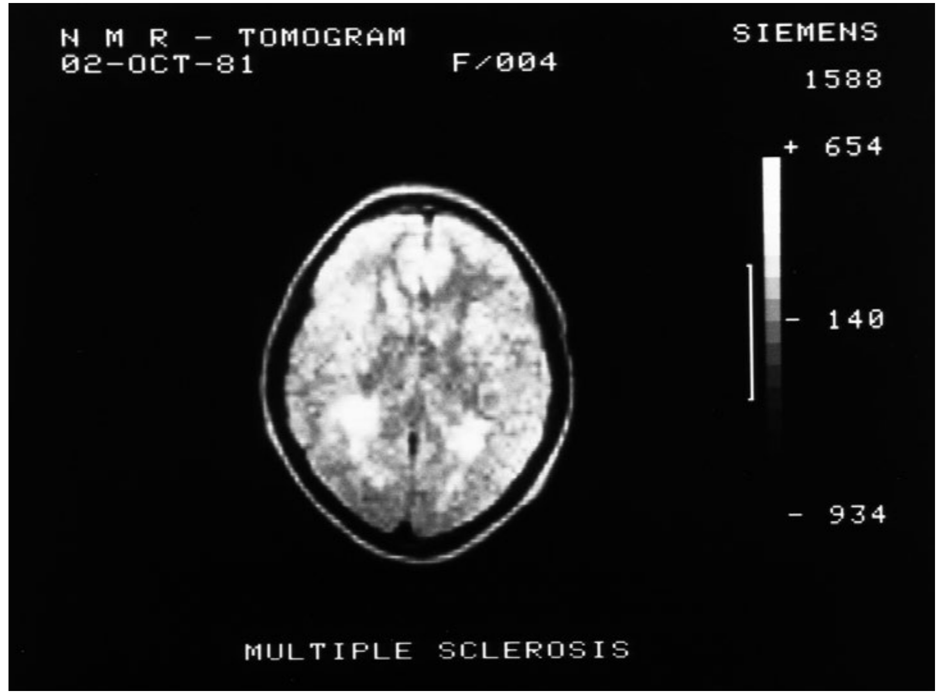
In early 1980, scanning Alexander Ganssen's head took around 20 minutes

Arnulf Oppelt's head inside the pilot system, 1980

Carola Wölfl preparing clinical tests in the spring of 1981

Flush with care!

Early in 1981, Siemens decided to further develop the prototype with a new magnet from Oxford Instruments, this time with double the field strength, 0.2 tesla. It was now time to move development from the wooden hut to a laboratory hall. “And when the system is up and running, we can also examine patients from local doctors’ practices.” Physicist Eckart Stetter and radiographer Carola Wölfl now joined the team. Stetter wrote the routines for the examination software, Wölfl performed the examinations and assisted Stetter with the programming. When the clinical tests finally got underway, a problem occurred on the second prototype that no one had expected: “When doctors and their patients came,” Oppelt recounted, “they sometimes had to go to the bathroom and when they flushed – ping, the magnet just switched itself off.” The pressure in the pipes was no longer sufficient to supply the water for cooling the magnet. “We then always made sure that anyone going to the toilet flushed very gently.”



By 1981, it was already possible to detect inflammatory foci in the brain using magnetic resonance imaging

Every day, Oppelt went to work early to switch on the magnet because “it took at least half an hour to become stable.” With an output of 70 kilowatts – about 40 times the output of an average radiator – the system increased the temperature in the laboratory hall in the winter of 1981 from “very cold” to “comfortably warm.” By this time, the prototype was operating largely without problems. The examinations that Siemens performed on patients over the years with the help of the Universitätsklinik Erlangen and Klinikum Nürnberg Nord hospitals, confirmed what by now were very high expectations of the new technique. “The potential of magnetic resonance imaging for diagnostic use became apparent when we detected the first tumor in the image of a head,” Arnulf Oppelt recalls. According to Wilfried Loeffler, a “more or less accidental discovery” clearly demonstrated the enormous power of MRI: The examination of a young patient with multiple sclerosis had revealed inflammatory foci in the brain. But “initially none of us was at all aware” that at this time it would not have been possible to detect multiple sclerosis with any other technique.

The light marker is used to position the patient correctly

Introduction to hospitals

In 1980, it was slowly becoming clear that magnetic resonance imaging could become a practical diagnostic method; by 1981 this expectation had become a reality. Siemens decided to establish product development for a magnetic resonance imaging scanner within the Computed Tomography division. On April 7, 1982, Peter Grassmann, head of development for computed tomography, and now also for magnetic resonance imaging, announced that the Magnetic Resonance Business Unit (initially known as NMR) was to be set up. “CT remains the method that – in medical terms – is increasingly being used,” Grassmann wrote in a memo to his employees. “Nevertheless, we believe that NMR has a long-term future alongside CT imaging.”

While the MR Business Unit was in the process of being set up, Oppelt’s team working on foundational development made plans to install an MRI scanner in a hospital. An advanced version of the prototype was to be tested under clinical conditions at the Hannover Medical School (MHH) for suitability in daily routine. Yet, in early 1982, the system was still nowhere near clinical maturity as patients still had to crawl into the magnet using a plank. An experienced design engineer from Siemens developed the first two-way motorized adjustable patient table for the system in Hannover. The patient could lie on the patient table, be automatically lifted to the height of the magnet bore and positioned at the correct location inside the magnet using a light marker. During this time, the team developed the first body coils to improve the signals emanating from inside the patient. “In the beginning, we had only one large coil,” Wilfried Loeffler recalls. “From the test tube MRI, we knew that the better the coil is adapted to the object, the better the signal-to-noise ratio." First, the team constructed a receiver coil for the head, followed a little later by more surface coils for other regions of the body. "That was relatively new in those days, today it's standard."

In early 1982, the magnet of the prototype had not yet reached clinical maturity either. "It was more like a laboratory magnet," Arnulf Oppelt explained. "That's why the central research unit offered to construct a proper professional magnet for us with oil cooling." With support from the German Federal Ministry for Research and Technology, the Siemens research center developed an oil-cooled normal-conducting 0.2-tesla magnet, which was then installed at the nuclear medicine department of the Medizinische Hochschule Hannover under the technical leadership of Eckart Stetter. The examinations of more than 800 patients performed there provided valuable experience with practical handling as input for product development. In the meantime, Wilfried Loeffler was now in charge of a group of physicists in product development, who optimized the imaging technique. "My work moved away slightly from actual software development and collaborative tinkering with Arnulf Oppelt toward writing algorithms and pulse sequences for the first MAGNETOM." While Oppelt and Loeffler had had to resort to many bought-in components in the foundational development phase, the era of in-house product development started with the advent of the MAGNETOM. "If I have everyone who understands the components in every detail in my department, I can better coordinate the components," Loeffler explained the reason for his decision in 1982. One of the few components that was not being developed at Siemens at this time would continue to be supplied by Oxford Instruments in England: the magnet.

From normal to super

Until this time, magnet technology used normal-conducting resistive magnets, in which the magnetic field was generated by large, current-carrying coils made of aluminum or copper. With the iron yoke required to shield or provide a return path for the magnetic flux, such a magnet could easily have a mass of more than 30 metric tons. Each increase in field strength of 0.1 tesla would increase the mass of the magnet by around two tons. Larger magnetic fields required a drastically increased current and for the coils to dissipate even more heat. In other words, the maximum achievable field strength was limited by the energy requirement of the magnet. In practical terms, a normal-conducting magnet could only be used up to a field strength of 0.2 tesla. As the magnetic resonance signal increased with the magnetic field strength, it was hoped to achieve strengths of 0.5 or 1.5 tesla in the next magnet generation. A technically practical solution for achieving these field strengths was to use super-conducting magnet coils.

Superconducting means that the wires of the magnet coil do not offer any electrical resistance at temperatures below minus 269 degrees Celsius. To reduce the temperature of the wires to this low temperature, they are cooled with liquid helium. In addition, liquid nitrogen is used to shield the helium so that it not heated up by outside thermal radiation and evaporate too quickly. In 1982, Peter Grassmann noted: "Although Siemens has wide experience in the construction of super-conductors and Siemens magnets have been in successful operation in many large research facilities for a number of years (for example, at the CERN in

In 1982, Siemens decided to place magnet development in the competent hands of Oxford Instruments

Geneva), we have decided not to develop such a magnet but instead use the magnet from Oxford Instruments." Our experience in magnetic resonance imaging and the experience of this company will be combined in our MAGNETOM systems, he continued. "This reflects our confidence in the state of development of Oxford Instruments."

The magnet specialists from Oxford had already started developing superconducting magnets in 1977. Five years later, when Grassmann announced the decision to use Oxford Instruments, the company was supplying around 300 superconducting magnets for analytical magnetic resonance annually. The superconducting material that Oxford Instruments was using came almost exclusively from a vacuum melting plant belonging to Siemens in the German city of Hanau. Even back in the early 1980s, superconducting magnets could be operated for several years without interruption. They have, as Grassmann mentioned in his forecast, only one marked disadvantage, which is that they are much more expensive to procure than normal-conducting magnets. "We have nevertheless decided to prioritize better image quality over procurement costs for our magnetic resonance imaging systems."

In August 1983, the first commercial MAGNETOM began operation at the Mallinckrodt Institute of Radiology in St. Louis

The MAGNETOM and the Röntgen prize

The first commercial MRI system from Siemens, the MAGNETOM GBS 1, was already based on a superconducting magnet from Oxford. GBS is short for the German term "Grundbausatz" meaning "basic construction kit." When the system began operation at the Mallinckrodt Institute of Radiology in St. Louis in August 1983 after an installation time of just under three months, the magnet operated with a field strength of 0.35 tesla. "It was actually a 0.5-tesla magnet," Loeffler explained, "but we reduced it to 0.35 tesla because of our initial caution regarding possible interference at higher frequencies." In the first MAGNETOM series manufactured between the beginning of 1983 and mid-1984, the magnet was not yet actively shielded. The strong stray field made extensive structural measures necessary to prevent incoming and outgoing interference. However, the Munich radiologist Hansjörg Heller who received the first 0.5-tesla MAGNETOM at the end of 1983, was prepared to shoulder the building costs: "Well, I couldn't very well move to the outskirts of town. No one would have come in if I had."

Following Eckart Stetter's installation of the prototype with a normal-conducting magnet at the Hannover Medical School, work in MR foundational development concentrated on improving image quality, extension of the pulse sequences to visualize different image contrasts, and accelerating image acquisition. Further prototypes were also to be developed with field strengths ranging from 0.23 tesla to 1.5 tesla. In 1986, Arnulf Oppelt wrote a report summarizing this work, for which he was awarded the German Röntgen prize in the same year.

The 0.35-tesla model of the first MAGNETOM weighed around 5.3 metric tons and required at least 95 square meters of space. The 1.5-tesla model that followed slightly later weighed roughly 7.3 tons and required 140 square meters

Journey to new frontiers

A story of mobile MRIs, flying wrenches, and levitating trolleys

The founding of the MR Business Unit presented many employees at Siemens with entirely new challenges. The Siemens Medical Technology Division – as the healthcare division of Siemens AG was known at the time – specialized primarily in the development and production of CT scanners, X-ray machines, ultrasound systems, and nuclear medical imaging devices. Although the team's experience in CT technology aided in the development of hardware and software for image generation, the physics of MRI technology differ fundamentally from the principles underlying the other imaging methods. The employees responsible for establishing the new business unit had to reassess and learn many things from the ground up. The solutions they concocted were by turns strange, complicated, or far ahead of their time – and time and again, they were called upon to demonstrate both patience and their powers of persuasion.

"Suddenly we were being asked to measure magnetic fields and build high-frequency systems and coils – and we needed to be able to test them, too," recalls Peter Scheuering, who, at that time, was a young engineer working in test planning for quality assurance. "Our background was in X-rays, and we were specialized in low frequencies and high voltages. Then the MRI came along and all of a sudden we needed high currents and high frequencies." The testing devices used up until then generally only cost around 100 German marks (DM) for the components in addition to a few hours' assembly work. Now, quality assurance for MRI devices required testing equipment that was a thousand times that price.

Examination at the Charlottenburg Hospital in 1983

The iron shielding significantly reduced the magnet's stray field, but weighed over 30 metric tons

Streetcars and flying wrenches

MRI technology also changed the kind of work that was performed in hospital radiology departments. Staff now needed to account for details that did not factor into any other medical imaging technique. For instance, anyone who came too close to one of the early MRI systems holding audio or video cassette tapes or magnetic tape would find afterwards that their tapes had been erased. Pushing a hospital bed past the examination room could alter the magnetic field of the MRI system and impact the image quality. Wrenches and plyers would fly out of technicians' pockets to the MRI scanner, and the magnet would refuse to hand them over again without a struggle. Ordinary tools made of magnetizable iron were pulled toward the device with a force several times their weight. Confoundingly, this happened with very little prior warning. At a distance of two meters from the magnet, you might feel a gentle tug but just ten centimeters closer and it was a challenge to hang onto any tools at all.

When planning the MRI room, all potential sources of interference had to be accounted for. Moving elevators, steel cabinets, and power cables all disrupted the magnetic field. Streetcars and trains moving past at a distance of any less than 50 meters from the magnet were particularly troublesome. Even the very first systems that operated with a field strength of "only" 0.35 tesla presented significant challenges for interior designers. Increasing the field strength to 1.5 tesla meant that components such as the control panel or peripheral devices such as monitors and hard drives needed to be kept at least twice as far away from the magnet. One solution for shielding the magnetic field, introduced in 1984, was highly efficient yet extremely cumbersome: this so-called direct shielding was made of iron and weighed over 30 metric tons.

"MAGNETOM with direct shielding: The best solution for installing an MRI system in existing buildings"

The idea behind this shielding solution was to attenuate the magnetic fields outside the magnet using a thick iron shell. This iron shielding decreased the size – and therefore the strength – of the magnet's stray field by a factor of five. However, the heavy structure required hospital floors to meet exacting standards that would have been extraordinary even for industrial buildings. The magnet of a 1.5-tesla system weighed around 7.3 metric tons in 1984; combined with the iron shielding, the MRI had a total weight of approximately 38 metric tons. Normal floors are designed to support a weight of 500 kilograms per square meter, while industrial floors can accommodate two metric tons per square meter – the direct shielding required floors to have a load capacity of seven metric tons per square meter. For new hospitals, it was possible to design rooms for these types of MRI systems during the construction process. But in many cases, it was impossible to install them in existing hospitals.

And it would be nearly five years until another idea would reduce the weight of the magnetic shielding considerably. So, how could hospitals without the requisite space or floor load capacity take advantage of MRI technology in the mid-1980s?

Magnetic resonance on wheels

The idea to bring mobile MRI systems to customers produced the concept of a truly extraordinary kind of radiology clinic. Siemens outfitted semi-trailers as complete MRI units equipped with the same examination, analysis, and operating equipment as a "real" hospital ward. All the semi-trailers were fitted with air suspension to protect the highly sensitive magnet technology on journeys over bumpy roads. In spring of 1986, the first MAGNETOM systems rolled through the USA, where they were used primarily by smaller hospitals that needed to accommodate a high number of patients.

Under a new name

As mentioned in the previous chapter, the MR Business Unit of Siemens was officially known as the *NMR Business Unit* (Nuclear Magnetic Resonance) in the mid-1980s. Paul C. Lauterbur's term *zeugmatography* was never truly embraced on a larger scale. For over three decades, the most widespread designation for all technologies and procedures applying the phenomenon of nuclear magnetic resonance in analytical methods was the abbreviation NMR. As the medical application continued to spread and become more commonplace, a growing number of specialists dropped the term *nuclear* from the name, as MRI technology had nothing to do with nuclear energy. The convention of referring to the medical application of this technology as *magnetic resonance* or *magnetic resonance imaging* ultimately became standard practice among specialists in the mid-1980s, and Siemens officially renamed its business unit accordingly in 1985.

The mobile MAGNETOM semi-trailers are outfitted as complete MRI units

Commotion in the production plants

Yet there was one problem still troubling Siemens MR at the time: Installing a MAGNETOM at a customer site generally took several months, and in exceptional cases, up to two years. The solution was to be found in an idea for the installation of angiography systems first tested in the 1970s by employees working in X-ray production. The technicians would assemble and test the complete system at the facilities of the Siemens Medical Technology Division and then disassemble the systems and ship them to the customer, where they would be reassembled, already fully tested. The MR team adopted this modern manufacturing technique for themselves in 1986. By pre-assembling the systems in Erlangen and Iselin, New Jersey, in the United States, technicians could spot possible faults prior to installation; since they had spare parts and the right specialists close at hand, they were able to quickly troubleshoot any problems. This "prestaging" dramatically reduced both installation time and costs.

A peek into the MRI production plant at Siemens in Erlangen in 1984

Yet production safety standards in the mid-1980s were not nearly as strict as they are today. Occasionally, an accident would cause some commotion in the plants at Siemens. "The magnets would sometimes grab onto magnetized parts and damage the patient table, the housing inside the bore, or the body coil – sometimes a little and sometimes a lot," recalls Peter Scheuering 35 years later. Objects weighing up to ten grams, such as screws, nuts, or coins, could simply be removed from the magnet. "But when the magnet dragged over a whole pallet trolley and lifted it off the ground, that's when the safety staff got involved." When an accident occurs, the magnet must be switched off as quickly as possible. This process of relaxation, as it is called, still took several minutes in the first generation MAGNETOM systems.

The development team created the *emergency run down unit,* or *ERDU,* which would allow the magnet to be switched off at the touch of a button, but the ERDU would need to function even if the power running the MRI system were to fail. That meant it needed a battery. "That was its own little challenge," explained Scheuering, "because batteries and charging technology weren't very sophisticated back then." The nickel-cadmium and lead batteries of the era were neither suitable nor reliable enough to endure extended periods of standby. "We had to build a battery that 'knew' when it was broken so that the hospital technicians could replace it in time. We needed clever, ingenious technology."

Like a kettle of boiling water

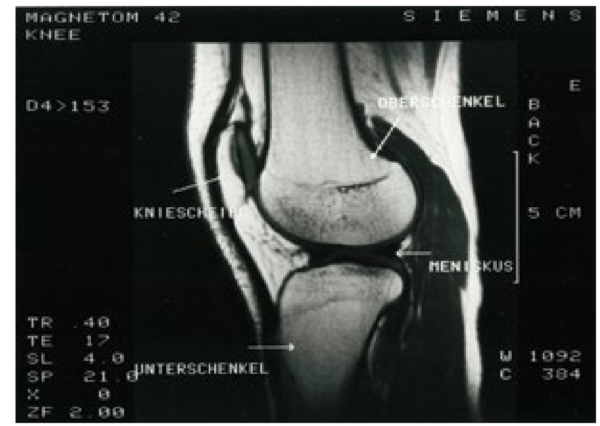
MRI technology required the innovation and development of a whole panoply of new, ostensibly minor technologies: lightbulbs with filaments that would not tear after just a few days in the vicinity of the MRI, monitors that produced images that would not be continuously distorted by the magnetic fields, fire extinguishers that could be operated near strong magnets. The superconducting magnets of the time carried a high risk of quenching. In the context of MRI technology, the term *quenching* refers to a process by which the magnetic coil suddenly loses its superconductivity and rapidly releases all of its stored energy as heat. Five-hundred liters of liquid helium evaporate to become 300,000 liters of helium gas. Normally, helium does not evaporate all at once; evaporation occurs gradually and the gas is discharged from the building via a so-called quench pipe. However, a portion of the helium gas might theoretically escape into the examination room. Commercial fire extinguishers are made of steel, which is magnetic and therefore cannot be used near an MRI system. To address the issue, Siemens collaborated with manufacturers to develop a special stainless steel MRI fire extinguisher with cylinders, valves, and gas canisters made from anti-magnetic material.

The helium was also a problem in its own right for these first-generation systems. Superconducting magnets of the time could be compared to an open kettle filled with boiling water. The helium would evaporate at a rate of around 100 liters each week, and even back then, each liter cost the equivalent of 20 euros today. Evaporated helium escapes into space and is lost to Earth forever. Supply is therefore falling at an ever-increasing rate, even though we create new helium from hydrogen on Earth through the process of nuclear fusion. In addition, the helium must be protected from the liquid nitrogen, of which the system also consumes a few hundred liters every week. In the mid-1980s, Siemens MR had an employee whose sole task it was to keep the cooling system running for the seven magnets in the development lab. From the very beginning, one key aim in the continuing development of the MAGNETOM systems was to reduce helium consumption as much as possible; the goal was to one day reach net-zero consumption.

The first major step in this direction was the development of a helium recovery system known as the liquefier. When evaporated helium is released from the chamber in the magnet, this device traps the noble gas, liquefies it with the help of an extremely powerful cooling system, and feeds the liquid back into the magnet. This lowered operating costs, dramatically increased the time between maintenance calls, and helped to conserve the world's helium reserves. On top of this, thanks to the helium liquefication system, Siemens was able to eliminate the formerly indispensable nitrogen cooling jacket, thereby simplifying the construction of the magnets and saving additional costs.

Progress that was never thought possible

Alongside these subtle improvements, the development team also made major strides in advancing the system's main components and software over just a few short years. While the first commercial MAGNETOM launched in 1983 operated with a field strength of 0.35 tesla, the magnet of the MAGNETOM GBS 2 from 1987 had a field strength of up to 2 tesla. The Helicon magnet with a liquefier developed by the central research laboratory in Erlangen generated the most homogeneous magnetic field of any working MRI system in the world at that time. The field strength could be adjusted anywhere between 0 and 2 tesla in less than 20 minutes, although 1.5 tesla was the standard value for clinical use while 2 tesla was intended for research. This variation in field strength – or ramping, as it was known – had previously taken several hours to complete.



Performance and image quality improved dramatically between 1983 and 1987

The increase in field strength of the main magnetic field is just one reason why the system's performance and image quality improved so swiftly between 1983 and 1987. The field strength of the gradients more than tripled over the same period. From the vast, nearly unmanageable array of different pulse sequences available, two in particular rose to the fore: The *half-Fourier matrix*, which had been in use since the first-generation systems, made it possible to measure only half of the required data. The MAGNETOM itself reconstructed the other half of the data automatically. This reduced the time patients would have to spend in the "tube" by half.

Advertisement for the
MAGNETOM from 1987

The second notable pulse sequence was based on an idea engineered in 1985 by Axel Haase, Jens Frahm, Wolfgang Hänicke, Klaus-Dietmar Merboldt, and Dieter Matthaei at the Max Planck Institute in Göttingen. Their *FLASH* procedure (fast low-angle shot) would significantly influence further MRI innovations. FLASH did not excite the proton spins in the standard 90-degree angle like other sequences at the time; instead, it flipped them in smaller angles. And these angles could be very small indeed, depending on the examination being conducted. This way, the MAGNETOM would no longer have to "wait" quite so long for the protons to relax. The *TurboFLASH* pulse sequence shortened the echo time of the MAGNETOM GBS 2 from 35 milliseconds to 2 milliseconds. TurboFLASH reduced the measuring time considerably.

By the mid-1980s, the incredible flexibility of MRI technology was becoming apparent. Up until then, it had "only" produced the highest tissue contrast of any imagining technique; now it could also visualize metabolic processes, the beating heart, and vascular plaques. For cardiac imaging, the imaging sequence was synchronized with the ECG signal, resulting in astonishingly clear MR images in spite of the rapid movement. The heart was measured only during certain phases of the heartbeat. By shifting the trigger point, it was possible to generate images of multiple cardiac phases step by step and subsequently display the images as a film of the beating heart. This gradual measurement technique meant that cardiac examinations would take far longer than half an hour, but the medical value of such images justified the time needed to create them. Thanks to its specialized software, the MAGNETOM GBS 2 could visualize the anatomy and function of the heart and measure key parameters such as volume and muscle thickness. Physicians took an immediate interest in these images, since at the time, no other imaging method was capable of producing such high-resolution images of inside the heart.

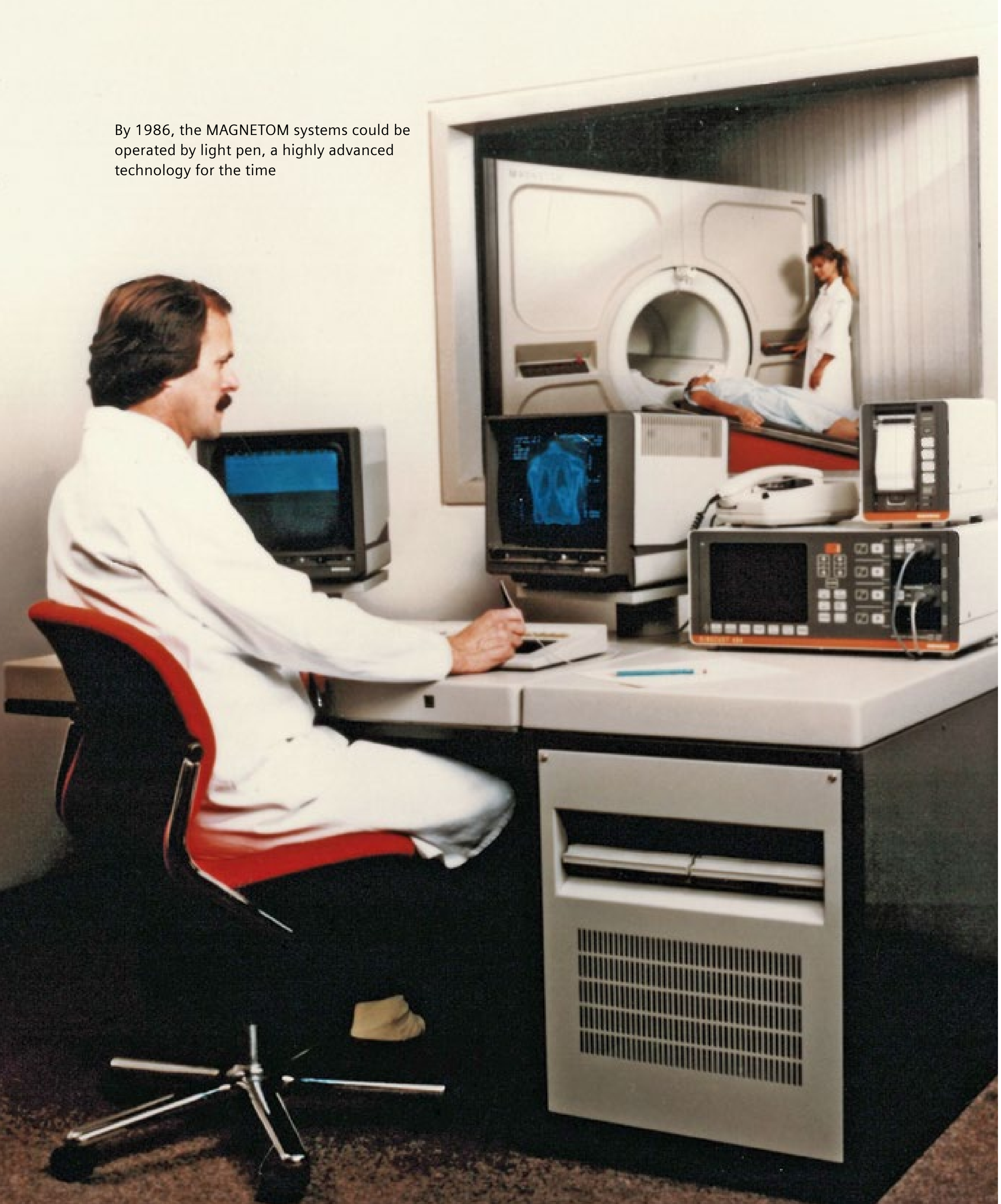
When it came to visualizing blood flow, Siemens was also making progress that had never before been thought possible. Together with the company Schering, which later became part of Bayer AG, Siemens had been researching potential contrast agents for use with MRI technology since back in 1981. Around the same time, it was discovered that by employing certain pulse sequences, it was possible to visualize the blood flow through vessels without the use of contrast agents. By 1987, the MAGNETOM was already capable of generating three-dimensional images of vascular trees down to a diameter of 1 to 2 millimeters. Shortly thereafter, the *3D volume MR angiography* software option made it possible, for instance, to detect plaques in blood vessels or diagnose vascular diseases such as thrombosis.

One of the early angiography images produced with the MAGNETOM, 1987

Far ahead of its time

The employees of the MR Business Unit within the medical technology division at Siemens were, in many ways, conducting pioneering work. The first MAGNETOM systems could be operated using a light pen, which was a highly advanced and relatively widespread innovation at the time. When the pen made contact with the 8-by-8-centimeter conductive interface, a point would appear on the corresponding monitor. Yet light pens were expensive and required labor-intensive calibration. This led Siemens MR to become the first business unit to begin operating its systems using a Logitech computer mouse in 1986. Unlike today, computer mice were a rarity in the mid-1980s, and they were highly sensitive to dirt and dust. These mice were not yet equipped with optical sensors; instead, they had a large ball inside that required regular cleaning. Nevertheless, this simple and precise method of operation paved the way for the development of the graphical user interface in the years that followed.


The MR Business Unit was the first business unit to begin operating its systems using a Logitech mouse



By 1986, the MAGNETOM systems could be operated by light pen, a highly advanced technology for the time

Another of the many examples illustrating how far ahead of its time Siemens MR was in the 1980s is remote maintenance, a technology that has since become a matter of course. There was no World Wide Web in the late 1980s. DEC (Digital Equipment Corporation), the company with which Siemens collaborated on image processors for both CT and MRI, offered a remote maintenance service for its computers via telephone wire, which could transfer 300 bytes per second in both directions. (At this speed, downloading a four-minute song in MP3 format would take approximately one hour.) Siemens MR used this feature to send log files from the MAGNETOM's analysis software to Erlangen or Iselin. Later on, the newly formed OPSIS (Online Program Support in Installation and Software) group offered the option to connect the hospital's MAGNETOM system to Siemens via a dedicated telecommunications line.

Technology from toy phones

Due to the physics of MRI technology, Siemens was practically forced to forge new paths. This also applied to communication between the system operator and the patient. Conventional speakers and microphones could not be used as an intercom system in the vicinity of the magnet. Initially, staff had to settle for speaking to patients using air tubes and membranes, just like the ones in a toy phone; Siemens then developed an intercom system employing electret microphones and speakers, technology that was truly a rarity at the time. To determine whether the patient was feeling well inside the machine, staff also needed a camera. But commercially available tube cameras did not work in the MRI room either. So, Siemens MR was the first business unit to introduce semiconductor cameras for patient monitoring. "At a price of several thousand marks, these cameras were sinfully expensive," remembers Peter Scheuering. "But as we know, the ends – and safety – justify the means."

Working on the 4-tesla magnet at the research center in Erlangen

The whole nine yards

The 1982 decision of Siemens to source magnet technology for the MAGNETOM from Oxford Instruments was further strengthened in 1987 when Siemens and the medical division of Oxford Instruments each contributed a 50-percent share to the joint venture Oxford Magnet Technology. Siemens also continued to conduct basic research on magnets with high field strength in Erlangen through the mid-1980s. With support from the Federal Ministry of Research and Technology, Siemens resolved to develop an experimental magnet. During initial discussions, Peter Grassman suggested that they first build a 4-tesla magnet for conducting experiments on animals. Rudolf Schittenhelm proposed that they expand the size of the magnet bore to facilitate examinations of the human head, too. “Well then we might just as well go the whole nine yards,” suggested Arnulf Oppelt, at the time head of basic research. “We could also build a full body magnet with a bore size of 1 meter, or better yet, 1.25 meters.” In 1987, the 4-tesla magnet with the unusually large bore commenced operation. This unique system generated the most homogenous magnetic field of any medical scanner of its time by far. Yet the magnet was not designed to be a magnet to be used in products for clinical use, but rather a magnet for research purposes to test the potential and the limits of higher field strengths. A different technology – one with shielding that was just as effective as the iron direct shielding but up to 30 metric tons lighter – was developed for series production. With active shielding, as it was known, additional coils were mounted on the magnet to weaken the magnetic field in areas in which it was not needed.

By 1987, between Siemens and its joint venture Oxford Magnet Technology, over 300 people were already working in development and marketing in the MR Business Unit. One year later, Siemens and Varian Associates founded the joint venture SISCO (Spectroscopy Imaging Systems Corporation) to collaborate on the development, production, and sales of small MRI spectrometers for use in industry and various scientific fields. In clinical practice, MRI technology remained a novel outsider compared with other imaging methods, but with these advances, this technique, though still in its infancy, was poised for a breakthrough.

Magnet with active shielding produced by the joint venture Oxford Magnet Technology

The breakthrough

From investment in the future to a cornerstone

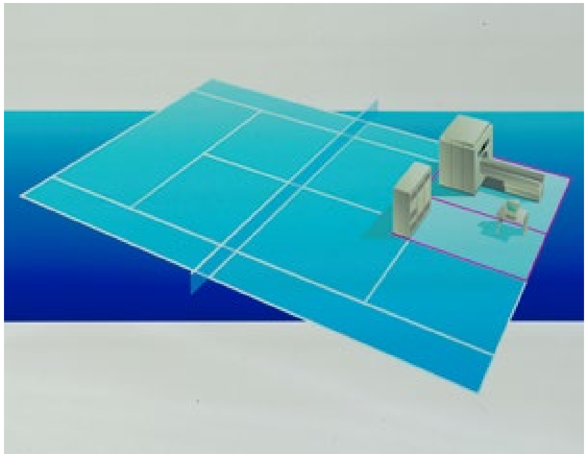
Interest in MRI technology rose steadily throughout the 1980s. Slowly but surely, the procedure was becoming established in a growing number of hospitals and doctor's offices the world over. There was a veritable explosion in the number of studies being conducted – and at Siemens, MRI technology had grown from a side project to a cornerstone on which the future of the medical technology division of Siemens would be built. In the early years, MRI technology represented an investment in the future, and the enormous costs of this venture had to be borne by the other business units at the Siemens Medical Technology Division. Yet in the early 1990s, once the new business unit had been established, Siemens generated its first profits in MR. At around the same time, MRI technology really began to take off. The two main reasons for the breakthrough relate directly to advancements in MR technology: New developments transformed the extraordinary physical complexity of MRI technology – which had been a barrier to its development and adoption up to this point – into an advantage. After all, it was this physical complexity that gave MRI its exceptional flexibility. The second key reason lay in the technical advancements that reduced the extensive efforts involved in converting spaces in hospitals and doctor's offices to a manageable level while lowering operating costs significantly. The first system of this new generation, which combined all the innovations of the 1980s, was the MAGNETOM Impact from 1991.

The MAGNETOM Impact rapidly became the world's bestselling MRI system

Match point!

The marketing campaign for MAGNETOM Impact was all based around the game of tennis, which was hugely popular at the time. "To stay in the game in today's MR market," read the 1991 product brochure, "a system must have it all: convenient siting, low installation and operating costs, high throughput, and advanced applications." While the first MAGNETOM, with its 0.35-tesla magnet, required at least 95 square meters of floor space, the 1-tesla MAGNETOM Impact could be installed in a space of just 40 square meters, thanks to its active shielding. For the very first time, an MRI system required just as little floor space as a CT scanner. MAGNETOM Impact could be installed in three weeks and needed just three helium refills each year.

One key objective for Siemens in the development of MAGNETOM Impact was to make MRI examinations far simpler and more convenient for hospital staff, improving on the performance of the first-generation systems. Users would navigate the new PC-like user interface using a computer mouse while functions and results were displayed on a high-resolution monitor. For the first time, all key sockets for the RF coils and other accessories were integrated into the patient table. Pulse sequences such as TurboFLASH made it possible to capture movements taking place inside the body or produce angiograms, for instance. A complete head examination now only took 15 to 20 minutes – two to three times the speed of the older systems. MAGNETOM Impact was a major success for Siemens, and the system rapidly became the world's bestselling MRI system, retaining that title for over six years.



The marketing campaign for MAGNETOM Impact in the early 1990s was all based around the game of tennis – hugely popular at the time

Results of a head examination photographed from the monitor, 1991

A practical alternative

By employing an unusual approach, Siemens was again able to drastically reduce the system's space requirements. In practice, the MAGNETOM P8, which was introduced on the market at around the same time as MAGNETOM Impact, required only 25 square meters of floor space and could be installed in just 10 days. How was that possible? The answer lay in the system's unusual magnet technology. The design of the MAGNETOM P8 incorporated a so-called permanent magnet. Unlike superconducting magnets, permanent magnets have a magnetic field that functions without the need for electricity and coils. Since the system has no electromagnet, operating costs were very low. The MAGNETOM P8 required neither helium, nitrogen, nor water cooling. In addition, the system used only around one tenth of the electricity required for a superconducting system. Yet there were two major disadvantages to permanent magnets, and these were the reasons why this magnet technology would be relegated to the sidelines of MRI technology in the years that followed: First, the field strength was limited to below 0.3 tesla, and second, the homogeneity was far lower than with superconducting magnets.

The unusual design of the MAGNETOM P8
saved on installation space and operating costs

In the early 1990s, however, permanent magnets were a practical alternative that made MRI technology accessible to more users and patients. Although there needed to be some compromise on image quality because of the 0.2-tesla magnet, still the powerful electronics of the MAGNETOM P8 meant that this system could be used for the same applications as the Siemens systems with superconducting magnets. Using sequences optimized for this alternative magnet technology, it was possible to acquire a gapless series of thin slices, which could then be viewed as a three-dimensional volumetric image in real time. In many ways, the MAGNETOM P8, an entry-level system, was technologically far more advanced than most MRI systems with conventional magnet technology. For instance, the system automatically detected the placement of the coils while the patient was being positioned in the magnetic field. The plasma screen above the bore could be used to display the functions of the patient table or the ECG signal and start the localizer scan, among other things. The first image would be displayed on the high-resolution monitor before medical staff even left the scanning room.

Vision to increase speeds

The technique introduced by Sir Peter Mansfield in 1977, echo-planar imaging (EPI), was well ahead of its time. This method was based on the idea of using a single radio-frequency pulse to excite the nuclear magnetic resonance. With this technique, each slice could be measured in milliseconds rather than seconds, meaning that many images could be acquired in a very short time. Echo-planar imaging – or more precisely, the speed of this technique – presented numerous advantages. Of these, one of the most impactful was the fact that EPI was fast enough to measure molecular motion inside the body. Another was EPI's ability to freeze motion inside the body that would create blurry artifacts in conventional sequences. Yet in the 1980s, hardware was still far too slow to manage these ultra-fast measurements and calculations. With the 1994 market launch of MAGNETOM Vision, however, flagship of the new generation and world's first real-time scanner, echo-planar imaging found a place in clinical practice for the very first time.

Aside from improvements to the imaging components, the primary driver for the enhanced performance of MAGNETOM Vision was the new gradient system with high-power amplifiers. Thanks to its speed, which was truly exceptional for the time, the 1.5-tesla system was particularly well suited for visualizing moving organs such as the heart and lungs and acquiring images of blood or low-contrast organs like the liver and kidneys. Due to the system's ability to freeze motion, high blood circulation through particular organs, such as the heart muscle, no longer presented an obstacle to image evaluation. MAGNETOM Vision allowed medical practitioners to localize early-stage stroke without contrast agent for the very first time
This system also made it possible to conduct studies on another technique that was coming to the fore, functional magnetic resonance imaging, or fMRI. In this technique, optimized pulse sequences analyze neural activity and link this metabolic data to the anatomical map of the brain. In this way, it is possible to distinguish between active and inactive regions of the brain. fMRI was used to conduct studies that compared the neural activity of people with anxiety disorders or depression with that of healthy control groups. By the mid-1990s, fMRI had started to become one of the most important tools in the field of neurological research. More on that later.

The gradients and radio-frequency technique employed by MAGNETOM Vision were powerful enough to be used for all of the ultra-fast imaging methods available at the time. *The **h**alf-Fourier **a**cquisition **s**ingle-shot **t**urbo spin-**e**cho sequence* (HASTE) developed by Siemens allowed medical staff to acquire images of the brains of uncooperative or nervous patients without motion artifacts. Compared to the faster echo-planar imaging, images acquired using HASTE have a far higher spatial resolution. In addition, HASTE images showed significantly higher contrast between cerebrospinal fluid and brain tissue than images obtained using conventional sequences. However, the technique made it more difficult to distinguish between gray and white matter in the brain. HASTE and echo-planar imaging were not competing analytical methods. Each had its own individual strengths and helped to expand the diagnostic capabilities of MRI technology.

Image from a 1994 advertisement for MAGNETOM Vision, the world's first real-time scanner

Ultra-fast sequences such as HASTE and EPI attained these speeds thanks to the development of more powerful gradient systems. The maximum switching rate of the gradients is the limiting factor in the speed of these sequences. Another method for improving image quality – and, most importantly, dramatically lowering examination times – is known as parallel imaging. The parallel imaging technique exploits the placement of the body coils in its calculations. The RF coils placed on the patient's body receive the MR signals. An array is an arrangement of multiple coils. Conventional array techniques acquire one image for each coil element. These individual array images are then combined to create a single image. With parallel imaging, the spatial arrangement of the array provides additional data about the origin of the MR signals. The information provided by the coils supplements the spatial encoding supplied by the gradients. The parallel imaging technique developed by Siemens is known as *iPAT* (integrated parallel acquisition techniques). iPAT generates either high-resolution images over a longer measuring time or rapid images with lower image resolution. Parallel imaging proved particularly valuable for time-critical procedures like cardiac examinations because patients were no longer required to hold their breath for 20 seconds during the cardiac exam.

Open to new ideas

In late 1993, Siemens took the MRI world by storm when it presented a one-of-a-kind magnet technology at the international congress of the Radiological Society of North America (RSNA) in Chicago. The 0.2-tesla magnet, developed in Erlangen, was shaped like an upright "C" and was open on three sides. At this time, the largest available bore of any tunnel magnet was 60 centimeters in diameter. The structure of MAGNETOM Open now made it possible to examine larger patients, children, and claustrophobic patients, too. The open design paved the way for the first dynamic joint studies, as patients had more freedom of movement during examinations. For example, shoulder movements could be measured throughout the different phases and then analyzed in motion on the monitor using the three-dimensional *cine mode*. All of the applications developed by Siemens were integrated in MAGNETOM Open, including the functions for MR angiography capable of imaging blood flow and the movements of the heart wall, for example.

In the mid-1990s, there were numerous research projects focused on evaluating the success of treatments using MRI technology. The MAGNETOM Open design introduced new types of applications in the field of intraoperative imaging. In 1996, Siemens began collaborating with Universitätsklinikum Erlangen and Heidelberg University Hospital in an effort to improve the quality of neurosurgical procedures. In both hospitals, the MAGNETOM Open scanner stood right next to the operating room so that the patient, lying on an air-cushioned operating table, could be wheeled from the operating theater to the MRI system, allowing the medical team to

The electromagnet of MAGNETOM Open is shaped like an upright "C" and is open on three sides

MAGNETOM Concerto was equipped with the most powerful gradients of any low-field strength MRI system available at the time evaluate the success of the procedure live during the operation. Studies in Erlangen and Heidelberg showed that in around half of all cases, MRI nalysis revealed remnants of tumorous tissue that could subsequently be removed. Just a short time later, these research findings were put to use in the next generation "C-magnet" system: For MAGNETOM Open Viva, released in 1996, Siemens employed new technologies to increase the clearance between the patient table and the upper magnetic pole, among other things. The 2000 model, MAGNETOM Concerto, had the most powerful gradients of any low-field strength MRI system available at the time.

Music, magic, and technology

When working to develop MRI systems with high field strengths, Siemens strove to combine open designs with low operating costs and the image quality of 1-tesla or 1.5-tesla systems. In late 1997, Siemens took a major stride toward that goal with the launch of MAGNETOM Harmony and MAGNETOM Symphony. These two systems had a number of basic similarities: Both magnets weighed around four metric tons, each was equipped with active E.I.S. (external interference shielding), and both MAGNETOM Harmony, with a field strength of 1 tesla, and MAGNETOM Symphony, at 1.5 tesla, required less than 30 square meters of floor space. Thanks to the integrated chiller, the systems no longer required a separate equipment room. Helium consumption was so low that the systems only needed to be refilled about once every two years.

The "free-floating" patient table could be lowered to a height of 45 centimeters from the floor using a joystick and was able to accommodate patients weighing up to 200 kilograms. During this time, system design was becoming increasingly important. The bright, open appearance of the MAGNETOM systems was designed to alleviate the fears of nervous patients. The housing and bore ring were

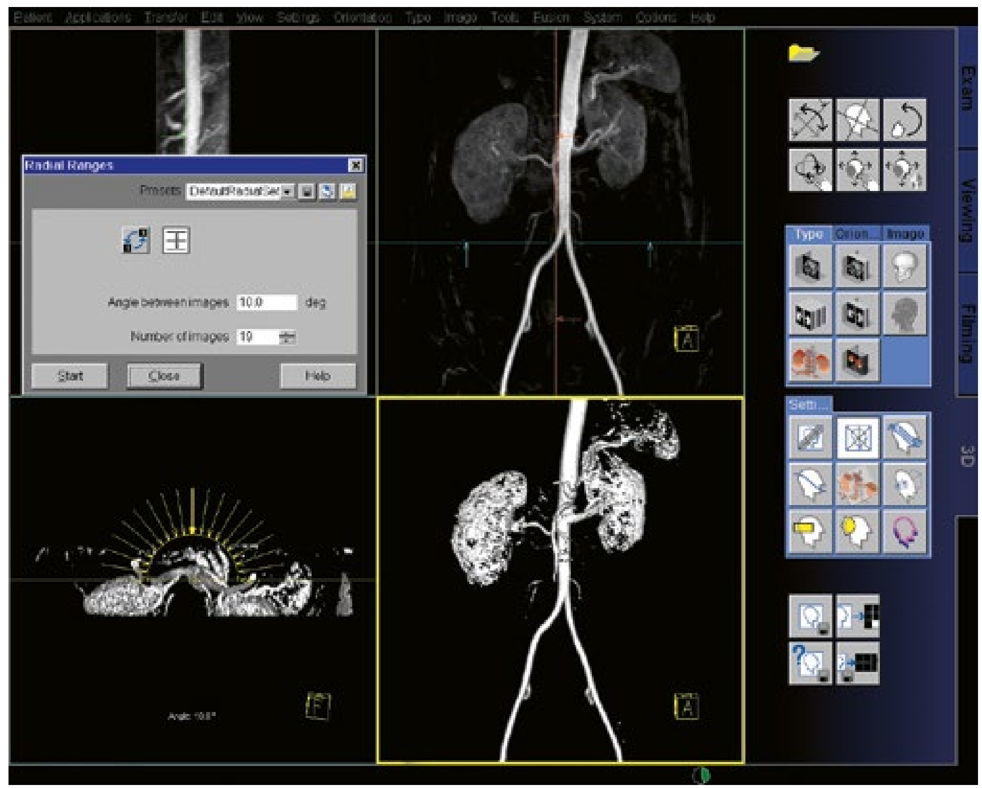
The bright, open appearance of the systems was designed to alleviate the fears of nervous patients

Brain scan acquired with MAGNETOM Harmony in 1997 available in various color combinations that could be adapted to suit the individual examination room. At the same time, the warm colors were intended to provide a soothing environment for patients and users. The introduction of the *integrated panoramic array* (IPA) provided additional comfort. This new coil concept integrated the spine coil and the lower section of the head coil into the patient table. Up to four coils of the IPA could be operated simultaneously using the software interface. In most cases, this eliminated the need to switch coils when examining the spine, the head, or the whole body. The slogan for this new MAGNETOM family was: "The Perfection of Care." The names Harmony and Symphony were intended to give a soft, harmonious touch to these highly technological machines. In June 1997, the product launch began with a "Festival of Technology." This event, held in Nuremberg, which drew countless MR staff members and 120 sales employees from around the globe, was billed as a celebration of "music, magic, and technology."

One for all

Computer applications had already begun to play a major role in many sectors by the late 1990s, and medical technology users had an intuitive grasp of computer mice, windows, and menus. Yet unlike office applications, the software used to operate these systems was still highly complex and complicated. To address this problem, the Siemens Medical Technology Division resolved to find a better solution. Siemens MR had already raised the bar in terms of user-friendly operation with the introduction of graphical user interfaces in MAGNETOM Impact; but magnetic resonance imaging, computed tomography, and other imaging systems from the same manufacturer still had different user interfaces – and users had to learn to operate each one separately. In 1999, Siemens became the first medical technology manufacturer to design a standardized user interface for all of its systems: This software was known as *syngo*™.

While developing *syngo*, Siemens gave special consideration to making the system intuitive to understand and operate. The entire graphical user interface consisted of clear, easy-to-understand symbols. The *syngo* interface served as the gateway to numerous different functions that had been optimized for the procedures in hospitals and doctor's offices. With just a single click, staff could display patient information such as medical scans, lab results, or operative reports, all arranged in a clear and concise format. All *syngo* workstations could be connected throughout the hospital via the hospital network or to workstations across the world via the Internet. New systems and software applications were simply integrated into the existing *syngo* architecture. If the hospital or doctor's office



With the development of *syngo* in 1999, Siemens became the first medical technology manufacturer to create a standardized user interface for all of its systems purchased a new imaging system from Siemens, the standardized appearance and style of *syngo* dramatically reduced the time needed to train staff on the new system.

Brain power

In the 1980s, the greatest advantage of MRI technology was in its ability to visualize the anatomy of soft tissue with far more clarity than any other imaging technique; but in the 1990s, MRI also became an effective method of differentiating between active and inactive regions of the brain. By the end of the decade, fMRI (functional magnetic resonance imaging) had already become a standard procedure for conducting scientific examinations of the brain. The BOLD effect (**b**lood **o**xygenation-**l**evel-**d**ependent imaging), discovered by Japanese biophysicist Seiji Ogawa, serves as the basis for fMRI. Due to the BOLD effect, certain regions of the MRI scan appear brighter or darker based on the oxygen content of the tissue's blood supply. Since areas of the brain with active neurons have a higher blood flow rate, fMRI can be used to identify the regions of the brain associated with hand movements or visual perception, for example.

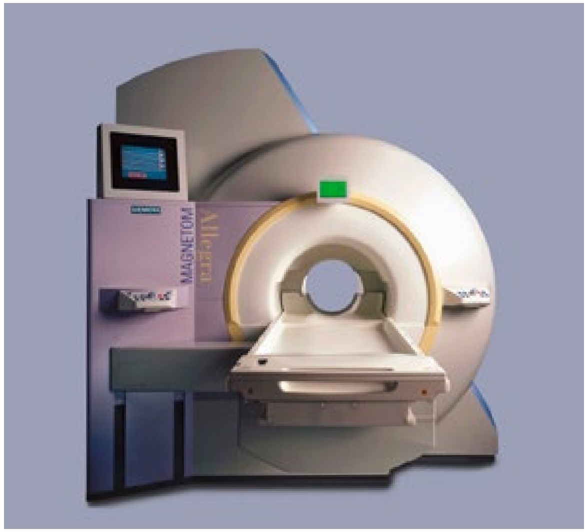
fMRI places enormous demands on the hardware and software of MRI systems. Just like any other MRI technology, fMRI is limited by the signal-to-noise ratio, which dictates the maximum quality of the images. (Quality, in this sense, means: What are the smallest body structures that can be visualized in the MRI scan? How large a difference in resonance signals is required to visualize the contrast between two structures on the scan?) Throughout the 1990s, a wide range of approaches were developed to eliminate the limits posed by the signal-to-noise ratio. One of the most effective options was to increase the field strength. However, optimizing the system for the improved signal-to-noise ratio meant redesigning the entire MRI system: Components such as RF coils, amplifiers, and filters had to accommodate the higher frequencies, and because more data would be gathered, the signals had to be processed by faster computers. That meant that up until the turn of the millennium, fMRI could only be used for neurological research in academic institutions with access to specialized supercomputers. Even then, it could take several hours to calculate the values.

For fMRI to be useful in clinical practice, the systems would have to become powerful enough to visualize the active regions of the brain while the patient was still lying in the MRI system. In the late 1990s, Siemens collaborated with the German Cancer Research Center (DKFZ) in Heidelberg to develop a software for processing fMRI data in real time. This application would be made available for current MAGNETOM systems around the turn of the millennium. By the year 2000, Siemens had become the world's only manufacturer to offer two specialized 3-tesla systems: MAGNETOM Allegra dating from the year 2000 was a system for head examinations designed specifically for the demands of neurology. One year later, this system was followed by MAGNETOM Trio, the first clinical whole-body scanner with a field strength of 3 tesla. Thanks to the new magnet design, the structural requirements for exam rooms housing a MAGNETOM Allegra or MAGNETOM Trio were now comparable to those of contemporaneous 1.5-tesla systems.

Everything under one roof

By the end of the 1990s, MRI technology had become a fixture of day-to-day practice in hospitals and doctor's offices. Siemens had already become

MAGNETOM Trio, the first whole-body scanner with a field strength of 3 tesla, launched on the market in 2001



MAGNETOM Allegra from the year 2000 is a system for head exams specially tailored to the demands of neurology

MAGNETOM Sonata was developed especially for the demands of cardiology

the market leader in MRI technology and was producing several hundred systems annually in Erlangen. On February 14, 2000, the company celebrated the opening of the new MR factory, which had been constructed over 18 months. Now, just a few minutes' walking distance from the Siemens Medical Technology Division headquarters in Erlangen, around 2,000 employees of Siemens MR would be working under one roof. This greatly simplified operations, as up to this point, development, production, logistics, sales, and service had been spread out over five different locations in Erlangen. Many of these were several kilometers apart. In this facility – now the world's most advanced factory for MRI systems – staff were able to make changes in the prefabrication stage that reduced installation times at customer sites from a period of four to ten weeks down to just a single week. Siemens operated more than 20 test systems, prototypes, and current MAGNETOM models in the new factory. These systems were made available for research and development as well as for training and customer presentations.

At the same time, a Chinese startup in Shenzhen had begun to build inexpensive, high-quality MRI systems. With its products, *Shenzhen Mindit Instruments Co., Ltd.,* founded in 1998, had become a major player on the Chinese MRI market in just a few short years. In 2002, Siemens and *Shenzhen Mindit Instruments Co., Ltd.,* formed the joint venture *Siemens Mindit Magnetic Resonance Ltd.,* based in Shenzhen. Over the next few years, that project would become the high-tech development center *Siemens Shenzhen Magnetic Resonance Ltd.,* which is seamlessly linked to Erlangen and Oxford as part of the global development network at Siemens Healthineers.

On February 14, 2000, Siemens celebrated the opening of its new MR factory in Erlangen

Enter the matrix

From patchwork pictures to seamless whole-body scans

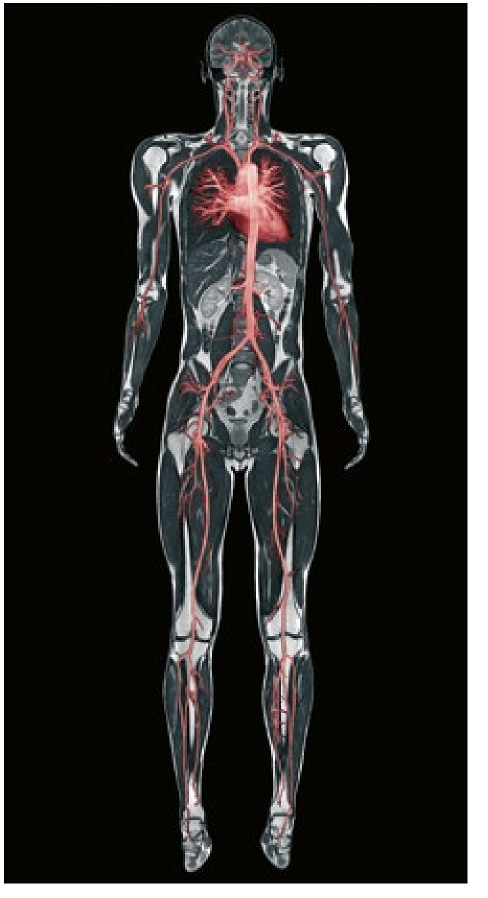
By the turn of the millennium, MRI technology had become an established part of clinical practice. At the time, over 60 million MRI examinations were being conducted worldwide each year. On October 6, 2003, two people who, according to experts, were among the most significant figures in the history of MRI, finally received a long belated message from Sweden: "Today, the Nobel Assembly at the Karolinska Institute has decided to award the 2003 Nobel Prize in Physiology or Medicine jointly to Paul C. Lauterbur and Peter Mansfield for their 'discoveries concerning magnetic resonance imaging.'" In an interview on Swedish radio, Mansfield shared that while he thought he might be eligible for the Nobel Prize several years back: "I'd given up on that notion." Lauterbur was also very excited and surprised to receive the message, exclaiming: "I'll have to let it sink in first!"

Tim changes MRI

The year 2003 was also an important mile-stone in the history of MRI technology at Siemens Healthineers. Around the same time that Lauterbur and Mansfield were preparing for the ceremony in Stockholm, Siemens was in Chicago at the Annual Meeting of the Radiological Society of North America (RSNA) presenting a new high-end technology: the *Total imaging matrix*, or *Tim* for short. Tim technology is essentially based on a large number of radio-frequency coils arranged in a matrix, which are read out through individual receiver channels and allow the scan time to be reduced to the minimum possible while maintaining good image quality.

Tim technology was pivotal in dramatically increasing the speed of the MAGNETOM systems in the years that followed and laid the groundwork for numerous new applications. For the first time in the history of MRI, it was possible to capture high-resolution images of the entire body from head to toe in a single scan without compromising image quality. The first system to apply Tim technology, the MAGNETOM Avanto with a field strength of 1.5 tesla, could scan a person up to 205 centimeters tall in just twelve minutes. That was half the time required by other systems, even under optimum conditions. Thanks to Tim, it was possible to significantly increase both the quality and quantity of examinations in the time available.

When compared with earlier coil technologies and considering the advantages it presented for patients, Tim represented a tremendous leap forward: Until the late 1990s, it was impossible to perform whole-body MRI scans without significantly compromising image quality. The patient's individual body parts had to be covered with numerous different coils, and each region scanned individually. Afterwards, the scans of the different regions of the patient's body were stitched together, producing a whole-



Thanks to Tim, it was finally possible to image the entire body from head to toe in a single scan without compromising image quality

In November 2003, Siemens introduced
the MAGNETOM Avanto, the first system
with the Total imaging matrix

body scan that was a kind of patchwork image made up of many parts. Image quality suffered at the edges of each “patch,” and the process was very laborious and sometimes even completely unsuitable for many patients. Accident victims and older or severely ill patients had to be moved and repositioned each time the coils were changed. When Siemens introduced the Integrated Panoramic Array (IPA) in 1998, a system in which most of the coils were integrated into the patient table, it became possible to capture whole-body scans without moving the patients for the first time. However, the users still had to decide whether to scan a small portion of the body with higher resolution and image quality or image the whole body at a lower resolution. The Total imaging matrix turned this trade-off into a thing of the past.

From the very first generation of Tim technology, users could seamlessly combine up to 76 coil elements with up to 32 radio-frequency channels (instead of the eight channels available up to that point) to create a Total imaging matrix. For the first time, it was possible to generate 3D images of the body using parallel acquisition techniques (PAT) without the need for the specialized PAT coils that used to be required. The *Tim Application Suite* provided routines designed specifically for numerous clinical applications, such as neurological, cardiological, or oncological examinations and for orthopedics, angiography, and pediatrics.[3] This technique also made examinations far more comfortable for patients because the so-called Body Matrix coil weighed only 950 grams. For many examinations, patients could be positioned in the bore feet first with their head outside of the bore. Although the MAGNETOM Avanto was equipped with the strongest and fastest gradient system of its time, Siemens managed to decrease the noise produced by the gradient coils by up to 97 percent compared with conventional systems.

By the time the MAGNETOM Avanto celebrated its world premiere on November 30, 2003, two of these high-end systems had already been installed in Tübingen and New York. Just a few months later, hundreds more had been installed around the globe.

Tim allowed users to seamlessly combine up to 76 coil elements with up to 32 radio-frequency channels

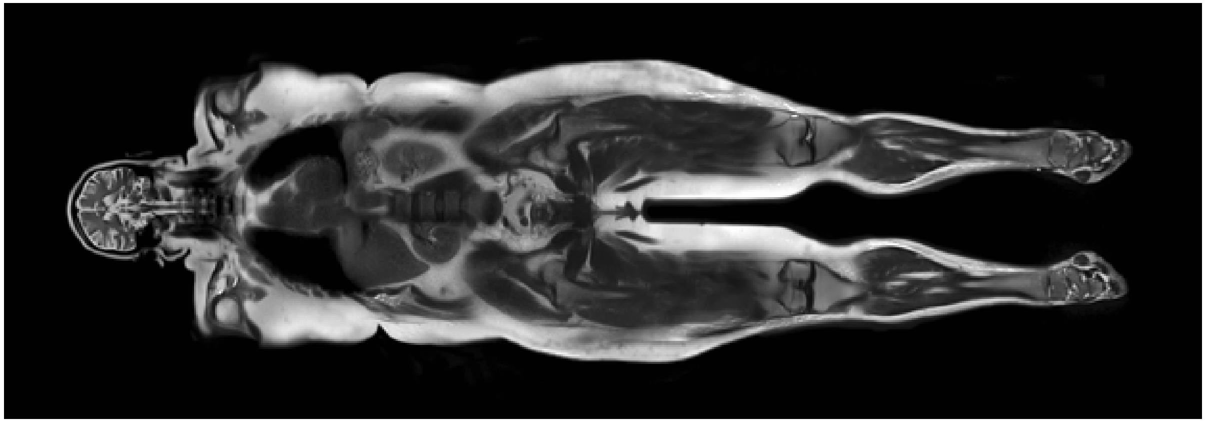
In a special publication on innovation in science and healthcare, Siemens released an MRI scan made using Tim technology that depicted the results of the first collaboration between the MR Business Unit and famous athletes. German swimmer Hannah Stockbauer, who had recently won three gold medals at the World Championship in Barcelona, was interning at Siemens at that time. In 2005, Siemens received the German Business Innovation Award for the development of Tim technology. That same year, the company integrated the new coil technology into its existing MAGNETOM Symphony and MAGNETOM Trio systems and launched an MRI system that both incorporated Tim technology and featured a unique new design: the *MAGNETOM Espree*.

Chinese advertisement promoting the option to retrofit the MAGNETOM Trio with Tim technology

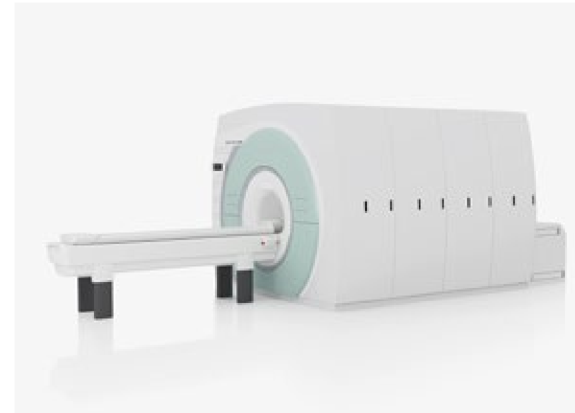
As part of a collaboration with star athletes, British Olympian Jo Fenn and others agreed to undergo MRI examinations performed using the MAGNETOM Avanto

Swimmer Hannah Stockbauer, winner of multiple World Champion titles, agreed to be scanned using Tim technology during her time as an intern at Siemens

MAGNETOM Espree from the year 2004 was the world's only 1.5-tesla MRI system with a 70-centimeter bore



Whole-body scan of a patient weighing around 130 kilograms acquired using HASTE in the MAGNETOM Espree



The magnet in the MAGNETOM 7T research system was around three meters long and weighed 32 metric tons

A new spirit of openness

At the system's launch in late 2004, the bore of the MAGNETOM Espree was described as an "open tunnel." Other so-called open MRI systems, such as the MAGNETOM Open or the 0.35-tesla MAGNETOM C! introduced in 2004 were well suited to handling many routine clinical examinations in fields such as orthopedics, pediatrics[3], or neurology. Yet the system design fell short at times, particularly for obese patients. For patients who are overweight, the relatively low field strength of these devices results in insufficient image quality compared to that of tunnel systems, particularly when it comes to diagnosing conditions affecting the musculoskeletal or circulatory systems. MAGNETOM Espree was the world's first 1.5-tesla system to feature a 70-centimeter bore. This increased the average distance between the inside of the bore and the patient's eyes from 22 centimeters to around 30 centimeters. In addition, the tunnel was only 125 centimeters in length, meaning that in around 60 percent of examinations, patients' heads could remain outside of the system. This magnet design, which was unique at the time, also helped patients who suffered from claustrophobia.

Combining Tim technology with especially high-performance gradients boosted the signal-to-noise ratio of the MAGNETOM Espree to up to four times that of other open systems. This made it possible for patients who were overweight to benefit from services that other systems were incapable of providing, such as diagnosis of and treatment planning for vascular diseases or diabetes. "All patients should have full access to high-quality MR technology," declared Dr. Heinrich Kolem, who headed the MR Business Unit at Siemens at that time. "The open MR systems that were available up to now didn't meet the standards of quality for MR images from high-field systems. Our new MAGNETOM Espree MR system is in a category of its own; it both increases patient comfort and produces diagnostic images with the quality of a high-field system."

140,000 times stronger than the Earth's magnetic field

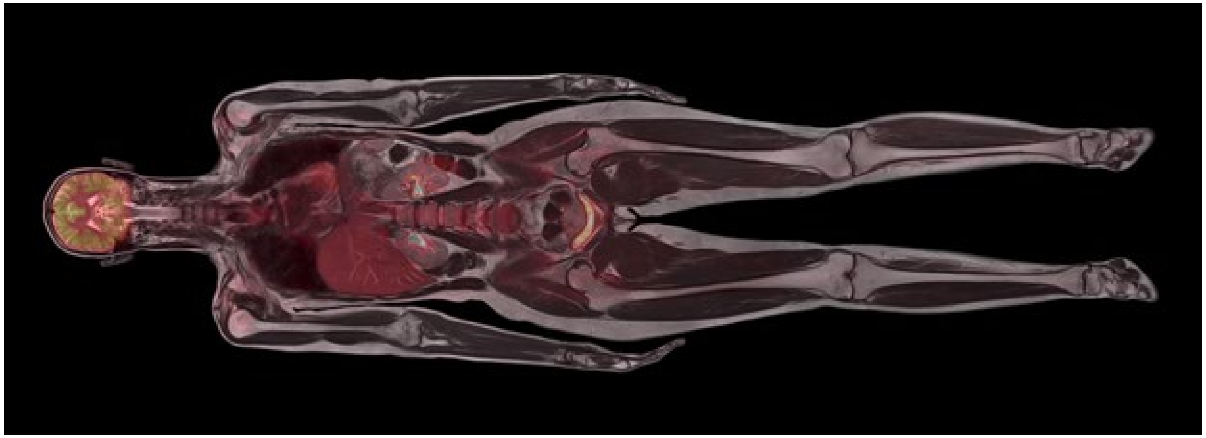
At the time, the term *high-field MR* encompassed both 1-tesla and 1.5-tesla systems; MRI systems with a field strength of 3 tesla or higher were known as *ultrahigh-field MR*. While 3-tesla systems such as MAGNETOM Trio became increasingly common in routine clinical applications throughout the 2000s, the first 7-tesla systems entered research labs starting in 2002. A field strength of 7 tesla is comparable to 140,000 times the strength of the Earth's magnetic field. The strong MR magnetic field produced images with even higher contrast and resolution in which it was possible to clearly differentiate between structures as small as 0.2 millimeters. When researching the causes of disease, for instance, this made it possible to observe tiny changes in the brain that occur during the early stages of such diseases as Alzheimer's or multiple sclerosis. When analyzing tissue metabolism, different chemical elements could be clearly identified and delineated, for example, in order to study the effect of medications on the body. In early 2002, Siemens was already supplying the main components for research systems with a field strength of 7 tesla. In the years that followed, the company worked together with cooperation partners to develop specialized coils and application-oriented technologies that would later be incorporated into the MAGNETOM 7T[4] research MRI system. The company's first two partners were the University of Minnesota and the Martinos Center, which is affiliated with Massachusetts General Hospital, Massachusetts Institute of Technology, and Harvard Medical School. In its first iteration, the three-meter-long magnet of the MAGNETOM 7T weighed in at 32 metric tons, had to be cooled using 1,750 liters of liquid helium, and yet could still be installed in an area of just 40 square meters. Many discoveries made during the development of the research systems also found their way into systems with lower field strengths. In 2007, when Siemens presented the latest trends in 7T ultrahigh-field imaging at the Annual Meeting of the International Society for Magnetic Resonance in Medicine (ISMRM), over half of all 7-tesla systems operating worldwide were Siemens devices.

The "impossible" invention

At the Annual Meeting of the ISMRM, Siemens also showcased the fully functional prototype of a development that had, until then, been thought physically impossible to implement in a clinical imaging system: It was the world's first system to combine MRI with positron emission tomography (PET). PET is a molecular imaging procedure that uses weak radioactive substances to produce images of bodily functions such as metabolic processes in greater detail than other techniques. PET is used primarily in tumor detection, coronary artery examinations, and for diseases of the nervous system. It was long considered impossible to construct a hybrid system that included both MRI and PET. The PET detectors are so sensitive that even the very weak magnetic field of the Earth has to be taken into account in the system's design. PET detectors could not function properly when located near an MRI system – and it was thought that the two systems could never be installed in the same housing. The solution to this issue of basic physics was found in semiconductor technology.

Back in the 1990s, the Molecular Imaging Business Unit at Siemens had begun the painstaking process of developing semiconductor detectors that were impervious to magnetic forces. These detectors were first installed in a kind of miniature MR-PET system, the so-called preclinical systems that were used to study metabolic processes in small animals. In 2006, Siemens built the first detector ring large enough to scan the human brain. This "BrainPET," which was integrated into the 3-tesla MAGNETOM Tim Trio, served as the basis for four research systems. With

One of the key strengths of the Biograph mMR – a hybrid MR-PET system – is its ability to acquire detailed images of the nervous system



Whole-body scan made using the Biograph mMR in 2010. The system is used primarily in research, for example, in the development of new therapies.

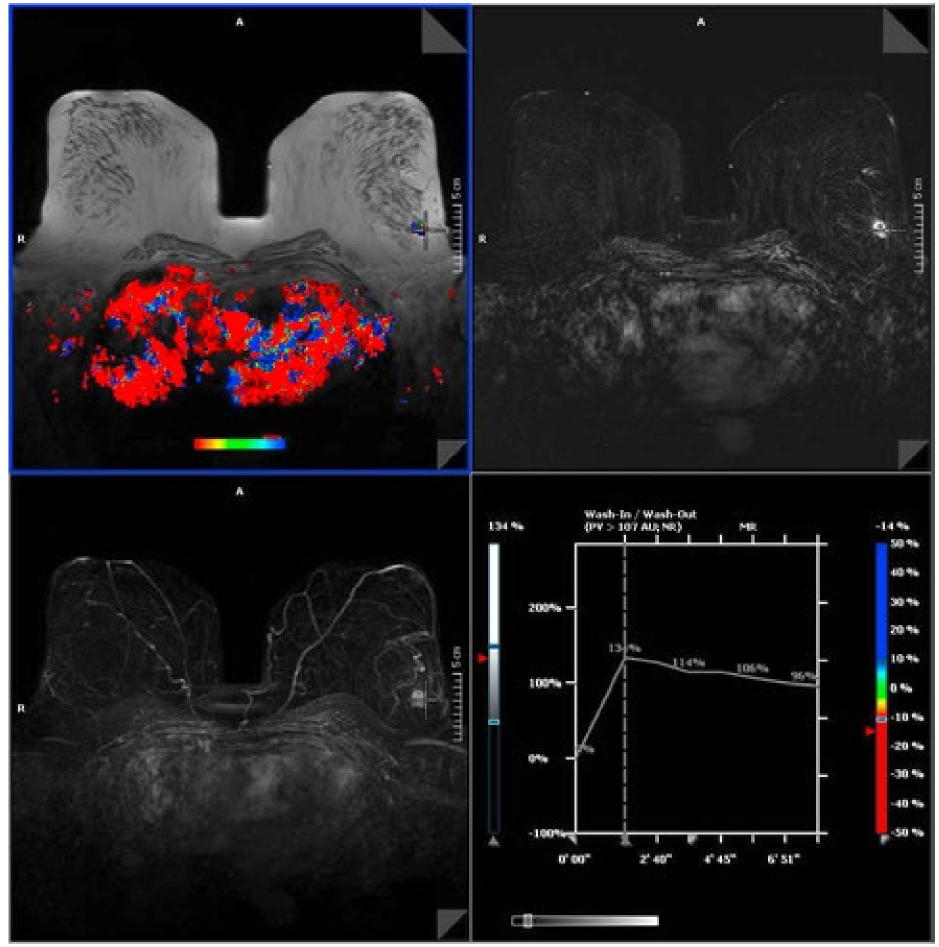
the support of scientists from the University of Tennessee in the U.S. and the University of Tübingen, researchers acquired the first MR-PET scans of the human brain, which Siemens unveiled at the Annual Meeting of the ISMRM in 2007. Following another three years of development funded by the German Research Foundation, the first clinical application test of the Biograph mMR ("molecular magnetic resonance") commenced in November 2010 at the University Hospital rechts der Isar of the Technical University of Munich. The idea was to use the Biograph mMR in Munich for treatment planning and in long-term cancer aftercare. One of the particular strengths of the Biograph mMR is its ability to acquire detailed images of the nervous system, which, during an examination, can help to precisely identify tissues affected by conditions such as dementia or epilepsy. In today's clinical practice, the MR-PET is used, for example, when investigating how a patient's body is responding to prescribed medications. The Biograph mMR also plays a role in research, for instance, in supporting the development of new therapies.

New potential

In the mid-2000s, Siemens collaborated with Massachusetts General Hospital (MGH) on the development of a new prototype. The system, which is based on the MAGNETOM Trio with a field strength of 3 tesla and Tim technology, was equipped with 128 independent radio-frequency channels instead of the 32 channels that were standard at the time. MGH studied the fundamental properties of the 128-channel MRI technology and explored potential applications. Findings published in 2006 demonstrated that the large number of channels were capable of producing images with a much higher resolution or speeding up examinations significantly. Tim technology with 128 channels processed signals emitted from the body up to 25 times faster than systems based on earlier standards. Complex examinations, such as cardiac imaging in cardiology or fMRI in neurology, were faster and easier to perform with 128 channels. At the time, MRI was becoming an increasingly common tool in cardiac examinations. Images of the heart could now be captured during a single phase of breath and observed on a monitor in real time.

Software was just as important as hardware when it came to maximizing the potential of MRI technology. As time went on, Tim technology, combined with new software, paved the way for new applications, including techniques that were optimized for cardiological standards. For example, Siemens developed *syngo* BEAT to improve the speed and precision of cardiac MRI, which had previously been a complicated, time-consuming procedure. Now, with just a few clicks of the mouse, *syngo* BEAT could capture three-dimensional images of the myocardium, the coronary arteries, cardiac functions, and much more – even for patients with arrhythmias. The software was based on algorithms that independently adjusted the settings of the MRI system to the patient's heart rate and automatically suspended data collection in the case of cardiac arrhythmias, among other features.

In the latter half of the 2000s, Siemens introduced more new software solutions than ever before. Using *syngo* SPACE, for instance, it is possible to image the entire central nervous system in just five minutes. The application can capture even the tiniest lesions and the precise locations at which nerve roots exit the spine. In 2006, Siemens released *syngo* GRAPPA, a parallel acquisition technique optimized for fast, high-resolution imaging. *syngo* GRAPPA dramatically streamlined the process of acquiring spinal images, MR angiograms, and other procedures for children[3] and patients who were unable to lie down and remain still for long periods of time. One of the key *syngo* MR applications at this time was *syngo* TimCT. The abbreviation CT stands for *Continuous Table move*, and the association with computed tomography was intentional. With *syngo* TimCT, the patients did not remain in a fixed position on the examination table; instead, they moved forward through the tunnel at a continuous speed just like with a CT scan. TimCT paved the way for new applications, sped up examinations, and improved workflow efficiency. In the past, an examination may have comprised up to twelve steps – from prepping the patient to completing the scan – but by the late 2000s, that number was down to only six, thanks to techniques like TimCT.



The analysis software *syngo* BreVis is one of the numerous applications developed by Siemens during the second half of the 2000s

MAGNETOM Verio, introduced in 2007, was the final addition to the first generation of Tim systems: As the first MRI system, the MAGNETOM Verio combined a field strength of 3 tesla with a 70-centimeter bore. In addition, the system's magnet, measuring 173 centimeters in length, was the world's shortest magnet to boast a field strength of 3 tesla. MAGNETOM Verio requires only slightly more space than the average 1.5-tesla system; weighing around 6 metric tons, it is extremely light for a 3-tesla system and consumes no helium, meaning that it is always ready for operation. At the turn of the millennium, 3-tesla systems were used mainly in research due to their superior image resolution, but by the middle of the next decade, they were starting to become more common in routine clinical procedures as well. By 2007, 3-tesla systems already comprised around 13 percent of all systems.

Cost pressures in the healthcare industry continued to mount over the first decade of the 21st century. In response, Siemens increased its investment in the development of more powerful and cost-effective systems that were tailored to the needs of hospitals and doctor's offices with tighter budgets. The 1.5-tesla MAGNETOM Essenza system developed

The MAGNETOM Verio was the first system to unite a field strength of 3 tesla with a 70-centimeter bore

The entry-level MAGNETOM Essenza system developed in Shenzhen with the support of Erlangen and Oxford was tailored to the needs of hospitals and doctor's offices with tighter budgets

The team in Shenzhen was focused primarily on making MRI technology accessible for a wider range of customers

in Shenzhen with the help of Oxford and Erlangen had a far lower price tag than other MRI systems in this market segment; nonetheless, the system combined the latest technologies, such as Tim, with innovations like the *Focus Shoulder Array*. This coil technique shifted the examination region of the magnet from the center of the system to the shoulders. Without the Focus Shoulder Array, the shoulders would be located at the very edges of the measurement area during examinations.
Not only did the system feature a lower purchase price and reduce operating costs, but it also generated savings of up to 25 percent in facilities and construction costs. This was made possible in part thanks to the comparatively light weight of the magnet – just 3.5 metric tons. This meant that the MAGNETOM Essenza would no longer be relegated to the basement due to its weight like other systems; it could now be installed on floors with a standard load capacity of 500 kilograms per square meter.

New workflows

Technological innovations are a major driver of increased productivity in the healthcare sector, so optimizing costs and continuously improving workflows were core concerns in the development of the next generation of Tim systems. The 1.5-tesla MAGNETOM Aera and the 3-tesla MAGNETOM Skyra, the new systems Siemens introduced at the 95th Annual Meeting of the Radiological Society of North America (RSNA) in November 2009, were the first to be equipped with the newly developed *Dot Engine*. *Dot* stands for *Day optimizing throughput*. Together, Tim and Dot improved the user experience, shortened examination times, and thereby increased the productivity of MRI examinations at hospitals by up to 30 percent. In just a few clicks of the mouse, examination parameters could be customized for each individual patient. For example, it was possible to take into account how long each patient could hold their breath. Dot was optimized for numerous workflows, including examinations of the heart, brain, and knee as well as for tumor diagnostics. The Dot Engine also provided images and text to guide users through complex examinations step by step.

Just like the Dot Engine, the new *syngo*.via[5] imaging software helped speed up examinations and improve patient comfort. *syngo*.via, for example, suggests appropriate and time-saving workflows tailored to suit the individual patient and disease profile. Separate workstations in the clinic were networked using *syngo*.via so that examination results could be accessed from any computer in the network. The examinations were also intended to be as comfortable as possible for patients: In addition to the 70-centimeter bore, which had since become the standard for almost all new Siemens MRI systems, the housing of the MAGNETOM Aera and the MAGNETOM Skyra were equipped with “mood lighting” that bathed the examination room in relaxing colors.

The Dot Engine guides users through complex examinations step by step

Tim technology, which had been integrated in the MAGNETOM Aera and MAGNETOM Skyra for the very first time, was an advanced version of the first-generation Tim technology dating back to 2003. In this new Tim 4G technology – the fourth generation of coils – the 76 coil elements and 32 receiver channels of the older generation were replaced with 204 coil elements and 128 channels. The new mobile table with an integrated, removable 32-channel coil was capable of supporting patients weighing up to 250 kilograms. Patients who were overweight, severely ill, or bedridden could now be prepped outside the MRI room and transported to the scanner on the patient table, which could then be docked to the system. Tim 4G coils were connected wirelessly via the DirectConnect interface and could be flexibly adjusted to fit the different regions of the body using SlideConnect. All RF transmitter and receiver components were connected to the system wirelessly using the new DirectRF digital in/out technology.

In the 2000s, techniques such as the Total imaging matrix, MR-PET, 7-tesla research systems, and TimCT again expanded the range of MRI applications considerably. It was now possible to perform high-resolution whole-body scans, produce three-dimensional images of the heart, and observe tissue metabolism. The introduction of the 70-centimeter bore and smaller improvements, such as lightweight, wireless coils, made the MRI experience far more comfortable for patients. Major advances in software development also led to a quantum leap in performance and improvements in hardware. And the years that followed would not be any less exciting. On the contrary, new ideas and approaches in MRI over the next decade would lead to groundbreaking innovations that still seemed like distant dreams back in 2010.

In 2009, Siemens introduced the next generation of Tim systems

New freedoms

Magnetic resonance imaging for more and more people

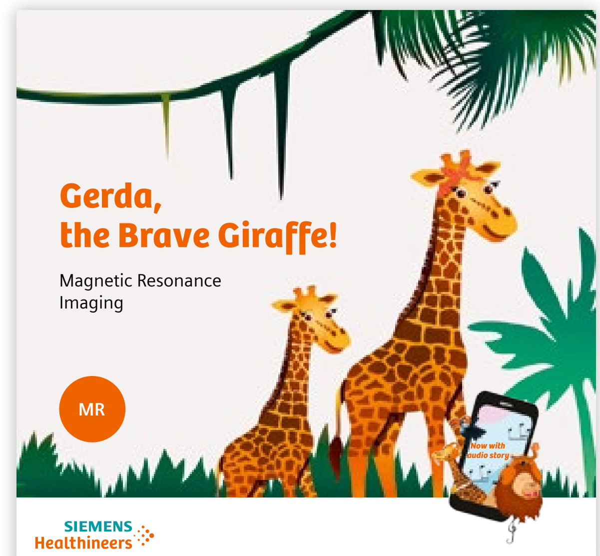
In its early years, magnetic resonance imaging was a method that was applied by only a few specialists and was accessible to relatively few patients. There were many reasons for this: Operating the early systems was so complicated that users required sound knowledge of physics to run a magnetic resonance scanner. Only a few radiologists were trained for the far from trivial interpretation of the result images in the early years. The systems also weighed up to 40 metric tons, required a considerable amount of maintenance, and their high helium consumption incurred substantial operating costs. In the 1980s, so much space was still required to install an MRI scanner that costly conversions were necessary in hospitals and practices. The narrow and long magnet bores made it difficult or even impossible to examine, for example, overweight or claustrophobic patients. The numerous new technologies and applications that have been developed since the early 1990s have made MRI accessible to more and more patients and vastly expanded the ways in which the technology can be used. Let us look at how progress has been made in one particular field, pediatrics.[3]

Children represent a significant challenge for medical imaging. Their faster heart rates and their higher respiratory rates present special requirements for the technology. The resolution of the images has to be higher to ensure that the small organs can be represented with the same

Since the end of the 2000s, special coils have been used to examine children in pediatric medicine

level of detail as the organs of adults. Techniques such as parallel imaging, special pediatric coils, higher field strengths, and faster sequences have enabled magnetic resonance imaging to be used in pediatrics, initially for brain examinations and then for all organs. For example, by the early 2010s, it was possible to scan the rib cage, the abdomen, the musculoskeletal system, and the heart of children with MRI. To prepare children for the examination as well as possible and to help them to stay still for as long as possible during the scan, children's picture books, MRI toys, music, and videos for specific age groups have been developed over time.

Gerda, the Brave Giraffe! prepares children for their MRI examination and is intended to dispel any fears they may have. It comes as a picture book, audio book, and a special "magic song" for children.



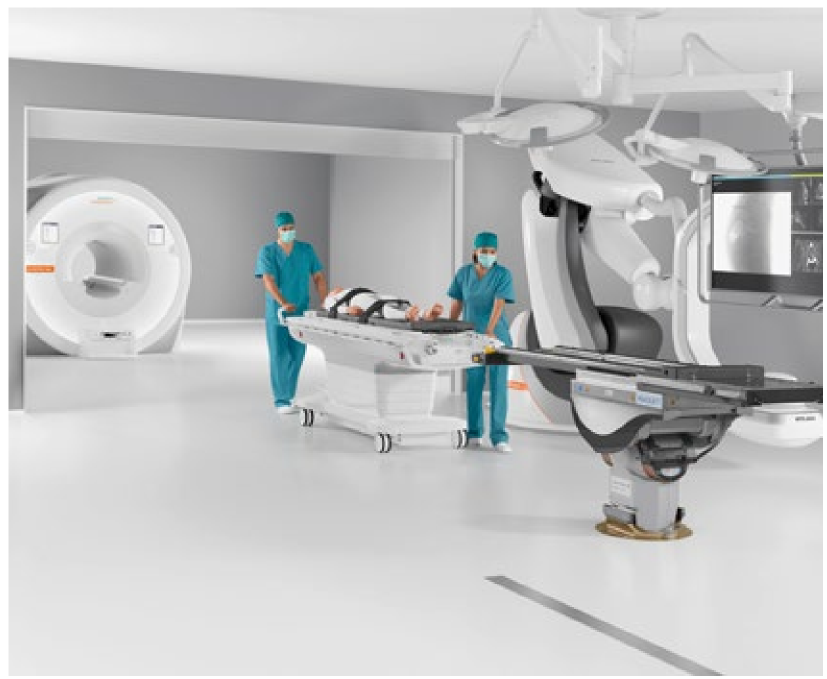
MRI toys can help children prepare as well as possible for the examination

The high-end system MAGNETOM Prisma introduced in 2013 was optimized for the requirements of fundamental neurological research but was also valued by many customers as a high-end system for clinical diagnostics

Neural pathways from as many as 514 directions

Systems with the highest clinically approved field strength at that time, 3 tesla, had also been improved substantially over the previous ten years in every respect. Whereas examination times of more than one hour were common with 3-tesla scanners in the first installations at the turn of the millennium, the scans performed with the technology of the early 2010s often took just a few minutes. And the image quality bore virtually no resemblance to that of the first 3-tesla systems. In 2012 and 2013, Siemens extended its portfolio of 3-tesla magnetic resonance scanners with the entry-level system MAGNETOM Spectra and the high-end system MAGNETOM Prisma. With its comparatively low entry price and low operating costs, MAGNETOM Spectra made 3-tesla technology accessible for smaller hospitals and radiology practices. The 4th generation Tim technology was based on newly developed coils with up to 204 elements, using up to 128 channels. Due to complete digitization of all signals, Tim 4G functions, such as *DirectRF*, enabled improvements in the signal-to-noise ratio, for example. This resulted in more stable images with fewer artifacts. Tim 4G sped up examinations due, among other reasons, to the new *DirectConnect* and *SlideConnect* coils. These could be positioned more flexibly and connected to the MRI scanner with far fewer cables.

MAGNETOM Prisma set new standards in many areas. Due to its unique gradient coils, the fastest and strongest at the time, it was now possible to measure even slight movement of liquids in the body, for such purposes as diagnosing hypoxia in the brain. New applications, such as DTI (diffusion tensor imaging), now made it possible to visualize neural pathways in the brain from as many as 514 directions, for example. Apart from the extraordinary gradient strength, the image quality was largely attributable to the homogeneity of the magnetic field. Shim coils, which are devices for homogenizing magnetic fields, compensated better for the inhomogeneities that arise due to the presence of the patient's body in the magnetic field. MAGNETOM Prisma was based on the 3-tesla MAGNETOM Skyra system in terms of technology but optimized for research applications such as fundamental neurological research. Healthcare providers that used MAGNETOM Trio could upgrade it with the technology of MAGNETOM Prisma.



The progress of a neurovascular or cardiovascular intervention can now already be monitored during the procedure using MRI

Combined solutions

One example of the numerous new technologies that Siemens launched in the first half of the 2010s was the product package *MAGNETOM Combi Suite*, which had been optimized for use of magnetic resonance imaging in surgical interventions. To integrate the MRI quickly and simply into the workflow of operations, Siemens developed a mobile scanner table, the *Combi Dockable Table*. It could be used, for example, to transport patients swiftly and safely to the MRI during a neurovascular or cardiovascular intervention to check progress of the treatment.

In 2014, Siemens introduced several innovations with MAGNETOM Amira. The 1.5-tesla system used 30 percent less power due to *Eco Power Mode*. This monitors the helium circuit and controls cooling and re-condensation of the helium more efficiently. *DotGO*, the latest generation of MRI examination software at the time, adapted the workflow for each scan to the specific diagnostic question. The *Quiet Suite* application lowered the noise volume for patients by up to 97 percent. Some examinations with MAGNETOM Amira could actually be performed with almost no noise at all.

7 tesla for clinical use

Just 15 years after 3-tesla systems had first been introduced to clinical practice, Siemens was preparing to launch MAGNETOM Terra, the world's first 7-tesla system for clinical use. The benefits of systems with a field strength of 7 tesla were apparent in neuro-imaging. Distinction between white and gray cerebral matter is substantially easier to depict at this field strength. The higher contrast, the improved signal-to-noise ratio, and the higher resolution of 7-tesla systems reveal important details in these exami-nations that are not visible with 3-tesla systems.

When Siemens first publicly presented MAGNETOM Terra prototype in May 2015, market approval for clinical use in certain neurological and orthopedic applications was in the planning. In July 2017, MAGNETOM Terra got the CE marking and could now be used in clinical diagnostics in Europe. This was followed two months later by the release in the US and commercial distribution for the U.S. market.

The actively shielded magnet developed by Siemens Magnet Technology in Oxford was the lightest 7-tesla magnet in the world, 50 percent lighter than previous actively shielded magnets. MAGNETOM 7T introduced in 2005 weighed 32 metric tons; MAGNETOM Terra only around 17 metric tons. This made it considerably easier to transport and bring into a hospital building. Thanks to its Dual Mode function, MAGNETOM Terra could switch between research[6] applications and clinical protocols in less than 10 minutes.

At the touch of a button

Siemens Healthineers was able to apply experience gained from developing the 7-tesla system to designing MAGNETOM Vida with a field strength of 3 tesla. The new high-end system became one of the strongest commercially available gradients of all scanners with a 70-centimeter magnet bore. After more than five years of development, the company presented MAGNETOM Vida in early 2017 at the Universitätsklinikum Tübingen and at the European Congress of Radiology (ECR) in Vienna, with a new technology that represented a significant milestone on the way to precision medicine and individual patient healthcare: *BioMatrix Technology* provided reproducible examination images reliably, irrespective of who is being examined or who is operating the system. In other words, BioMatrix Technology considered both the physiological and anatomical differences between patients and the different levels of experience and training of users. For example, the *BioMatrix Sensors* in the examination table measure the breathing cycles and enable automatic triggering of the sequence measurement based on the respiration signal. In the past, that had required application of a dedicated respiration belt. This saved examination time for users and increased comfort for patients.

BioMatrix Technology also included *BioMatrix Tuners*, which enabled the local magnetic field to be optimally adapted to an individual patient. In this way, image artifacts that might impair the diagnostic quality of the high-precision 3-tesla systems in particular could be better avoided. The touchscreen user interface of MAGNETOM Vida, called *BioMatrix Select&GO*, now made optimum positioning of the patient possible with just one click: The examination table auto-matically moves into the correct position for scanning based on intelligent body models. In this way, the BioMatrix technology sped up patient positioning by up to 30 percent. With the *Compressed Sensing application*, which permits up to ten times faster MRI scans than without this technology, it was now possible, for example, to perform dynamic exami-nations much more efficiently and comfortably for the patient. For example, with Compressed Sensing, dynamic examinations of the liver could be performed at the press of a button in one scan run without breath-holding. Such images could previously only be acquired in four separate steps with breath-holding for about 20 seconds each time. For planning and performing the previously complicated whole-body images, just a few clicks were now necessary: The *Whole-Body Dot Engine* of MAGNETOM Vida simplified and automated examination planning to a noticeable degree so that a whole-body examination could now be performed within 25 minutes.

In 2017, Siemens Healthineers introduced BioMatrix Technology with MAGNETOM Vida

MAGNETOM Terra was the first 7-tesla system worldwide to be cleared for clinical use

MAGNETOM Sola, introduced in 2018, was the first 1.5-tesla system to feature BioMatrix Technology

Around one year after presenting MAGNETOM Vida, Siemens Healthineers introduced BioMatrix Technology to 1.5-tesla imaging: MAGNETOM Sola combined many innovations into a 1.5-tesla system and was, later, also equipped with two new BioMatrix Sensors: The *BioMatrix Beat Sensor*[7] integrated into the body coil automatically detects the movements of the heart so that no electrodes have to be applied to the patient's skin. Used in combination with parallel imaging, the *Simultaneous Multi-Slice* and *Compressed Sensing* technologies, which are explained in more detail below, reduced the examination times with MAGNETOM Sola by up to 50 percent.

Free breathing

By the mid 2010s, magnetic resonance imaging had reached a level at which no significant increase in examination speeds was possible even with the hardware of high-end systems. For example, due to the relatively long acquisition times required for certain heart examinations, patients had to hold their breath fourteen times for a prolonged period. Together with the regeneration phases, imaging of the heart took up to six minutes. At the end of 2016, Siemens Healthineers presented a solution in which patients could breathe freely during the same examination, where the scan took just 25 seconds: The *Compressed Sensing Cardiac CINE* software technology is based on algorithms that can speed up image calculation by a factor of ten. Compressed Sensing only includes the data points required for diagnosis and reconstructs high-resolution images step by step without any loss of image information.

"Compressed Sensing enables scanning speeds that we could only dream of before," explained Dr. Christoph Zindel, who was Vice President of Magnetic Resonance at Siemens Healthineers at the time. The algorithm on which Compressed Sensing is based was first presented to the public in 2014 by a working group in cooperation with Siemens at the conference of the International Society for Magnetic Resonance in Medicine (ISMRM). After the technology had emerged as the winner in the competition for dynamic imaging, Siemens Healthineers further developed the algorithm and took it to market readiness together with research partners around the globe. "Working closely with our cooperation partners, we have really been able to pioneer this technology," said Zindel. "Compressed Sensing Cardiac CINE is just the first step; we're already working together with our partners to expand this technology, and will bring further applications to the market."

A short time after the application for cardiology, Siemens Healthineers introduced Compressed Sensing for examinations of the abdomen. Repeated breath-holding and complex timing for contrast medium administration were no longer necessary with *Compressed Sensing GRASP-VIBE*[8]. The application acquires the image data of the abdomen region being examined in one continuous run while the patient breathes freely. With *3D Compressed Sensing SPACE*, it was now possible to acquire high-resolution images of the pancreas and the bile duct system either with a single short breathing pause or within two minutes with free breathing.

Image of the liver. Compressed Sensing GRASP-VIBE made this type of abdomen examination possible without patients having to hold their breath several times.

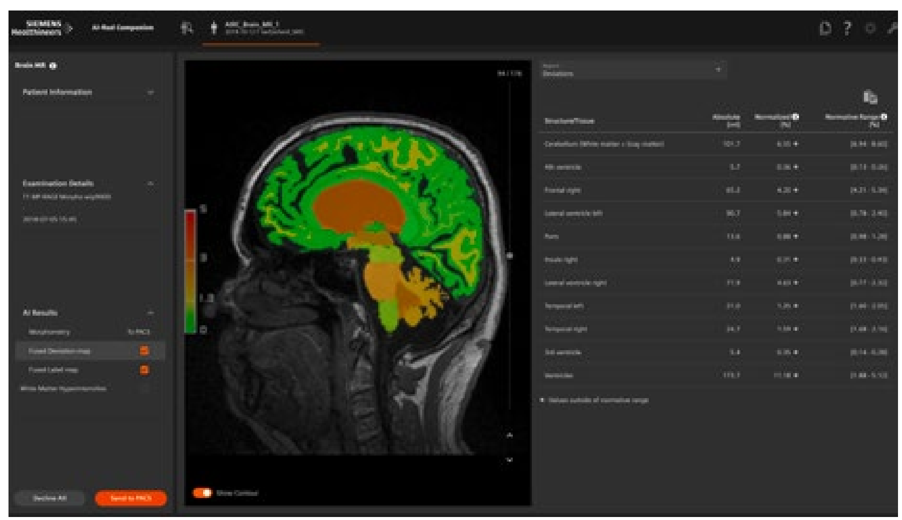
Simultaneously instead of sequentially

One of the most significant innovations that Siemens Healthineers introduced to magnetic resonance imaging with MAGNETOM Vida and MAGNETOM Sola included *Simultaneous Multi-Slice (SMS)* technology. Like Compressed Sensing, Simultaneous Multi-Slice technology also substantially shortens the duration of certain examinations. The technique is based on parallel imaging, the most frequently used method of clinical MRI. SMS goes one step further than parallel imaging and acquires the slices not sequentially, but rather simultaneously. The combination of Simultaneous Multi-Slice technology with pulse sequences such as echo-planar imaging can halve the duration of brain scans, for example. Instead of saving time overall, images can also be acquired with higher resolution or thinner slices in the original scanning time. Again, Siemens Healthineers developed Simultaneous Multi-Slice technology to market readiness with numerous cooperation partners, including the Center for Magnetic Resonance Research (CMRR) of the University of Minnesota and the Massachusetts General Hospital of the Harvard Medical School. Siemens Healthineers has combined Simultaneous Multi-Slice and Compressed Sensing with technologies such as parallel imaging in the *Turbo Suite* solution.

Learning for the future

In addition to technologies for faster image acquisition, artificial intelligence (AI) has been contributing to considerably shortening examination times for some years now. The Dot Engine is based on machine learning and helps users to perform examinations quickly and efficiently using the best possible parameters. The idea is to relieve the clinical personnel of standardized and recurring tasks as far as possible. With advances in recent years in computer power and the development of algorithms, novel and more complex applications are increasingly becoming possible. In particular, training neural networks – deep learning – has huge potential for the future. AI can recognize quickly and precisely patterns in vast and complex data volumes that the algorithm has learned based on high-quality training data. The more training data is made available to the AI, the more precisely it will be analyzed. Possible applications in magnetic resonance imaging include, for example, preparation of the examination, image calculation, reducing the workload of the radiologist during evaluation of the result images, and support with clinical decision-making.

The success of artificial intelligence in clinical practice depends on the performance of the algorithms and on seamless integration of these digital wizards into radiology workflows, and other factors. Siemens Healthineers makes use of the technology in the *AI-Rad Companion* platform[9], which was presented initially for examinations of the rib cage in computed tomography in 2019. At this time, a prototype of the smart wizard in magnetic resonance imaging to support reporting of the prostate with numerous analysis steps also became available. A short time after that, Siemens Healthineers presented the *AI-Rad Companion Brain MR*[10], which can be used in evaluating brain images. Software such as AI-Rad Companion will not replace radiologists but rather relieve them of routine activities so that they have more time to dedicate to difficult diagnoses.



AI-Rad Companion Brain MR can provide support with evaluating images and, among other capabilities, automatically generate a report with a volumetric analysis of the brain

Faster and quieter

At the beginning of 2019, Siemens Healthineers presented two cost-efficient scanners that enable access to high-end technologies: MAGNETOM Altea at 1.5 tesla and MAGNETOM Lumina at 3 tesla were designed from the outset to make MRI examinations as fast and as comfortable as possible. With these two systems, Siemens Healthineers introduced the new patient infotainment system *Innovision* from Innovere[11]. This also became available for the high-end systems MAGNETOM Vida and MAGNETOM Sola a short time later. Innovision can make examinations more relaxing and comfortable. As soon as patients are in position on the table, Innovision plays videos or music with excellent hi-fi quality. At the same time, Innovision dampens the sounds of the MRI by means of unique foam pads.

Most of the MAGNETOM systems are equipped with technologies that dampened the sometimes very loud noises that arise when gradients switch. The *Quiet Suite* solution took the noise suppression in MAGNETOM Altea or MAGNETOM Lumina to a new level without impairing image quality. Quiet Suite covers sequences such as *QuietX* and *PETRA* (**p**ointwise-**e**ncoding **t**ime **r**eduction with radial **a**cquisition) and optimized protocols for neurological and orthopedic examinations. QuietX lowers the volume of the MRI system by around 20 decibels, PETRA is overall the quietest sequence from Siemens Healthineers. In many cases, PETRA can even provide diagnostic advantages, for example, for imaging of nasal sinuses. Such sequences can help make the examination more pleasant, above all, for children and dementia sufferers.

The *Innovision* patient infotainment solution can make examinations more relaxing and comfortable

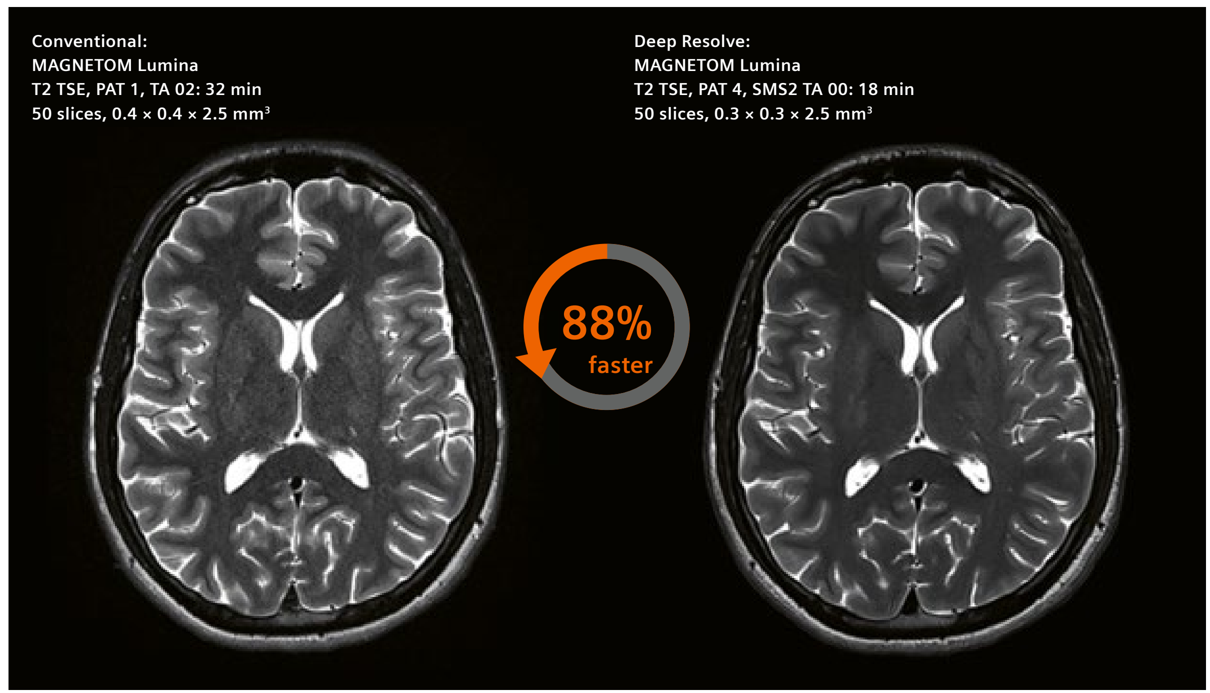
Fingerprints of the tissue

Even today, magnetic resonance imaging still has vast new potential that could find useful application through further technological advancements. One promising new approach, *MR Fingerprinting (MRF)*, could expand the possibilities of MRI considerably and make a significant contribution toward the growing field of precision medicine and individual therapies. MR Fingerprinting differs from conventional magnetic resonance imaging substantially in data acquisition, postprocessing, and visualization. Instead of visualizing the properties of tissue in the conventional way, MR Fingerprinting generates unique "fingerprints" that code the properties of the scanned tissue and anatomy numerically instead of mapping it visually. This process, known as MR quantification, was developed with the aim of characterizing tissue more precisely, i.e., to distinguish healthy tissue from diseased tissue in a standardized way.

Siemens Healthineers has been working in a research partnership with the Case Western Reserve University and the University Hospitals in Cleveland for several years on achieving substantial further improvements in the quantifiability and reproducibility of MR measurements through MR Fingerprinting. The cooperation partners presented the results to the public at the International Society for Magnetic Resonance in Medicine (ISMRM) in Montreal in 2019: The MRF application for clinical research and the associated database were initially available for MAGNETOM Vida and were followed by further software packages for other 3-tesla systems from Siemens Healthineers[12]. The data obtained from the research into MR Fingerprinting can be used to refine the method still further. Today, the focus is on extending the results from neurological MRF research to further regions of the body and on finding additional quantifiable biological characteristics that could be useful in supporting diagnosis.

Images through intelligence

In the 1980s, magnetic resonance imaging quickly became established because of the extraordinarily high soft-tissue contrast although it had one characteristic disadvantage compared with other imaging methods: An examination with MRI took much longer than, for example, with computed tomography. To obtain imaging of smaller body regions with maximum image quality, a CT scanner at that time required just a few seconds, while an MRI scanner often took 30 minutes or more, depending on the pulse sequence used. Over the years, the scanning time in the magnetic resonance scanner has been greatly reduced, above all by technologies such as parallel imaging, Simultaneous Multi-Slice, and Compressed Sensing. For some years, artificial intelligence has also been speeding up planning and preparation of examinations and providing support with the interpretation of images. Artificial intelligence also has enormous potential in another work step: The scanning time can be substantially shortened even with improved image quality, if special algorithms are used to reconstruct the image.



The AI-assisted image reconstruction technology Deep Resolve can speed up examinations considerably with the same or even better image quality

Without the use of artificial intelligence for image reconstruction, the quality of MR images is influenced by three interdependent factors: speed of acquisition, resolution of the images, and signal-to-noise ratio. Improving any one of these three factors has a negative effect on at least one of the other two factors. If the acquisition time is shortened substantially, the image can be impaired in various ways, especially by an increase in noise in the image. AI-based image reconstruction has the potential to improve all three factors at the same time. With the deep learning technology of *Deep Resolve*, Siemens Healthineers introduced AI-assisted algorithms for image reconstruction to magnetic resonance tomography in 2020. A knee examination with a 3-tesla system, for example, takes around 10 minutes with conventional image reconstruction; with Deep Resolve algorithms, this time can be reduced to under two minutes for the same image quality.

Instead of improving the completed clinical image, Deep Resolve works directly with the raw data from the scan. The reconstruction algorithm reduces image noise step by step in iterative reconstruction. The underlying neural network was trained using many thousands of data pairs to reduce the noise resulting from shortening scan times especially efficiently. Deep Resolve consists of several algorithms that can be combined, for example, to calculate sharper images or for the requirements of certain examinations, such as brain scans. To maintain the diagnostic value and the quality of the images, Deep Resolve automatically checks the consistency of the data step-by-step over the entire image reconstruction.

Less is sometimes more

The technical progress of the past decades has resulted in magnetic resonance imaging being available for examinations of more and more people. However, for various reasons, most of the world's population still has no access to MRI: The higher costs compared with other imaging methods can be a big obstacle to small healthcare providers, especially in rural areas. MRI systems are large and heavy systems that require costly conversions of the premises and complex infrastructure. Patients with implants[13] can so far only be examined to a limited degree in superconducting MRI systems. For many claustrophobic or obese people, the 70-centimeter magnetic bore is too narrow. To make the technology accessible to more people and to bring magnetic resonance imaging to places where it was previously not possible to use it, Siemens Healthineers is overcoming these obstacles with a new approach to system design. In November 2020, the company presented the first system of a new class of magnetic resonance scanners: MAGNETOM Free.Max – the world's first magnetic resonance scanner with an 80-centimeter wide opening for the patient.

Previously, the installation of a magnet was complicated and required much planning and preparation before the system could be brought into the building. With MAGNETOM Free.Max, installation becomes considerably easier. Instead of lifting the magnet into an expensively converted examination room using a crane, with its transportation height of less than two meters, MAGNETOM Free.Max can be moved through doors, corridors, and in hospital elevators. For installation, it is no longer necessary to make holes in walls or even roofs. The entire system requires just 24 square meters of room area, weighs less than 3.2 metric tons, and can therefore be installed at many locations in the hospital.

Conventional MRI systems require up to 1,500 liters of helium and expensive installation of a quench pipe that guides the evaporating helium out of the building if the magnet is switched off. The *DryCool technology* of MAGNETOM Free.Max, by contrast, is a self-contained magnet design that works with 0.7 liters of liquid helium. The entire infrastructure required for operation is integrated into the magnet.

The world's first magnetic resonance scanner with an 80-centimeter wide opening for the patient: MAGNETOM Free.Max

Clinical image of a spine acquired with MAGNETOM Free.Max

Siemens Healthineers combined digital technologies with the extraordinary field strength of 0.55 tesla in MAGNETOM Free.Max and named this *High-V MRI* technology. The Deep Resolve algorithm was combined with other digital technologies such as Simultaneous Multi-Slice and Compressed Sensing to achieve a system performance that had been inconceivable at such a low field strength in the past. In conjunction with the field strength of 0.55 tesla, High-V MRI enables examinations that were previously scarcely achievable in MRI. For examinations of the lung, for example, the signal quickly falls away at the air-tissue transition when higher field strengths are used. The higher the field strength, the more difficult lung imaging becomes. High-V MRI also has clear advantages over conventional MRI for patients with metal implants. Metal causes image artifacts that occur much less frequently at 0.55 tesla. The user guidance of MAGNETOM Free.Max is also based on artificial intelligence and was developed from scratch for novice MRI users. The *myExam Autopilot* application, which is available as part of the *myExam Companion* package, automates routine examinations completely. The time-consuming positioning of patients is made much easier and faster with the world's first 3D camera integrated completely into the scanner. *myExam 3D Camera* is also used in other imaging technologies at Siemens Healthineers such as computed tomography. The camera senses the outer contours of the body and the exact position on the table, for example, of the elbows and hands. The AI-assisted algorithm of the camera calculates three-dimensional data from this and automatically positions the patient optimally at the center of the magnetic field. At the same time, the examination remains fully configurable for experienced users via the *myExam Assist* and *myExam Cockpit* applications. This overcomes a further obstacle in MR imaging, complicated operation, so that MR imaging becomes accessible to more people.

The MRI comes to the patient, not the other way round

Even around 35 years after the first MAGNETOM scanners were installed on a low-loader, to make magnetic resonance imaging accessible to the greatest number of people, mobile MRI scanners are still a flexible alternative or addition to permanently installed systems. Medical service providers such as RAYUS Radiology give healthcare facilities in the USA the chance to rent mobile scanners for a short time or long time. The systems can, for example, help with screening programs in poorly served areas or provide a stopgap while a building is being converted. In November 2022, Siemens Healthineers introduced the latest generation of mobile scanners – MAGNETOM Viato.Mobile[14]. The system is based on the current 1.5-tesla platform from Siemens Healthineers and will provide the same options as permanently installed scanners with technologies such as Deep Resolve and myExam Companion. If necessary, MAGNETOM Viato.Mobile will be operated and maintained via a cellphone link. This means that fewer personnel will be required on site; specialists can work, for example, from home and support colleagues at the system remotely.

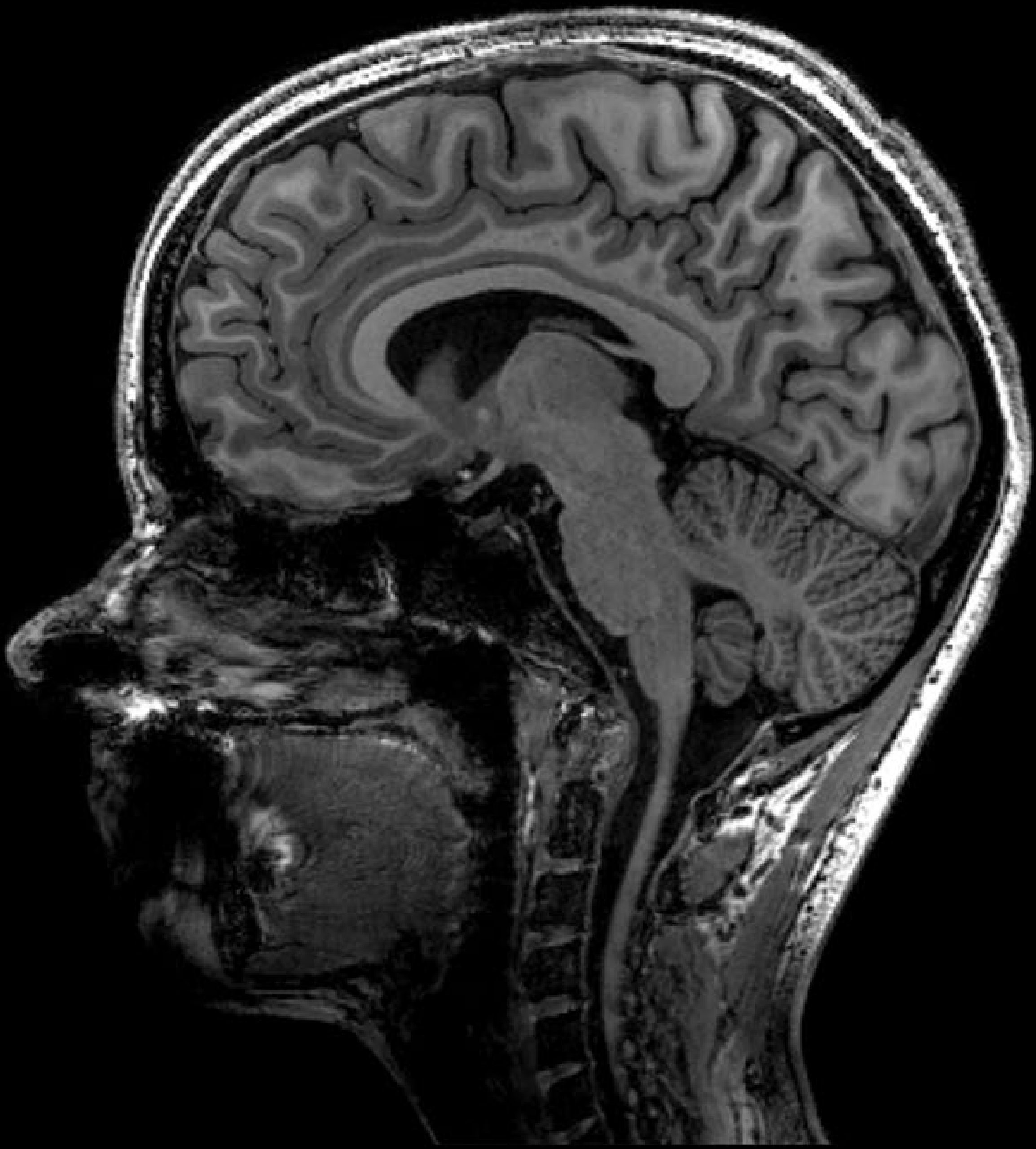
Research and routine clinical use combined

Each year since the end of 2020, Siemens Healthineers has brought together some of the most influential opinion makers from the global healthcare industry at the *Shape* in-house event and presents the latest innovations. At the *Shape 23* press conference in November 2022, Arthur Kaindl, at that time head of Magnetic Resonance Imaging at Siemens Healthineers, introduced the two latest high-end magnetic resonance scanners for research and routine clinical use: the 3-tesla system MAGNETOM Cima.X[15] and MAGNETOM Terra.X[16] with a field strength of 7 tesla. In presenting MAGNETOM Cima.X, the focus was on the gradient technology. The strength of the gradients is very important in magnetic resonance imaging where the aim is to visualize microstructures clearly. A high gradient strength could, for example, play a crucial part in understanding neurological diseases like multiple sclerosis. The gradients of MAGNETOM Cima.X will be 2.5 times stronger than the most powerful gradients previously available from Siemens Healthineers. In this way, microstructures will be imaged with much more detail than was previously possible.

In November 2022, Siemens Healthineers introduced MAGNETOM Viato.Mobile, the latest generation of mobile scanners

The gradients of MAGNETOM Cima.X presented in 2022 will be 2.5 times stronger than the most powerful gradients previously available from Siemens Healthineers

Ultra IQ technology, which is still under development, is intended to exploit the full potential of 7T MRI. The image shown is acquired using a non-commercial system (MAGNETOM Terra.X) under institutional review board permission.



For MAGNETOM Terra.X, too, the level of detail in the examination images was the focus of the presentation. The magnitude of the field strength of the system will enable especially high-resolution images in which even the smallest changes or tissue lesions can be seen. For certain diseases, imaging of such lesions will be decisive for further treatment. With new hardware and software, which Siemens Healthineers groups together under the name *Ultra IQ technology*, MAGNETOM Terra.X will eliminate a side-effect of conventional acquisitions with extremely high field strength: Until now, head images produced with a field strength of 7 tesla often included a sort of shadow effect, which darkened the lower part of the image, for example. Ultra IQ technology has been developed to eliminate such shadow effects. At the same time, the speed of acquisition will be considerably increased with Deep Resolve: "By introducing AI-based algorithms on these high-end scanners for the first time, we reduce the scanning time in MRI by up to 50 percent, while improving image quality," said Arthur Kaindl at the presentation of MAGNETOM Cima.X and MAGNETOM Terra.X during the Shape 23 Keynote.

Innovations of this type would not be possible without the research partners of Siemens Healthineers, both on the technical and on the clinical side. In 2022, the company worked on the further development of magnetic resonance imaging with around 1,000 partners around the globe to develop new technologies for routine clinical use. To streamline this collaboration, Siemens Healthineers introduced the software-based platform *Open Recon*[17] in 2022.

The people behind the technology

Whereas the first MAGNETOM from the year 1983 was developed by a small team working in a wooden shed in Erlangen, today systems such as MAGNETOM Free.Max are created by hundreds of people working together around the globe. The technological progress and the people involved in bringing it about are a single phenomenon: Physicians, researchers, physicists, engineers, patients, numerous cooperation partners and a host of employees of Siemens Healthineers all make these developments possible. Even after the huge progress of past decades, there is still enormous potential in MRI waiting to be unleashed, and no doubt many more fascinating chapters will be added to this book about the history of magnetic resonance imaging at Siemens Healthineers ...

Publishing notes

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Data on file. Results may vary.

[1] The MRI restrictions (if any) of the metal implant must be considered prior to patient undergoing MRI exam. MR imaging of patients with metallic implants brings specific risks. However, certain implants are approved by the governing regulatory bodies to be MR conditionally safe. For such implants, the previously mentioned warning may not be applicable. Please contact the implant manufacturer for the specific conditional information. The conditions for MR safety are the responsibility of the implant manufacturer, not of Siemens.

[2] MR examination is contraindicated for patients with electronic or electronically conductive implants or metals. A qualified physician must evaluate the risk/benefit ratio of the MR examination for every patient.

[3] MR scanning has not been established as safe for imaging fetuses and infants less than two years of age. The responsible physician must evaluate the benefits of the MR examination compared to those of other imaging procedures.

[4] MAGNETOM 7T is for research only. All data shown are acquired using a non-commercial system under institutional review board permission.

[5] syngo.via can be used as a standalone device or together with a variety of syngo.via-based software options which are medical devices in their own right. syngo.via and the syngo.via based software options are not commercially available in all countries. Due to regulatory reasons their future availability cannot be guaranteed. Please contact your local Siemens Healthineers organization for further details.

[6] Research mode as part of dual mode is available as an option and not intended for clinical use. Research operation may require observation of national regulations.

[7] Beat Sensor Cardiac triggering for examinations other than Cardiac Cine is still under development for 3T BioMatrix systems and MAGNETOM Avanto Fit, and not yet commercially available. Its future availability cannot be ensured

[8] Compressed Sensing GRASP-VIBE for other regions than liver is not for sale in the U.S.

[9] AI-Rad Companion consists of several products that are (medical) devices in their own right, and products under development. AI-Rad Companion is not commercially available in all countries. Future availability cannot be ensured.

[10] AI-Rad Companion Brain MR application is not commercially available in all countries. Due to regulatory reasons their future availability cannot be guaranteed.

[11] The information shown herein refers to products of 3rd party manufacturer's and thus are in their regulatory responsibility. Please contact the 3rd party manufacturer for further information.

[12] This is not commercially available in all countries. Due to regulatory reasons their future availability cannot be guaranteed.

[13] The MRI restrictions (if any) of the metal implant must be considered prior to patient undergoing MRI exam. MR imaging of patients with metallic implants brings specific risks. However, certain implants are approved by the governing regulatory bodies to be MR conditionally safe. For such implants, the previously mentioned warning may not be applicable. Please contact the implant manufacturer for the specific conditional information. The conditions for MR safety are the responsibility of the implant manufacturer, not of Siemens."

[14] MAGNETOM Viato.Mobile is still under development and not commercially available. Its future availability cannot be ensured.

[15] MAGNETOM Cima.X is still under development and not commercially available yet. Its future availability cannot be ensured

[16] MAGNETOM Terra.X is still under development and not commercially available yet. Its future availability cannot be ensured

[17] Open Recon is to add clinical reconstructions to the system, if signed and released for clinical use by SHS. The Open Recon Framework only allows FDA cleared 3rd party algorithms to be imported for clinical use.

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