FROM BATHTUB TO REFRIGERATOR

The use of superconducting magnets for high-field magnetic resonance imaging poses a big cooling challenge. Classic magnet cooling technology comes with operational and environmental issues, related to the venting and refilling of large quantities of helium. These issues are overcome by the Philips BlueSeal micro-cooling technology, which uses only seven litres of helium in a fully sealed system. This is just one step on the technology roadmap towards more patient- and environment-friendly MRI systems.

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MRI for hospitals

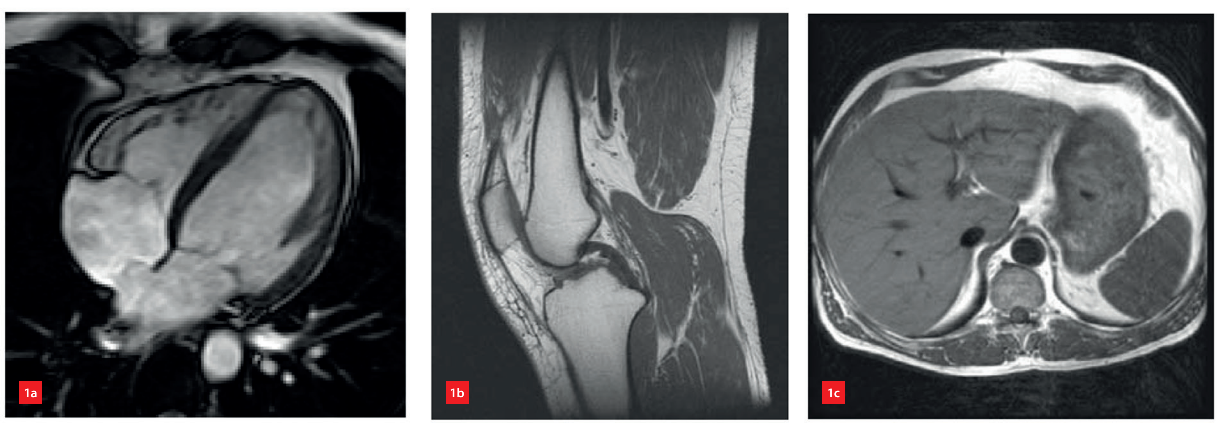
MRI, or magnetic resonance imaging, is the preferred imaging modality when it comes to imaging soft tissues – such as the brain, liver, heart, among others – but also for imaging joints and blood vessels; see Figure 1 for a few examples. In contrast, CT, or computed tomography, scans are used for imaging fractures, tumours and cancer screening. In some cases, a patient may have a CT scan, followed by an MRI – with the images overlaid to determine abnormalities in pathologies.

Classic MRI technology

MRI is an imaging method based on the sensitivity to the presence and properties of water, which – incidentally – makes up between 70% and 90% of most tissues. The amount of water (or to be precise, mobile hydrogen atoms), and thereby its properties, can vary substantially with disease or injury, making MRI a sensitive and useful tool for patient diagnosis. MRI is able to detect the tiny perturbations in the magnetism of the nucleus – the entity at the centre of an atom.

Hydrogen happens to contain the simplest nucleus – a single, positively charged proton. Protons possess an inherent characteristic – spin. Atomic nuclei with an uneven number of protons will have a net spin, known as nuclear spin – as is the case with hydrogen ^{1}H, while nuclei with an even number of protons (and neutrons) do not have a net nuclear spin, like oxygen ^{16}O. This is in line with the Pauli exclusion principle – which posits that in an atomic nucleus, two identical particles cannot be in the same state [2,3].

In free space (without an external magnetic field), the spins are randomly oriented and their effects cancel each other. However, when these same spins are placed in an external magnetic field (such as that of an MR magnet), the spins align themselves parallel (spin up) or anti-parallel (spin down) to the magnetic field. The ratio of spin-up and spin-down states is not 1:1 – instead, there is a small number of excess spins (aligned parallel to the external magnetic field). These excess spins add up, resulting in a net magnetisation M. MR imaging exploits this net magnetisation M to generate images (Figure 2). Therefore, a well-designed



Magnetic resonance imaging applications [1].
(a) Cardiac imaging.
(b) Knee imaging.
(c) Liver imaging.

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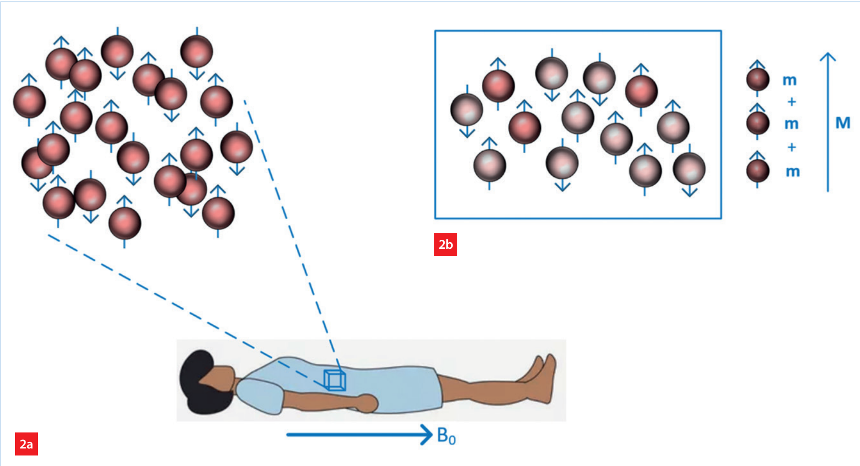


MRI's concept of net magnetisation.
(a) Alignment of spins in a small section of the body when subjected to an external magnetic field.
(b) The net vector sum of the spin-up and spin-down states results in a net magnetisation M.

The Philips MRI 5300 1.5T scanner.

magnet that is capable of producing a homogeneous B_0 field (or main magnetic field) is crucial for MRI.

But how do we go from spins to an MRI image? For this, see Figure 3. It requires the confluence of several different hardware and software solutions, working in perfect sync with each other. With the subject prepped for a scan, they are placed inside the bore such that the anatomy under investigation (brain, heart, knee, for example) is centred around the magnet isocentre (the area of the magnet with the most homogeneous B_0 field).

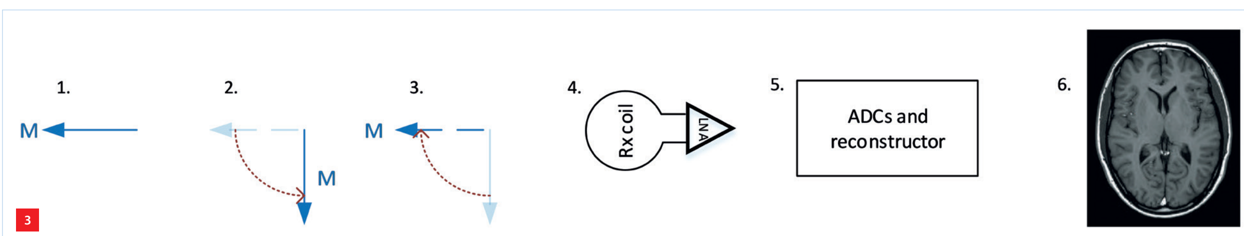
With the spins in the subject aligned along the main magnetic field, an instantaneous RF (radio-frequency) pulse (called a transmit pulse, or B_1 field) generated using a transmit coil is made incident on the subject, orthogonal to the B_0 field. This flips the net magnetisation away from the B_0 field and into the plane transverse to the main magnetic field. Spatial localisation of the MR signal requires the use of three orthogonal linear magnetic field gradients – and these are generated by gradient coils mounted on a cylindrical former just inside the bore of the magnet.

Once the RF excitation plays out, the nuclei start releasing the absorbed energy and slowly move back in alignment with the B_0 field. A receive (Rx) coil, placed in close proximity to the subject, picks up this energy and produces an electrical signal across its terminals. This electrical signal is then fed into a low-noise amplifier that further amplifies the signal, upon which the resulting signal is routed to a signal processor (containing analog-digital convertors and other processing hardware) that helps form the final image [7].

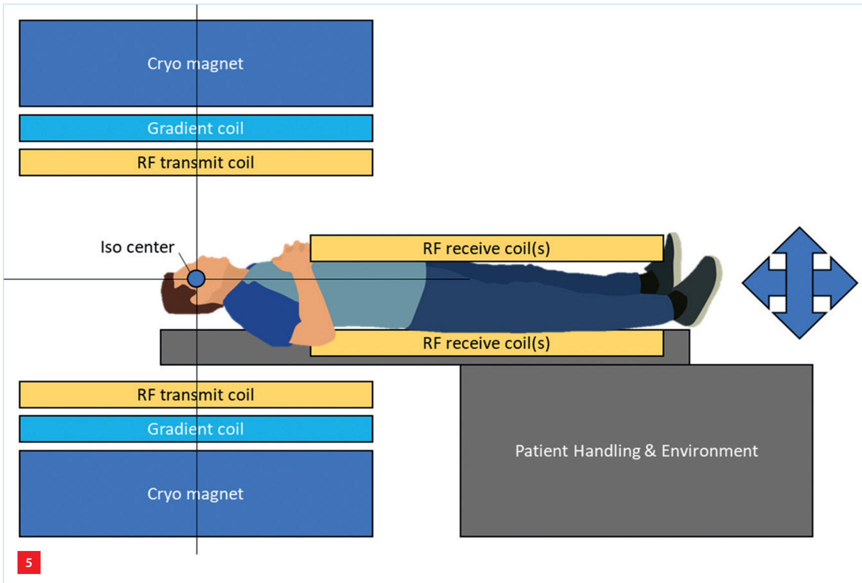
Figure 4 shows the Philips MRI 5300, a 1.5T scanner. A very basic hardware decomposition could be summarised as depicted in Figure 5.

MRI superconducting cryo magnet technology

While permanent and resistive magnets are capable of generating fields of up to 0.4 T, superconducting magnets are used for generating stable magnetic fields above 0.4 T [1]. Superconducting magnets use alloy wires (niobium-titanium, for example) cooled to ~4 K (–269 °C) using liquid helium, at which point they become superconducting. The conductor used in most clinical MRI scanners is



Going from spins to an MRI image.
(1) Net magnetisation M aligned with the main magnetic field.
(2) An orthogonal transmit pulse flips the magnetisation into the transverse plane.
(3) Excited spins now start moving back towards B_0 and release energy.
(4) The released energy is picked up by a local receive coil, thus generating the MR signal.
(5) The amplified signal is fed into a reconstructor.
(6) The final MR image is generated.

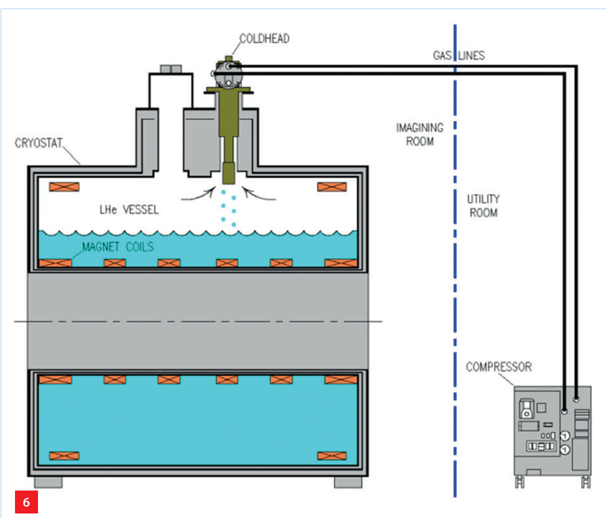


A very basic hardware system decomposition of an MRI machine.

niobium-titanium (NbTi), which becomes superconductive below 9.4 K.

The wires are composed of several microfilaments of NbTi embedded in a copper matrix – the copper not only provides support to the microfilaments, but also a low resistance path for large currents in the event of loss of superconductivity. Instead of a continuous winding, the coils are broken up into several windings, spaced apart, for increased B_0 field homogeneity [4]. The magnets also include additional shim coils (to increase B_0 field homogeneity) and active shielding coils, one at each end of the magnet (to minimise stray fields). The current direction in the active shielding coils is opposite to that in the main coils [5].

In order to enable the superconductivity in these coil windings, magnets employ a cryostat – a large chamber



Cut-out of a magnet showing the cryostat and superconductors.

filled with liquid helium (up to 1.500 ℓ, boiling point of 4.2 K) in which the magnet coils are immersed, surrounded by a further vacuum chamber (Figure 6). Early magnets added a further chamber of liquid nitrogen (at 77 K) to help reduce the continuous boil-off of the helium (due to external thermal energy entering the cryostat). Modern MRI magnets use cryogenic coolers to reduce or even eliminate helium boil-off, and thus do not require liquid nitrogen.

Compressed helium gas is circulated around a two-stage ‘cold head’ mounted on the magnet. Controlled gas expansion in this cold head is used to create very low temperatures at the two stages of the cold head. When the cooling cycle is completed, the helium gas is returned to a water-cooled compressor [1]. In older magnets, the two stages of the cold head were connected to two circumferential aluminium shields that intercept heat and thereby reduce the evaporation (boil-off) of the helium to a level of less than 50 mℓ/h. Later magnets have the first stage connected to a single shield, and the second stage connected to a recondensor so that helium reliquefies and cannot escape the magnet; see Figure 6. These latter magnets are referred to as ‘zero-boil-off’.

Superconducting magnets are a costly proposition, and the use of cryogenic helium in such vast quantities results in an added expense – not to mention the environmental impact. Nonetheless, helium-cooled superconducting magnets are still the best option when it comes to generating stable, high magnetic fields for MRI.

Cooling innovation

Based on a decade of innovation, Philips BlueSeal (Figure 7) is a fully sealed magnet designed to simplify MRI installation, reduce lengthy and costly disruptions in MR services, and help hospitals transition to sustainable, helium-free operations. This revolutionary magnet operates with only 7 ℓ of liquid helium and is fully sealed [6].

Here, fully sealed refers to the fact that the helium used to transfer the dissipated energy to the second stage of the cold head is completely enclosed, without loss of helium for the lifetime of the magnet (leakage nor vaporisation). The cooling system does not require to be vented or refilled, even in an emergency event, since it is designed for the apparent pressure at room temperature.

The superconducting magnet coils are situated in vacuum to provide thermal isolation from the surroundings, and cooling channels are thermally connected to the coils. At the highest point of the system, a cold head is installed to exchange the heat. A self-generated heat flow sustains itself since the specific weight of helium increases at lower

Innovation in magnet cooling.
(a) Classic magnet technology with ~1.500 ℓ of liquid helium.
(b) BlueSeal micro-cooling technology using only ~7 ℓ of liquid helium [6].

temperatures. The power capacity of the heat exchanger increases when the medium temperature increases, ensuring a self-regulating and intrinsically reliable system. With the use of a redundant compressor and an uninterruptible power supply, the system can keep its magnetic field even during loss of electricity or water.

With the BlueSeal magnet, Philips aims to help MRI facilities overcome potential helium-related issues related to the classic magnet design, and eliminate dependency on scarce helium supply, which is now more expensive than ever before. The concept of sealed magnet technology also offers a variety of benefits to both the site architect as well as the MR system designer. Since the procedures for ramping the main magnetic fields up and down are simplified (venting and refilling the coolant medium is not required anymore), these can even be executed without the need for specially trained service personnel. With the introduction of additional sensors and digital controllers, this gets further simplified to a single click of a button, whilst increasing the reliability of the process through continuous monitoring.

One can draw an analogy here: it is a bit like moving on from using a bathtub's worth of cryogenic fluid to using a refrigerator's worth. The traditional safety measures that MRI facilities would otherwise have to adhere to (concerning infrastructure related to conventional MR systems cryogenics), do not apply anymore, since the helium will remain within the system even during emergency situations [6].

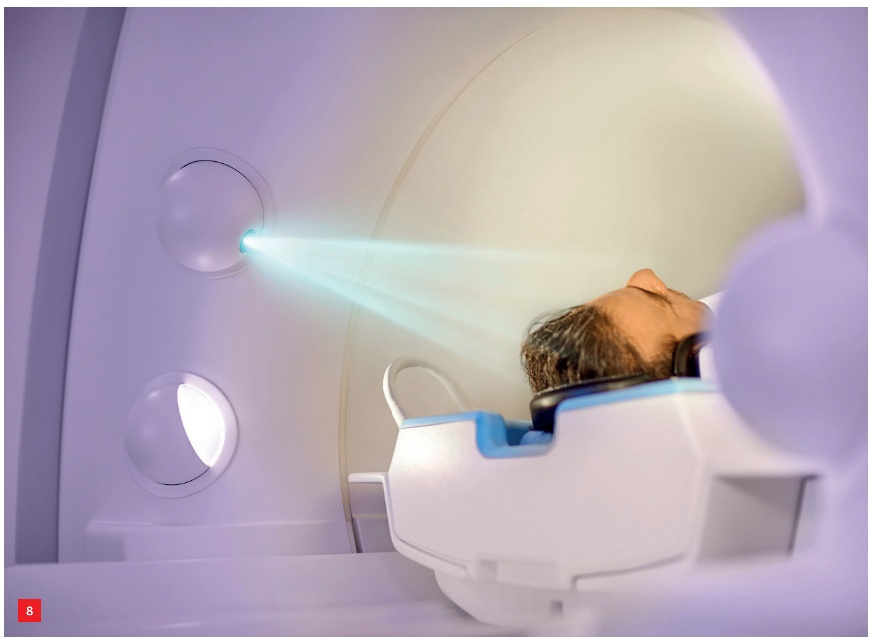
MRI future in patient handling & environment

MRI scans are being made every day in almost every corner of the world. Therefore, one can say that MRI is a common imaging modality. When compared to the car industry, one could observe similar trends in what customers want from their machine.

At the start of MRI in the early 1980s, customers were happy if the technology worked. Much like cars should get one from point A to point B, MRI scanners should create MR images. Later, when this was achieved, power became the selling point: customers demanded cars with larger engine displacements and substantial horsepower. For MRI, this meant higher magnetic fields, and with that came sharper, clearer pictures.

Then, accuracy became the next big thing: optimising the motor meant that a new 1.6ℓ engine was able to provide the power that an older 2.0ℓ engine would make; so, the car got more efficient. Again, same for the MRI machine: improved hardware, coupled with innovative software advancements made for improved image quality on a 1.5T system, parallelling that on earlier 3T systems. The cost reduction generated through this increased efficiency was a big selling point. This competition on accuracy and cost-down started in the early 2000s, and we are now at the verge of a new era: value up.

This trend has been observed in the car industry for some time now: prices go up, but the value – and the outcome – goes up as well. Nowadays, one would not necessarily have a look under the hood when buying a car, but would rather check how easily their phones connect to the car, and whether all the apps work. This is exemplary of the marketing shift for MRI systems as well. The customer's ease of use, patient safety and comfort, along with the diagnostic support that the system provides to the technologist and radiologist, are the current selling points.



The Philips VitalEye comprises a camera that uses vision software to observe the respiratory behaviour of a patient. Easy hardware? No, this should work in extreme environments, where large magnetic and RF fields could harm the hardware, while the hardware could disturb the quality of the picture or, when coming loose, even harm the patient. Hence, perfect performance on all competencies is needed in development.

These selling points require a lot of new functionalities and technologies to assist patients and staff. Engineers can now focus on exciting and emerging technologies to integrate into the MRI system (which is just plain fun for mechatronic engineers); harnessing optical fibre technologies for enabling patient and machine diagnostics; time-of-flight camera and vision technologies for sensing (see the example of the Philips VitalEye in Figure 8) and communicating; self-driving systems, biometric sensing technologies, integrating virtual and augmented reality for patient comfort (and early system validation in the development phase), novel electronics, piezo technology, and much more. All in all, a fine play-ground for mechatronic (system) engineers,

Besides, there is an increasing demand for new fundamental technologies in the MRI domain, just like cars are advancing into new technological domains through autonomous electric vehicles. Similarly, architects are looking into developing ultra-wide-bore MRI systems with a view on eliminating patient anxiety; building digital twins, combined with SysML and field data, to help refine simulations to predict and eliminate the dreadful sounds that MRI systems generate; achieving superior image quality with lower field strength systems (< 1 T), and of course, how to eliminate the radio-frequency coils that enclose the patient during scanning.

In the future, MRI systems will become more autonomous, faster and less intimidating – maybe even comfortable. Philips has already made a big step by eliminating the big helium systems.

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