On July 3, 1977, an event took place that would forever alter the landscape of modern medicine. Outside the medical research community, this event made scarcely a ripple at first. This event was the first MRI exam ever performed on a human being.

It took almost five hours to produce one image. The images were, by today's standards, quite ugly. Dr. Raymond Damadian, a physician and scientist, along with colleagues Dr. Larry Minkoff and Dr. Michael Goldsmith, labored tirelessly for seven long years to reach this point. They named their original machine "Indomitable" to capture the spirit of their struggle to do what many said could not be done.

This machine is now in the Smithsonian Institution. As late as 1982, there were but a handful of MRI scanners in the entire United States. Today there are thousands. We can image in seconds what used to take hours.

MRI is a very complicated technology not well understood by many. In this article, you'll learn all about how a huge, noisy MRI machine actually works. What is happening to your body while you are in the machine? What can we see with an MRI and why do you have to hold so still during your exam? These questions and many more are answered here, so let's get started!

The Basic Idea

If you have ever seen an MRI machine, you know that the basic design used in most is a giant cube. The cube in a typical system might be 7 feet tall by 7 feet wide by 10 feet long (2 m by 2 m by 3 m), although new models are rapidly shrinking. There is a horizontal tube running through the magnet from front to back. This tube is known as the bore of the magnet. The patient, lying on his or her back, slides into the bore on a special table. Whether or not the patient goes in head first or feet first, as well as how far in the magnet they will go, is determined by the type of exam to be performed. MRI scanners vary in size and shape, and newer models have some degree of openness around the sides, but the basic design is the same. Once the body part to be scanned is in the exact center or isocenter of the magnetic field, the scan can begin.
In conjunction with radio wave pulses of energy, the MRI scanner can pick out a very small point inside the patient's body and ask it, essentially, "What type of tissue are you?" The point might be a cube that is half a millimeter on each side. The MRI system goes through the patient's body point by point, building up a 2-D or 3-D map of tissue types. It then integrates all of this information together to create 2-D images or 3-D models.

MRI provides an unparalleled view inside the human body. The level of detail we can see is extraordinary compared with any other imaging modality. MRI is the method of choice for the diagnosis of many types of injuries and conditions because of the incredible ability to tailor the exam to the particular medical question being asked. By changing exam parameters, the MRI system can cause tissues in the body to take on different appearances. This is very helpful to the radiologist (who reads the MRI) in determining if something seen is normal or not. We know that when we do "A," normal tissue will look like "B" -- if it doesn't, there might be an abnormality. MRI systems can also image flowing blood in virtually any part of the body. This allows us to perform studies that show the arterial system in the body, but not the tissue around it. In many cases, the MRI system can do this without a contrast injection, which is required in vascular radiology.

**Magnetic Intensity**

To understand how MRI works, let's start by focusing on the "magnetic" in MRI. The biggest and most important component in an MRI system is the magnet. The magnet in an MRI system is rated using a unit of measure known as a tesla. Another unit of measure commonly used with magnets is the gauss (1 tesla = 10,000 gauss). The magnets in use today in MRI are in the 0.5-tesla to 2.0-tesla range, or 5,000 to 20,000 gauss. Magnetic fields greater than 2 tesla have not been approved for use in medical imaging, though much more powerful magnets -- up to 60 tesla -- are used in research. Compared with the Earth's 0.5-gauss magnetic field, you can see how incredibly powerful these magnets are.

Numbers like that help provide an intellectual understanding of the magnetic strength, but everyday examples are also helpful. The MRI suite can be a very dangerous place if strict precautions are not observed. Metal objects can become dangerous projectiles if they are taken into the scan room. For example, paperclips, pens, keys, scissors, hemostats, stethoscopes and any other small objects can be pulled out of pockets and off the body without warning, at which point they fly toward the opening of the magnet (where the patient is placed) at very high speeds, posing a threat to everyone in the room. Credit cards, bank cards and anything else with magnetic encoding will be erased by most MRI systems.

The magnetic force exerted on an object increases exponentially as it nears the magnet. Imagine standing 15 feet (4.6 m) away from the magnet with a large pipe wrench in your hand. You might feel a slight pull. Take a couple of steps closer and that pull is much stronger. When you get to within 3 feet (1 meter) of the magnet, the wrench likely is pulled from your grasp. The more mass an object has, the more dangerous it can be -- the force with which it is attracted to the magnet is much stronger. Mop buckets, vacuum cleaners, IV poles, oxygen tanks, patient stretchers, heart monitors and countless other objects have all been pulled into the magnetic fields of MRI machines. The largest object I know of being pulled into a magnet is a fully loaded pallet jack (see below). Smaller objects can usually be pulled free of the magnet by hand. Large ones may have to be pulled away with a winch, or the magnetic field may even have to be shut down.
Safety Check
Prior to allowing a patient or support staff member into the scan room, he or she is thoroughly screened for metal objects. Up to this point, we have only talked about external objects. Often however, patients have implants inside them that make it very dangerous for them to be in the presence of a strong magnetic field. Metallic fragments in the eye are very dangerous because moving those fragments could cause eye damage or blindness. Your eyes do not form scar tissue as the rest of your body does. A fragment of metal in your eye that has been there for 25 years is just as dangerous today as it was then -- there is no scar tissue to hold it in place. People with pacemakers cannot be scanned or even go near the scanner because the magnet can cause the pacemaker to malfunction. Aneurysm clips in the brain can be very dangerous as the magnet can move them, causing them to tear the very artery they were placed on to repair. Some dental implants are magnetic. Most orthopedic implants, even though they may be ferromagnetic, are fine because they are firmly embedded in bone. Even metal staples in most parts of the body are fine -- once they have been in a patient for a few weeks (usually six weeks), enough scar tissue has formed to hold them in place. Each time we encounter patients with an implant or metallic object inside their body, we investigate thoroughly to make sure it is safe to scan them. Some patients are turned away because it is too dangerous. When this happens, there is usually an alternative method of imaging that can help them.

In this photograph, you can see a fully loaded pallet jack that has been sucked into the bore of an MRI system.

This image set is comparing a young individual (left) with an
There are no known biological hazards to humans from being exposed to magnetic fields of the strength used in medical imaging today. Most facilities prefer not to image pregnant women. This is due to the fact that there has not been much research done in the area of biological effects on a developing fetus. The first trimester in a pregnancy is the most critical because that is the time of the most rapid cellular reproduction and division. The decision of whether or not to scan a pregnant patient is made on a case-by-case basis with consultation between the MRI radiologist and the patient's obstetrician. The benefit of performing the scan must outweigh the risk, however small, to the fetus and mother. Pregnant MRI technologists can still work in the department. In most cases, they are simply kept out of the actual scan room during their pregnancy.

The Magnets

There are three basic types of magnets used in MRI systems:

- **Resistive magnets** consist of many windings or coils of wire wrapped around a cylinder or bore through which an electric current is passed. This causes a magnetic field to be generated. If the electricity is turned off, the magnetic field dies out. These magnets are lower in cost to construct than a superconducting magnet (see below), but require huge amounts of electricity (up to 50 kilowatts) to operate because of the natural resistance in the wire. To operate this type of magnet above about the 0.3-tesla level would be prohibitively expensive.

- **A permanent magnet** is just that -- permanent. Its magnetic field is always there and always on full strength, so it costs nothing to maintain the field. The major drawback is that these magnets are extremely heavy: They weigh many, many tons at the 0.4-tesla level. A stronger field would require a magnet so heavy it would be difficult to construct. Permanent magnets are getting smaller, but are still limited to low field strengths.

- **Superconducting magnets** are by far the most commonly used. A superconducting magnet is somewhat similar to a resistive magnet -- coils or windings of wire through which a current of electricity is passed create the magnetic field. The important difference is that the wire is continually bathed in liquid helium at 452.4 degrees below zero. Yes, when you are inside the MRI machine, you are surrounded by a substance that is that cold! But don't worry, it is very well insulated by a vacuum in a manner identical to that used in a vacuum flask. This almost unimaginable cold causes the resistance in the wire to drop to zero, reducing the electrical requirement for the system dramatically and making it much more economical to operate. Superconductive systems are still very expensive, but they can easily generate 0.5-tesla to 2.0-tesla fields, allowing for much higher-quality imaging.

More Magnets

The magnets make MRI systems heavy, but they get lighter with each new generation. For example, at the institution where I work, we are getting ready to replace an eight-year-old scanner that weighs about 17,000 lbs (7,711 kg) with a new one that weighs about 9,700 lbs (4,400 kg). The new magnet will also be about 4 feet shorter (about 6 feet / 1.8 m long) than our current one. This is very important.
to claustrophobic patients. Our current system cannot handle anyone who weighs more than 295 pounds (134 kg). The new one will be able to accommodate patients over 400 pounds (181 kg). The systems are getting more and more patient friendly.

A very uniform, or **homogeneous**, magnetic field of incredible strength and stability is critical for high-quality imaging. It forms the main magnetic field. Magnets like those described above make this field possible.

Another type of magnet found in every MRI system is called a **gradient magnet**. There are three gradient magnets inside the MRI machine. These magnets are very, very low strength compared to the main magnetic field; they may range in strength from 180 gauss to 270 gauss, or 18 to 27 millitesla (thousandths of a tesla). The function of the gradient magnets will become clear later in this article.

The main magnet immerses the patient in a **stable** and very intense magnetic field, and the gradient magnets create a **variable** field. The rest of an MRI system consists of a very powerful computer system, some equipment that allows us to transmit RF (radio frequency) pulses into the patient’s body while they are in the scanner, and many other secondary components.

Let's find out about some of the basics involved in creating an image.

**Understanding the Technology: Atoms**

The human body is made up of untold billions of atoms, the fundamental building blocks of all matter. The nucleus of an atom spins, or **precesses**, on an axis. You can think of the nucleus of an atom as a top spinning somewhere off its vertical axis.
Imagine billions of nuclei all randomly spinning or precessing in every direction. There are many different types of atoms in the body, but for the purposes of MRI, we are only concerned with the hydrogen atom. It is an ideal atom for MRI because its nucleus has a single proton and a large magnetic moment. The large magnetic moment means that, when placed in a magnetic field, the hydrogen atom has a strong tendency to line up with the direction of the magnetic field.

Inside the bore of the scanner, the magnetic field runs straight down the center of the tube in which we place the patient. This means that if a patient is lying on his or her back in the scanner, the hydrogen protons in his or her body will line up in the direction of either the feet or the head. The vast majority of these protons will cancel each other out -- that is, for each one lined up toward the feet, one toward the head will cancel it out. Only a couple of protons out of every million are not canceled out. This doesn't sound like much, but the sheer number of hydrogen atoms in the body gives us what we need to create wonderful images.
Understanding the Technology: RF

The MRI machine applies an RF (radio frequency) pulse that is specific only to hydrogen. The system directs the pulse toward the area of the body we want to examine. The pulse causes the protons in that area to absorb the energy required to make them spin, or precess, in a different direction. This is the "resonance" part of MRI. The RF pulse forces them (only the one or two extra unmatched protons per million) to spin at a particular frequency, in a particular direction. The specific frequency of resonance is called the Larmour frequency and is calculated based on the particular tissue being imaged and the strength of the main magnetic field.

These RF pulses are usually applied through a coil. MRI machines come with many different coils designed for different parts of the body: knees, shoulders, wrists, heads, necks and so on. These coils usually conform to the contour of the body part being imaged, or at least reside very close to it during the exam. At approximately the same time, the three gradient magnets jump into the act. They are arranged in such a manner inside the main magnet that when they are turned on and off very rapidly in a specific manner, they alter the main magnetic field on a very local level. What this means is that we can pick exactly which area we want a picture of. In MRI we speak of "slices." Think of a loaf of bread with slices as thin as a few millimeters -- the slices in MRI are that precise. We can "slice" any part of the body in any direction, giving us a huge advantage over any other imaging modality. That also means that you don't have to move for the machine to get an image from a different direction -- the machine can manipulate everything with the gradient magnets.

When the RF pulse is turned off, the hydrogen protons begin to slowly (relatively speaking) return to their natural alignment within the magnetic field and release their excess stored energy. When they do this, they give off a signal that the coil now picks up and sends to the computer system. What the system receives is mathematical data that is converted, through the use of a Fourier transform, into a picture that we can put on film. That is the "imaging" part of MRI.

So how is this image converted into a picture that reveals the specific details we're looking for?

Visualization

Most imaging modalities use injectable contrast, or dyes, for certain procedures. MRI is no different. What is different is the type of contrast we use, how it works and why we use it.

The contrast or dye materials used in X-ray and CT scan work in the same way because both areas use X-rays (ionizing radiation). These agents work by blocking the X-ray photons from passing through the area where they are located and reaching the X-ray film. This results in differing levels of density on the X-ray/CT film. These dyes have no direct physiologic impact on the tissue in the body. The contrast used in MRI is fundamentally different.

MRI contrast works by altering the local magnetic field in the tissue being examined. Normal and abnormal tissue will respond differently to this slight alteration, giving us differing signals. These varied signals are transferred to the images, allowing us to visualize many different types of tissue abnormalities and disease.

Photo courtesy NASA

Compared to most CAT Scan images, those made by MRI tend to be more detailed and often have more contrast.
processes better than we could without the contrast.

Now that you know how MRI works, let's find out what circumstances might call for an MRI scan.

**Advantages**

Why would your doctor order an MRI? Because the only way to see inside your body any better is to cut you open. MRI is ideal for:

- Diagnosing **multiple sclerosis** (MS)
- Diagnosing **tumors** of the pituitary gland and brain
- Diagnosing **infections** in the brain, spine or joints
- Visualizing **torn ligaments** in the wrist, knee and ankle
- Visualizing **shoulder injuries**
- Diagnosing **tendonitis**
- Evaluating **masses** in the soft tissues of the body
- Evaluating bone tumors, cysts and bulging or herniated discs in the spine
- Diagnosing **strokes** in their earliest stages

These are but a few of the many of reasons to perform an MRI scan.

The fact that MRI systems do not use ionizing radiation is a comfort to many patients, as is the fact that MRI contrast materials have a very low incidence of side effects. Another major advantage of MRI is its ability to image in any plane. CT is limited to one plane, the axial plane (in the loaf-of-bread analogy, the axial plane would be how a loaf of bread is normally sliced). An MRI system can create axial images as well as images in the sagittal plane (slicing the bread side-to-side lengthwise) and coronally (think of the layers of a layer cake) or any degree in between, without the patient ever moving. If you have ever had an X-ray, you know that every time they take a different picture, you have to move. The three gradient magnets discussed earlier allow the MRI system to choose exactly where in the body to acquire an image and how the slices are oriented.
Disadvantages
Although MRI scans are ideal for diagnosing and evaluating a number of conditions, it does have drawbacks. For example:

- There are many people who cannot safely be scanned with MRI (for example, because they have pacemakers), and also people who are too big to be scanned.

- There are many claustrophobic people in the world, and being in an MRI machine can be a very disconcerting experience for them.

- The machine makes a tremendous amount of noise during a scan. The noise sounds like a continual, rapid hammering. Patients are given earplugs or stereo headphones to muffle the noise (in most MRI centers you can even bring your own cassette or CD to listen to). The noise is due to the rising electrical current in the wires of the gradient magnets being opposed by the main magnetic field. The stronger the main field, the louder the gradient noise.

- MRI scans require patients to hold very still for extended periods of time. MRI exams can range in length from 20 minutes to 90 minutes or more. Even very slight movement of the part being scanned can cause very distorted images that will have to be repeated.

- Orthopedic hardware (screws, plates, artificial joints) in the area of a scan can cause severe artifacts (distortions) on the images. The hardware causes a significant alteration in the main magnetic field. Remember, a uniform field is critical to good imaging.

- MRI systems are very, very expensive to purchase, and therefore the exams are also very expensive.
The almost limitless benefits of MRI for most patients far outweigh the few drawbacks.

The Future of MRI

The future of MRI seems limited only by our imagination. This technology is still in its infancy, comparatively speaking. It has been in widespread use for less than 20 years (compared with over 100 years for X-rays).

Very small scanners for imaging specific body parts are being developed. For instance, a scanner that you simply place your arm, knee or foot in are currently in use in some areas. Our ability to visualize the arterial and venous system is improving all the time. Functional brain mapping (scanning a person's brain while he or she is performing a certain physical task such as squeezing a ball, or looking at a particular type of picture) is helping researchers better understand how the brain works. Research is under way in a few institutions to image the ventilation dynamics of the lungs through the use of hyperpolarized helium-3 gas. The development of new, improved ways to image strokes in their earliest stages is ongoing.

Predicting the future of MRI is speculative at best, but I have no doubt it will be exciting for those of us in the field, and very beneficial to the patients we care for. MRI is a field with a virtually limitless future, and I hope this article has helped you better understand the basics of how it all works!

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About the Author

Todd A. Gould, RT-(R)(MR)(ARRT) is a Registered Technologist in Radiography and Magnetic Resonance Imaging with the American Registry of Radiologic Technologists. He works at Rex Healthcare in Raleigh, NC. He lives in Apex, NC, with his wife and daughter.