

## Technology Brief 27

### Magnetic Resonance Imaging (MRI)

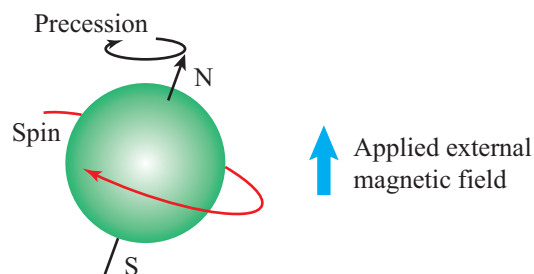
**Magnetic resonance imaging** (MRI), also called **nuclear magnetic resonance** (NMR), is a powerful medical imaging tool that provides extremely detailed 2-D and 3-D images of the body, an example of which is shown in **Fig. TF27-1**. MRI is particularly useful for imaging soft tissues (organs, ligaments, spinal column, arteries and veins, etc.). Unlike X-ray, which uses very high frequency ionizing radiation, MRI uses lower frequency magnetic and radio frequency fields, which are non-ionizing and do not damage cells. Since MRI's early demonstration in the 1970s, its applications have burgeoned, and research is continually opening up new and improved MRI techniques.

MRI utilizes the fact that the bulk of the human body contains water and every water molecule has a permanent **magnetic dipole moment**, which means that a water molecule behaves like a small magnet. The hydrogen atoms in the ( $\text{H}_2\text{O}$ ) water molecule have a natural spin associated with them, and because they are weakly charged, this spin (charges moving in a circle) creates a **magnetic field** as shown by the S-to-N arrow in **Fig. TF27-2**. Thus, the water molecule acts like a weak bar magnet with North and South poles. Normally, these spins are randomly aligned in the body, but if a strong external magnetic field is applied, they all line up with the applied magnetic field. Almost exactly half line up in the N-S direction, and almost exactly half in the opposite S-N direction. This **dc magnetic field** will just hold them in place for the rest of the MRI scan time.

But you can never have *exactly* half of the spins in each of the two directions, so a few extra spins (about 9 out of 2 million for a typical 1.5 tesla magnet) always



**Figure TF27-1:** MRI scan of the head.

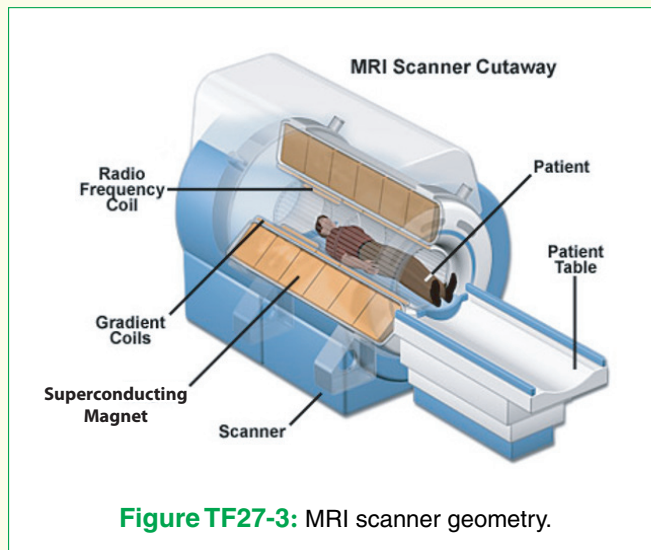


**Figure TF27-2:** The spin of the charged hydrogen atoms in  $\text{H}_2\text{O}$  produces a magnetic field.

show up in neither the N-S or S-N configuration. These extra outlier molecules are the ones the MRI scanner actually uses to create the image.

A second magnetic field is then applied, but unlike the strong dc magnetic field imposed to hold the rest of the molecules in place, this magnetic field is a **radiofrequency** (RF) pulsed signal, at a particular frequency for which the outlier molecules are known to resonate strongly (this is the resonance part of MRI). This natural resonant frequency is called the **Larmor frequency**, and it depends on the chemical makeup, density, and structure of the tissue, thus allowing MRI to distinguish different tissues, identify and detect chemical composition, and even determine the status (such as inflammation) of various tissues. When the RF pulse turns on, the outlier molecules align with that magnetic field. When the pulse turns off, they relax back to their original state. As they relax, their spin precesses (becomes tipped like a toy top slowing down) and produces yet another magnetic field, which returns to and is picked up by the same coil that produced the original RF signal.

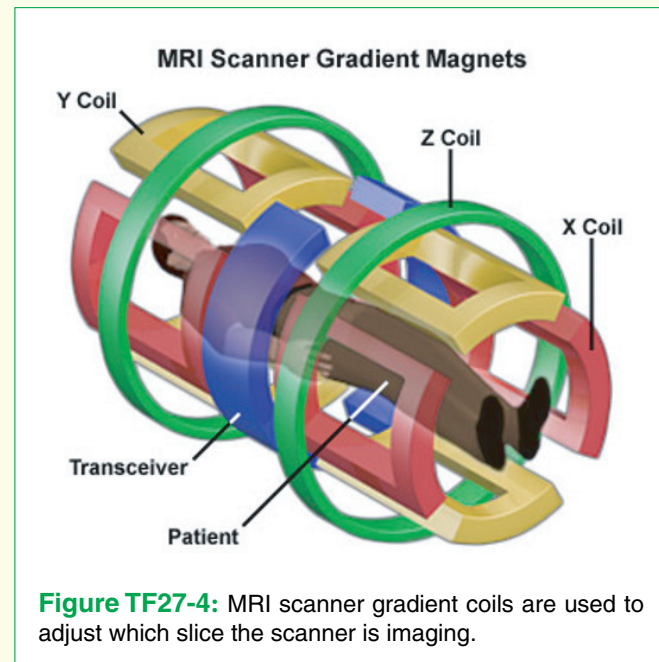
Now let's look at the MRI machine and the hardware (**Fig. TF27-3**) that makes this all happen. The large applied magnetic field is produced by a large **superconducting electromagnet**. A typical medical MRI scanner is 1.5 teslas (1 tesla = 10k gauss). By comparison, a strong refrigerator magnet is 100 gauss, and the Earth's magnetic field at its surface is around 0.5 gauss. The superconducting magnet is cooled with liquid nitrogen down to the point where its resistance is virtually zero (see Technology Brief 3 on superconductivity), so that the current and hence magnetic field can be maximized. These magnets weigh several tons and cost hundreds of thousands of dollars a year in electricity and liquid nitrogen to keep them running. They take weeks to cool down enough to reach superconductivity, and days to ramp up the current to produce their large magnetic field.



**Figure TF27-3:** MRI scanner geometry.

The patient is slid into the bore (hole) in the center of the magnet, where the field is strong, and also quite uniform. Because the body is “nonmagnetic” ( $\mu_r = 1$ ), this strong magnetic field does not move or hurt the person, although it does polarize (line up) the spins in his/her hydrogen atoms. If the person has any metal inside of him/her (such as implantable medical devices, artificial joints, or bone repair surgeries), this can preclude the use of MRI for that patient. It is also important to keep all metal (oxygen tanks, wheelchairs, pens, clipboards, etc.) away from the magnet, or it can be pulled irretrievably and dangerously into the bore. The magnetic field is so strong that these materials cannot be removed without slowly (days or weeks) reducing the current in the electromagnet to turn it off.

The MRI scans the body in slices, like a loaf of bread. The slice being scanned is adjusted by creating a very small gradient in the RF field using yet another set of coils, the **gradient coils** shown in **Fig. TF27-4**. The current in these coils is ramped up and turned on and off very quickly to move through hundreds of scan slices quickly. When the current in a coil decreases, the magnetic field decreases too. The energy stored in this magnetic field has to go somewhere—it is returned to the circuit, creating a voltage spike at the source driving the coil. The voltage spike must be controlled by managing the current decay. In addition, this decreasing magnetic field creates another current that tries to oppose the change (you may have learned about **Lenz's law** in physics), making it impossible to instantly turn off a large magnetic field. Another interesting (and often very noisy!) effect is seen in these gradient coils. The coils themselves vibrate from their strong magnetic field, which creates a constant hum and often loud

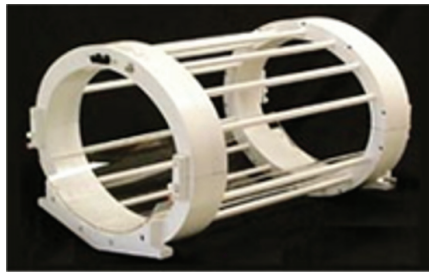


**Figure TF27-4:** MRI scanner gradient coils are used to adjust which slice the scanner is imaging.

thumps and even crashing noises, so patients receiving MRI scans generally wear earplugs to block the noise.

Now let's look at the RF coils that transmit and receive the RF pulses. RF coils come in many different designs, shapes, and sizes as shown in **Fig. TF27-5**. The coil must be large enough to surround the region being imaged (the head, torso, knee, etc.). The most common coils for whole-body or whole-head imaging are the birdcage coil shown in part (a) of the figure and the planar or surface coils shown in part (b). The **signal** of interest is determined by how much of the RF energy gets from the coil to the feature of interest, and back to the coil. Coils such as the birdcage coil are designed to have a field as constant as possible over the head, for instance, with no particular focus on the optic nerve. So, the signal (S) from the head is relatively large but the signal from the optic nerve is relatively small. The **electrical noise** (N) picked up by the receiver is generated by the entire field of view of the coil. So for imaging the head, the **signal-to-noise ratio** (SNR), given by  $S/N$ , is relatively large, but for the optic nerve, the signal is lower while the noise is the same, so SNR is smaller and not good enough to provide an accurate measurement of the signal. Much of the research on MRI coils today is therefore focused on development of coils such as the one in part (c) of **Fig. TF27-5**, which focus the RF energy on a specific feature of interest (in this case, the optic nerve) thus increasing the signal (S) in the SNR and often decreasing the noise (N) as well. The effect of SNR on image quality is seen in **Fig. TF27-6**.





(a) Birdcage coil

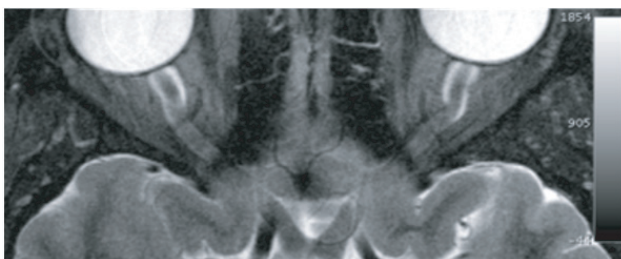


(b) Surface coil

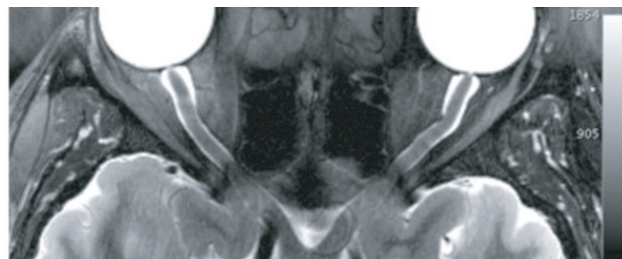


(c)

**Figure TF27-5:** Coils used in MRI: (a) birdcage coil; (b) surface coil (one on the front and another on the back of the body). (Credit: Emilee Minalga.)



(a) Low SNR



(b) High SNR

**Figure TF27-6:** Imaging of the optic nerve (seen just below the eyeballs) with (a) low SNR and (b) high SNR. (Photo courtesy Robb Merrill.)