MRI Hardware

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Introduction The quality of the hardware in your MRI scanner critically affects its imaging speed and image quality. Here we outline the key components of hardware that allow for the creation of an MRI scan, and point out the quality requirements for each component. You may be surprised to find that signficant improvements can be effected by relatively inexpensive upgrades. You also may be surprised that the hardware for an MRI scanner is far simpler to understand than you might expect.

Basic Operating Principles MRI is, to my knowledge, the only imaging modality that shows images with resolution significantly finer than the wavelength of radiation used. Typical image resolution is 1 mm or finer, whereas the wavelength of a 64 MHz electromagnetic field is about 55 cm in the body. The wavelength is nine times longer in the air than in the body. By contrast, consider microscopes and ultrasound scanners. The optical resolution of a microscope is about half a micron, roughly the wavelength of visible light. The resolution of an ultrasound scanner depends on the wavelength of sound in a human, so the resolution is finer when using higher frequency probes. MRI forms images by a completely different method, and the resolution does not depend on the wavelength. MRI exploits a unique quantum effect in all protons, including the hydrogen nuclei in water. In short, we can force the hydrogen in water to emit a magnetic field whose tone (frequency) reveals the proton's exact location. More protons at a location means you receive a stronger tone at that frequency. This allows one to image with much finer resolution than the wavelength.

As a simple illustration of MRI, consider the problem of listening to an AM radio station broadcast by one of three AM radio transmitters on the top of a hill. First note that your car radio antenna is "unfocussed"—you never need to aim it. In fact it is impossible to aim it precisely because the wavelength is quite large (about 300 m). Hence, an antenna would receive the AM broadcast from all three of the stations. The long wavelength means it is impossible to resolve the broadcast towers by focusing an antenna on just one transmitter, akin to what we do routinely with microscopes. Fortunately, we have no need to resolve the towers in space, since we can tune the frequency of our radio receiver to play just one AM broadcast signal on our speakers. So we use frequency resolution rather than spatial resolution to resolve the stations. This is exactly analogous to the way MRI works.

Two Key Facts about NMR Physics Before proceeding, you need to know two straightforward facts about nuclear magnetic resonance, also known as NMR, that were predicted by quantum mechanics and later verified experimentally. The first is that hydrogen atoms can be magnetized by a magnetic field. This is akin to magnetizing steel in a magnet, only the effect is about a *trillion times weaker* in water than in steel. The nuclear magnetization induced is directly proportional to the applied magnetic field, $B0$, and the proportionality factor in water at body temperature (310K) is quite tiny— $4.0x10^{-9}$. Hence we need a fairly strong magnetic field to induce a measureable magnetization. Practically speaking, it is impossible to measure this static magnetization in the presence of the much larger static magnetic field $B0$—the induced field is simply too tiny an effect. So NMR would be impractical in water without the phenomenom of precession, described immediately below.

The second fact you need to know about NMR is that, once tipped away from the applied field, nuclear magnetization will *precess* at a frequency proportional to the applied field. For hydrogen atoms in water, the proportionality factor is quite large—42.58 MHz/Tesla. To observe this precession, we need to reorient magnetization away from the the $B0$ field that induced it in the first place. While nuclear precession is a quantum effect, the precession of a spinning top in the Earth's magnetic field is an analogous classic phenomenom. A spinning top will precess much faster on Jupiter than on Earth! A hydrogen atom will precess at about 64 MHz at 1.5 T and it will precess at about 128 MHz at 3.0 T. We can easily measure the small magnetization when it is precessing by measuring the voltage induced in an radiofrequency coil (called an RF coil). Since the RF coil is completely insensitive to DC magnetic fields, we avoid the problem of measuring a tiny DC magnetization in the presence of an intense 3.0 T field.

The Brilliant Idea of Paul Lauterbur You now know everything you need to know to understand the basics of MRI. A brilliant idea came to Paul Lauterbur in the 1970s. As an NMR chemist, Prof. Lauterbur knew the two facts about NMR listed above. He also realized that a magnetic field *gradient* could be safely created in a human, and that humans are essentially no different from air as far as the gradient field is concerned. A gradient is a magnetic field created by a current through a set of magnet coils outside the patient that causes the field to be larger, say, at the top of the head than at the chin. Lauterbur realized that in the presence of a magnetic field gradient, hydrogen atoms would precess at a frequency determined by their location in the gradient field. Furthermore, he realized that with a linear field gradient on, there was only one location that could produce a particular frequency. Hence, to create an image, one only needs to estimate the number of water molecules precessing at a each frequency (this is called Fourier analysis) and assign that number to each unique position in the image.

The imaging idea generalizes to three dimensions. To make a 3D image of the human, you only need three gradient coils, one for each of the three spatial directions x, y, and z. We allow hydrogen atoms to precess in the presence of the gradients in all three dimensions and then use frequency analysis to map hydrogen density to position.

Note the similarity to the radio transmitter example. We can tune into a particular AM radio station simply by tuning our radio receiver to a particular frequency. We can also tune into a particular spatial location by tuning into the expected frequency created by the sum of the applied field and the gradient field.

Now we can discuss the individual coils and their requirements. Each component has a key role in determining image quality. Lower cost items, such as a smaller RF coil or a stronger gradient amplifiers can often make a more noticeable improvement in image quality than can a higher field magnet.

Main Field $B0$ The main field has to be quite strong to induce an appreciable magnetization. For this role, we would like it the field $B0$ to be as strong as possible. But the main field has a second role, namely setting the average frequency of the MRI data. The magnetic field must be exceptionally precise; a fractional variation of 1 part per million (or ppm) is typical. For this role, there are some disadvantages to working at higher field strength. Higher field strengths lead to more patient heating (called specific absorption rate, or SAR). It is also quite expensive to make a high-field (3-4 T), homogeneous whole body magnet. Magnetic field penetration becomes a problem at higher field strengths. Finally, the relaxation time $T1$ becomes longer at higher field strengths, which can slow your study. Hence, we see an optimum field strength may emerge for each part of the body. 3T magnets are becoming more popular for neuro applications whereas 1.5T magnets are still preferred for whole body MRI.

In order to keep the magnetic field as homogeneous as required in MRI, several additional coils called "shim" coils should be tuned precisely once the magnet is sited. There are superconducting shims, passive shims, and resistive shims. There are often as many as twelve coils in each shim set, each uniquely responsible for a particular field shape. The superconducting shims are fine tuned on site by the manufacturer's installation team. Your MRI technician will adjust the resistive shims on an individual patient if that particular study is sensitive to field errors.

Gradient Coil and Amplifiers You can think of the gradient strength of your MRI scanner as the engine of your car, since it determines the maximum imaging speed. The gradient coils are the magnets that create the loud banging noise while imaging. The noise is due to an unwanted but unavoidable loudspeaker force (called the "Lorentz" force) between the currents in the gradient coil and the main field. The biggest change in the last fifteen years of MRI has been the strength of the gradients, which were typically 10 mT/m circa 1990 and are now four times stronger, with 40 mT/m typical on most commercial whole body MRI scanners. This is a factor of sixteen greater power, so a significant engineering effort was required to drive this innovation. Roughly speaking, a 4-fold increase in gradient strength translates to a 4-fold increase in imaging speed. This has enabled faster MRI sequences with dozens of acronyms like SSFP, RARE, spiral and EPI. While these sequences show differences in contrast and artifacts, the most important feature is speed, and imaging speeds approaching 20 frames a second are now possible for 2D images. 3D images that used to take about 10 minutes to acquire now require only 2 minutes of acquisition time. This allows for more studies and significantly better patient tolerance of the exam.

You may be surprised to hear that the gradient coil is not as precise as the main field. It is common to allow more than 10% degradation in the field linearity over the patient. This error is quite simple to fix in the image reconstruction.

RF Coils and RF Coil Arrays The best and least expensive way to improve the quality of an MRI scan is to use the smallest possible RF coil that will allow you to see the anatomy in question. It turns out that the noise in the image (the white fuzz that obscures the image quality) comes mostly from the patient, so this noise is unavoidable. But you can limit the amount of noise by ensuring that the RF coil is as small as possible. Surface coils are commonly used to image anatomy within a few centimeters of the skin. In fact, reducing the coil coil diameter by a factor of 2 can improve image quality by a factor greater than 5, at least near the surface. Of course, the tradeoff is less depth penetration.

The last fifteen years has also seen an explosion of interest in arrays of coils. The arrays can improve image quality near the surface, and there is no loss of quality deeper in the human. Hence, arrays are a very cost-effective way to improve image quality over a large area of the body.

In some parts of the body, motion obscures anatomy more than the noise from the patient. Imaging fast enough to "freeze" the motion is the best way to improve image quality. There are two ways to image faster: employ stronger gradients, or using parallel imaging methods. Parallel imaging is a newer method that uses arrays of coils to collect different parts of imaging information simultaneously in different coils. It is now common to use parallel imaging to effect an "acceleration" factor of 2 or 3, depending on the number of coils in the array and the specific geometry. This can remove motion artifacts, but does come at a cost in image quality. Imaging four times faster worsens image quality by a factor of two. Using parallel imaging methods has a small additional (electronic) noise penalty compared with imaging faster using faster gradients.

The RF field inhomogeneity is typically about 5%-10% with a volume coil. This is generally ignored in the image reconstruction, but some planning is required when designing each software program to create a certain contrast (called a pulse sequence) to tolerate this level of inhomogeneity.

Further Reading The first text below (by A. Webb) is an excellent introduction to MRI and all the other main imaging modalities. The others are more advanced texts on MRI. Chen and Hoult's text focuses on the hardware used in MRI.

1. Andrew Webb, "Introduction to Biomedical Imaging," Publisher: Wiley-IEEE Press, December 26, 2002. ISBN: 0471237663.

2. C. N. Chen, D. I. Hoult, "Biomedical Magnetic Resonance Technology," Institute of Physics Publishing, November, 1989, ISBN: 0852741189

3. Bernstein, King and Zhou, "Handbook of MRI Pulse Sequences," Elsevier Academic Press, 2004. ISBN 0-12-092861-2.

4. "Magnetic Resonance Imaging: Physical Principles and Sequence Design," Haacke, Brown, Thompson, and Venkatesan, John Wiley & Sons New York, NY 1999. ISBN: 0-471-35128-8.

5. "An Introduction to Functional Magnetic Resonance Imaging: Principles and Techniques," Richard B. Buxton, ISBN: 0521581133. Publisher: Cambridge University Press.

Conclusion You now possess a complete vocabulary and have all the concepts necessary to understand MRI hardware. Further reading on image contrast and pulse sequence development is covered in my colleagues' talks.