"The best way to predict the future is to invent it."

Theodore Edward Hook, 1825

Magnetic Resonance Imaging at Siemens: A success story

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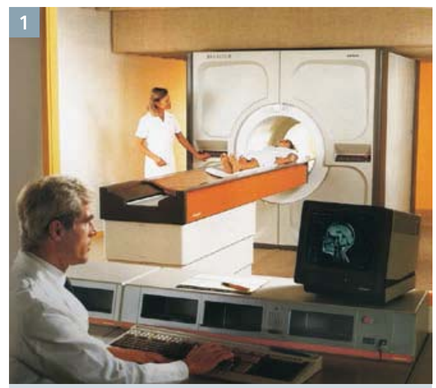
In 1983 the first Siemens MRI system bearing the MAGNETOM name was installed at Mallinckrodt Institute of Radiology, in St. Louis, Missouri, USA. That was thirty years ago.

Today MAGNETOM systems feature our integrated Tim coil technology; our unique Dot scanning software; our applications, which continue to set trends in imaging; and naturally also the design of our MRI systems, which makes scans increasingly efficient for MAGNETOM users and increasingly patient-friendly. Let's take a look back and see how we got there.



1 The very first MAGNETOM system in 1983.

Making the invisible visible

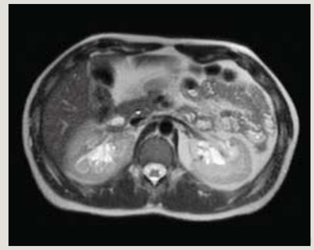
On November 8, 1895, Wilhelm Conrad Röntgen revolutionized the field of medical diagnostics when he discovered X-rays. Over time, researchers developed other imaging methods to help doctors diagnose disease: Computed tomography, ultrasound, and nuclear medicine all use different techniques, each one supplying especially good images for specific scans. In the second half of the 20th century, scientists also began researching the fundamentals of a technology that turned out to be outstanding for medical imaging purposes: Magnetic resonance imaging (MRI).

In 1946, two physicists independently discovered the principle of magnetic resonance: Felix Bloch and Edward Mills Purcell showed that atomic nuclei in a magnetic field tilt when they are excited by a high-frequency electromagnetic field. If this high-frequency field is switched off, the atoms release the energy they have absorbed and return to their original state. By making this discovery, Block and Purcell laid the technical foundations for magnetic resonance imaging. It was an accomplishment for which they shared the Nobel Prize in Physics in 1952.

In 1950, Erwin Hahn proved that atomic nuclei generate an echo – a 'spin echo' – when they are influenced with two high-frequency pulses. But magnetic resonance remained a slow and imprecise method until 1968, when a group of researchers from Zurich made groundbreaking

Innovation track

1984



First passive direct magnetic shielding

progress in enhancing its sensitivity. Richard Ernst, Weston Anderson, and Kurt Wüthrich improved the pulse excitation and used a new method to analyze the resonance signal. This made magnetic resonance technology about a thousand times faster and significantly more sensitive. Ernst went on to receive the Nobel Prize in Chemistry in 1991 for this achievement.

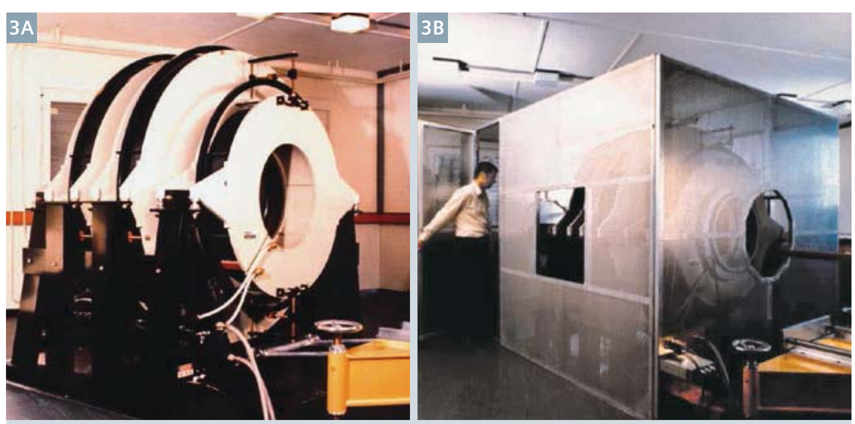
In the years that followed, magnetic resonance imaging became an important analytical method suitable for solids, liquids, and gases – until, in 1971, Raymond Damadian showed that it could also be used to distinguish between tumors and healthy tissue. Modern MRI technology is considered to have been born in 1973, when chemist Paul C. Lauterbur and physicist Sir Peter Mansfield were the first to make it possible to visualize a fluid-filled object. The two men together received the Nobel Prize in Medicine in 2003 for their groundbreaking work in developing MRI technology.

Early history at Siemens

Siemens recognized the new method's potential and displayed great interest in research and development involving this technology. Engineers at the Siemens research lab used magnetic resonance to study the qualities of plastics back in 1959. In 1965, the company hired a man who would play a significant role in shaping the development of MRI in the years to come: The physicist Alexander Ganssen (Fig. 2). Ganssen became intrigued by magnetic nuclear resonance while still a student, and remained true to this passion for the rest of his life. At Siemens, his research focused on MR techniques for medical diagnostics. He developed a system that was built in 1966 and patented a year later: The world's first unit that used magnetic resonance to measure a patient's blood flow at the carotid artery or arm.

On February 1, 1978 Siemens began to develop an MRI system. Alexander Ganssen engaged physicist Arnulf Oppelt to manage the project and the team built the first MRI prototype: A 0.1-tesla system with a magnet already able to fit a person's whole body. This magnet was ordered from Oxford Instruments Ltd. – later to become Siemens Magnet Technologies. This experimental system (Fig. 3A) was completed in a wooden shed built specifically for the purpose (Fig. 4). To avoid disrupting the magnetic field, the building was constructed without any magnetic parts – not even a single steel nail. Even so, the researchers still struggled with issues: The power supply to the magnet fluctuated, and since the frequency of the nuclear resonance was in the same range as that of radio waves, the physicists received shortwave broadcasts instead of MRI signals in the evening. To solve this problem, they built a Faraday cage around the magnet to shield it (Fig. 3B).

2 Alexander Ganssen, around 1954.



3 **(3A)** Air-cooled 0.1 Tesla magnet, 1978. **(3B)** 0.1T magnet with Faraday cage, 1979.

1989

First actively shielded 1T system

1993

First open MR 0.2T system

In 1979, Oppelt's team looked around for a suitable test object, ultimately deciding on a green bell pepper (Fig. 5), since "It would definitely hold still, it was big enough to stand in for a human organ, and you could also cut it open to ascertain the similarity between the potential image and its anatomy." The team's research soon brought further successes. The first image of a human skull followed just a few months later, in March 1980 (Fig. 6). Ganssen himself volunteered for the scan, which took only eight minutes – already significantly shorter than the amount of time needed to scan the bell pepper just a few months before.

In September 1980 the first few patients were scanned using an MRI system (Fig. 8). The early scanning process was not very comfortable for the test subjects, who had to crawl into the magnet – which was a very tight fit – on a wooden board.

Over the course of the year in 1981, the engineers significantly enhanced the MRI system's image quality. A second pilot unit was built, this time with a field strength of 0.2T. Ernst Zeitler, a radiologist in Nuremberg, Germany, used the new system to scan his patients. By then, the images were so good that tumors in the head or abdomen and changes in the brains of patients with multiple sclerosis could be localized. "The potential that MRI technology had for diagnostic purposes was clear in 1981, when we saw the first tumor in a head scan," Oppelt says.

It wasn't long before the superconducting magnets made it possible to achieve higher field strengths, and the third pilot system reached 0.5T. Soon after Siemens began developing 1.5T magnets.

In early 1983, the time had come: At Hannover Medical School, Germany, Siemens installed the first MRI system to be tested in a clinical setting to ensure that it was suitable for day-to-day clinical use. The system's centerpiece was an oil-cooled, normally conductive 0.2T magnet. The testing went so well that Siemens ramped up product development efforts, establishing the new Magnetic Resonance Business Unit within the Medical Technology Division. Not long after that Siemens installed the first 0.35T MAGNETOM system at the Mallinckrodt Institute of Radiology, in St. Louis, MO, USA (Fig. 9). This made Siemens one of the first providers worldwide to offer magnetic resonance imaging for clinical applications.

The first MAGNETOM systems were available in different field strengths (0.35, 0.5 and 1.5 tesla). Once the system had been set up in the shielded MRI room, the magnet was cooled to minus 269 degrees Celsius using liquid nitrogen and liquid helium and then charged with electricity. After that, no further electrical power to the magnet was needed, and the power supply was permanently cut off. The helium and nitrogen, however, slowly evaporated, so regular replenishments were necessary – the first MAGNETOM systems used about two liters of nitrogen and half a liter of helium per hour (Fig. 10). Today's advanced MAGNETOM systems rely on 'zero helium boil-off' technology, which allows MRI systems to keep running in normal operation without using up any helium.

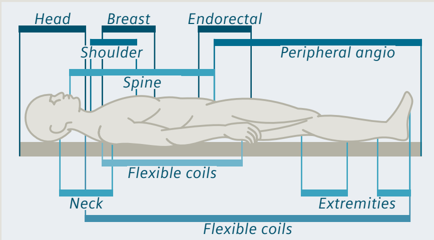
In December 1983, Klinikum Charlottenburg, a hospital operated by Freie

4 The wooden building used as the first MRI research lab, Erlangen, 1979.

5 MR image of a green bell pepper, November 1979.

6 Alexander Ganssen's head, 1980. 128 matrix, 8 minutes.

1997



First integrated Panoramic Array Coil concept for whole body imaging

2001

MAGNETOM World

The MRI community consisting of internet platform, MAGNETOM Flash magazine and MAGNETOM World Summits

Universität Berlin, became the first university medical center in Germany to receive an MRI system with superconducting magnets from Siemens (Fig. 11). From then until June 1984, Siemens shipped 14 MAGNETOM systems to destinations all over the world. That same month, the U.S. Food and Drug Administration granted the MAGNETOM its final approval for the U.S. market. In 1986, Siemens became the first manufacturer of MRI systems to win approval for 1.5-tesla systems in Japan.

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7 Arnulf Oppelt with the 0.1T MRI prototype, 1981.

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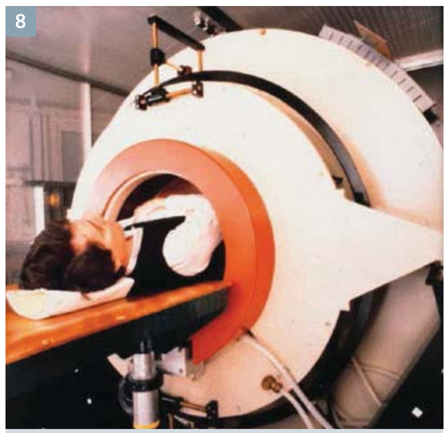

8 A whole-body scan using the pilot system, 1980.

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9 The first MAGNETOM, St. Louis, 1983.

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10 Replenishing helium in the early 80s.

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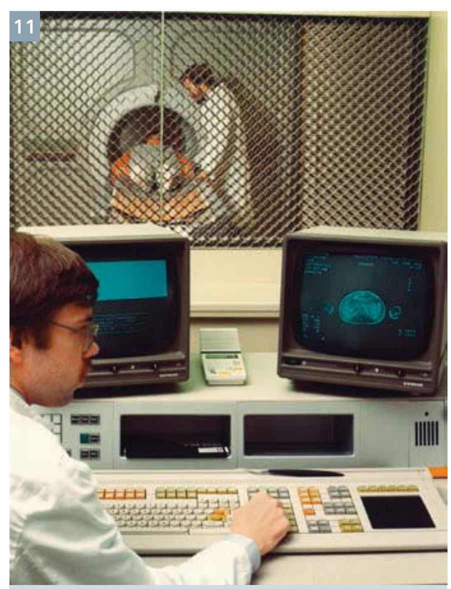
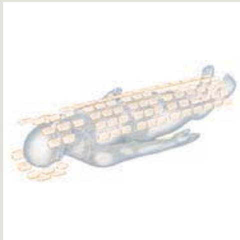


11 Klinikum Charlottenburg, operated by Freie Universität Berlin, 1983.

2003

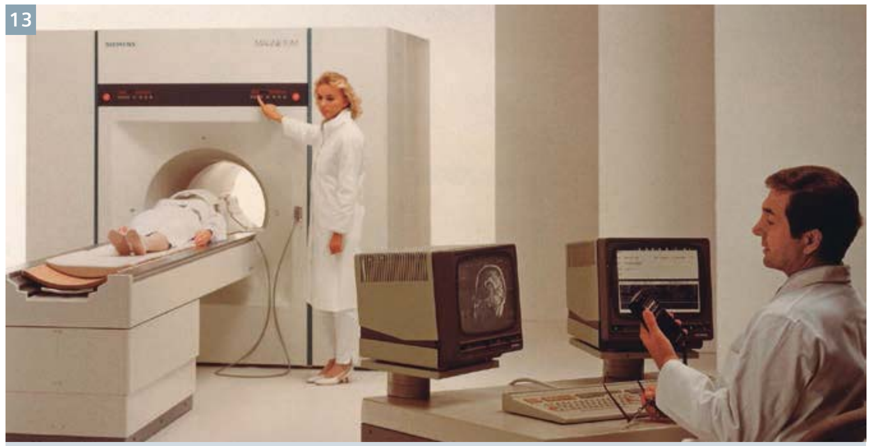


New Technology Tim RF and coil technology

2004

First Open Bore (70 cm) system

12 Magnet shielding, 1984.



13 Actively shielded 1T MAGNETOM 42 SPE.

The magnets used in the first MRI systems lacked any shielding for the magnetic field and therefore could only be installed in rooms measuring at least 40 m². So Siemens developed a superconducting magnet with a stray field about five times smaller. This design, found nowhere else in the world, shielded the magnetic field through 'self shielding', where a cage-shaped shield conducted the stray field back to the magnet. These magnets required only a quarter of the space. Many of the changes that rooms had previously needed in order to accommodate an MRI system were no longer necessary, cutting installation costs (Fig. 12).

In 1989, Siemens launched a 1.0-tesla system with an actively shielded magnet, the MAGNETOM 42 SPE (Fig. 13). Active shielding means that in addition to the coils that generate the magnetic field, there are also coils installed on the magnet itself, which weaken the magnetic field toward the outside – where no magnetic field is needed for imaging purposes. It was followed in 1991 by an MRI system with an actively shielded 1.0-tesla whole-body magnet operated via an intuitive user interface similar to that of a PC: The MAGNETOM Impact (Fig. 14).

Even as these performance gains were being made, Siemens was also introducing a number of technological innovations that unlocked new diagnostic possibilities, shortened scan times, and reduced power consumption. As early as 1985, the company was able to cut scanning time nearly in half by using a 'half-Fourier imaging'. In this measurement technique, only about half the data was determined through direct measurements, while the other half was reconstructed mathematically.

14 MAGNETOM Impact, 1991.

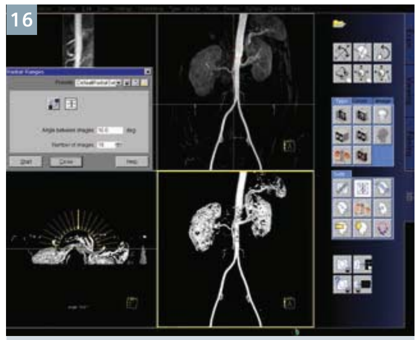
Open and standardized

By the early 1990s, MRI had become an integral part of everyday clinical practice. In 1992, the standard was 20 patients in eight hours. However, some patients felt uncomfortable

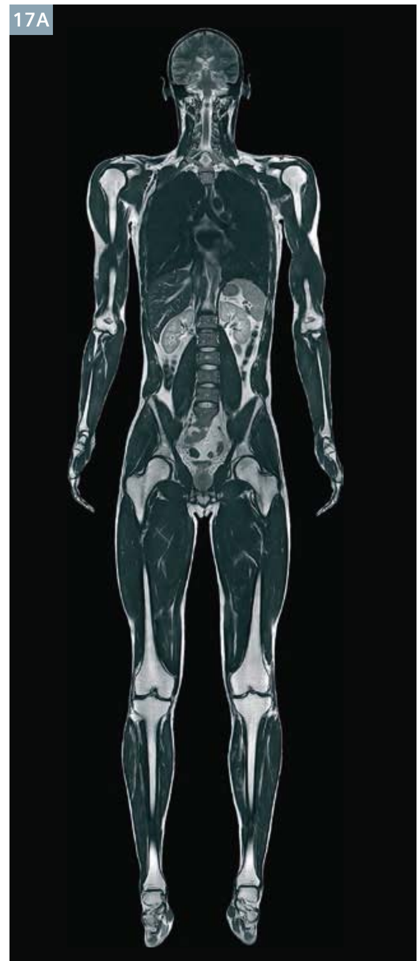
2009

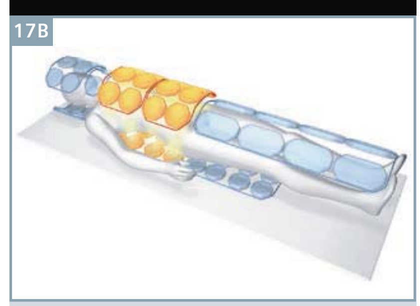
New Technology
Dot workflow engines
and Tim 4G

15 Using the MAGNETOM Open to monitor an operation at Cleveland University in 1994.



16 Angiography with *syngo*, 2001.





17 **A, B:** Whole-body imaging with Tim (Total imaging matrix).

when they were moved into the MRI system's narrow bore. In 1993, Siemens succeeded in making MRI accessible to everyone by introducing the first truly open MRI system, the MAGNETOM Open.

The 0.2T MAGNETOM Open even made it possible to monitor patients during surgery (Fig. 15).

The software used for the Siemens MRI systems in the 1990s was structured similarly to PC software, so it was already much more intuitive to use than the software for the first MRI systems. However, MRI and CT or other imaging systems from the same manufacturer had always used different software interfaces – which operators had to learn individually. Around the turn of the 21^{st} century, Siemens became the first medical technology manufacturer to craft a standardized user interface for all of its systems: *syngo* software (Fig. 16). When a hospital or medical practice purchases a new system from Siemens, the learning curve for staff is much shorter.

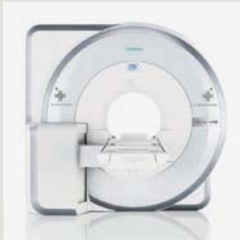
From then on, all imaging systems from Siemens featured standardized operation.

In late 2003, Tim – the Total imaging matrix – revolutionized MRI (Fig. 17). The centerpiece of Tim technology is the completely innovative HF coils that collect data based on a matrix concept.

Whole-body scans without changing coils and without repositioning the patient finally came true. Tim makes it possible to produce images of the entire body from head to toe in a single pass, since the matrix coils cover all areas of the body at the same high level of detail. Scanning the entire body is possible in about twelve minutes for patients as much as 2.05 meters tall.

Tim represents tremendous technological progress in image quality, significantly lower patient preparation time, and shorter scanning times, but it also has additional advantages for operators and patients. Patient comfort is also

2010



First MR-PET Biograph mMR

2011

First parallel transmit application: Tim TX TrueShape

18 MAGNETOM Espree, the world's first 1.5-tesla system with a 70-centimeter open bore.

enhanced by light-weight coils: At just 950 grams, the body matrix coil is lighter than some winter bed comforters. Tim technology allows patients to be positioned feet first for almost all scans – a big relief for many patients, since it means the head can stay outside the tube. Siemens combined all of these features in the MAGNETOM Avanto, which was commissioned for clinical operation at University Hospital Tübingen, Germany on November 25, 2003.

A few months later, Tim technology, working in tandem with optimization of components such as the magnet, gradient system, and receiver electronics, enabled another milestone in magnetic resonance imaging: The MAGNETOM Espree was the world's first 1.5-tesla system with a 70-centimeter opening (Fig. 18). This allowed invasive procedures and gave obese patients unrestricted access to high-field MRI for the first time.

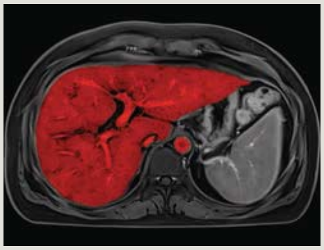
Biograph mMR	first simultaneous acquired MR-PET images across all body regions
FLASH	fast imaging
PACE	inline motion correction for fMRI
ASL	non-contrast MRI perfusion
AutoAlign	standardized, reproducible patient scan positioning
SWI	new insights with susceptibility-weighted imaging
DTI task card	easy visualization of fiber tracks
SPACE	high-speed TSE imaging in 3D
TrueFISP cine	excellent blood-tissue contrast and cardiac function
Inline Dynamic Signal	fully automated myocardial perfusion analysis incl. motion correction and quantification of myocardial first pass perfusion with Cardiac Dot Engine
Delayed Enhancement	visualization of myocardial scar and fibrosis
Inline VF	inline analysis of ventricular function
TWIST	low-dose time resolved MR Angiography with high resolution in space and time
QISS*	non-CE MR Angiography technology
Cardiac Dot Engine	standardizes Cardiovascular MR examinations with workflow guidance and automation
Tissue4D	pharmakokinetic modeling of dynamic studies
TimCT	moving table whole-body MR imaging
TWIST-VIBE	always the right contrast in dynamic liver MRI
StarVIBE	free-breathing contrast-enhanced body imaging
GRAPPA	small FOVs with parallel imaging in *k*-space
WARP	minimizing artifacts from metal implants
MapIt	quantitative cartilage characterization
Phoenix	drag and drop protocol sharing
Inline	motion correction and analysis such as MIPs and ADC maps on the fly
Dot Engines	automated and personalized scanning for each body region

19 Leading applications developed together with our international collaboration partners.

*QISS is pending 510(k) clearance and is not commercially available in the US.

Innovation drives our success

2014



FREEZEit body imaging

Siemens engineers have since worked on technologies and software that further improve and support Tim technology. The *syngo* software has received numerous new MRI applications that further enhance comfort and convenience, expand the range of scanning options (Fig. 19).

Healthcare providers face mounting pressure to work on a cost-optimized basis while also offering the very best in diagnosis and treatment. Technological innovations and enhanced productivity play a large role in achieving this balance. In 2009, Siemens launched the fourth generation of Tim technology (Tim 4G) as well as Dot – Day optimizing throughput – technology (Fig. 20). Dot simplifies workflows, thereby boosting productivity by as much as 30 percent. It uses images and text to guide operators step by step through the scanning process, even during complex scans.

Another technological breakthrough from Siemens has unlocked completely new views of the inside of the human body in 2010: The Biograph mMR system combines MRI and PET (Fig. 21). These two methods have different strengths, and they supply complementary information on diseases.

On the journey from fundamental research in the wooden shed to world market leadership in MRI technology, Siemens has grown around the globe. With production sites in Erlangen (Germany), Oxford (UK), Shenzhen (China) and Joinville (Brazil) Siemens has all the technology and capabilities needed to build state-of-the-art MRI systems entirely from a single source. The sites work seamlessly together on research and development. Ongoing investments give rise to numerous innovations that add to the product family and are adjusted to meet the needs of the various markets Siemens serves. At all of the locations, the superior standard of quality that applies to development and production activities is supplemented by consulting and other services for customers from all over the world.

This retrospective shows the impressive development of this technology from the early days to the first commercial steps and right through to today's technology and market leadership.

Many innovations from Siemens have changed the world. With MRI, we have been unlocking new possibilities for 30 years now – what we once dreamed about is now reality. And today's dreams will become tomorrow's reality.

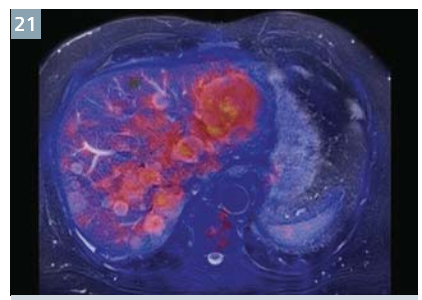
Further reading

If you are interested in the whole story of MRI development at Siemens, please visit

www.siemens.com/magnetom-world > Publications > MR Basics

where you will find a 43-page booklet with many more images and all the details on 30 years of innovation at Siemens.

20 Screenshot of a Dot Engine.



21 Molecular MR image generated with Biograph mMR at TU Munich, Germany in 2011.

22 Since 2001 the MAGNETOM World offers a platform to meet, discuss and exchange valuable information with your peers.