INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392-1

SMR.300/53

College on Medical Physics
(10 October - 4 November 1988)

What is MRI?

J. CAMERON
Dept. of Medical Physics, University of Wisconsin, Madison, USA

** These notes are intended for internal distribution only

WHAT IS MRI?

by John Cameron
Department of Medical Physics
University of Wisconsin
Madison, Wisconsin 53706

[Draft of a chapter in a book tentatively titled PICTURES OF YOUR INSIDES. Your comments and suggestions would be appreciated. 6/24/88]

In the post office in Panacea, Florida the other day I heard someone tell an acquaintance that a mutual friend had an MRI done. It was said as though no explanation was necessary. Here was a set of initials that a few years ago were in nobody's vocabulary. What do they stand for and what is MRI all about? I hope this article gives you some idea how this new way to diagnose disease works.

MRI USED TO BE CALLED NMR IMAGING

MRI stands for Magnetic Resonance Imaging. Ten years ago when the technique was first coming into use it was called Nuclear Magnetic Resonance or NMR. NMR has been known and used by physicists and chemists for several decades for basic research on material structure. You still occasionally hear the technique being called NMR rather than MRI.

The change of initials is not important except possibly as a social comment on current attitudes toward the word "nuclear". It is said to have been eliminated to avoid scaring people who might associate the technique with nuclear weapons, nuclear power or nuclear radiation. Another explanation for the change is that it avoids confusion with another common medical imaging specialty called Nuclear Medicine.

In order to explain MRI to a nonscientist it is necessary to talk a little about magnetism and about resonance. Let's talk about magnetism first. What is it, what causes it, and how is it involved in MRI?

WHAT IS MAGNETISM?

Most people have some feel for magnetism. As kids, we were fascinated by magnets. Magnets could pick up nails which then picked up other nails. There are natural magnets -- loadstones which have been known for several thousand years. Magnetic compasses were invented about 600 years ago. They work because the earth is really a big magnet with a magnetic pole near each of the geographic poles that produce magnetic fields. The magnetic field of the earth produces a force on other magnets causing them to align with the earth's magnetic field.

The first person to study magnets scientifically was William Gilbert who lived in the sixteenth century and was physician to the Queen of England. Gilbert gets credit for noticing the existence of the two magnetic poles and determining the general rules of magnetic force. He described the magnetic field of the earth. Until that time it was not known why a magnetic compass worked. However, that didn't stop Columbus from using one.

Magnets have some characteristics in common with electricity. There are two types of electric charge, negative and positive. Opposite charges attract each other while charges of the same sign repel each other. In magnetism, each magnet, no matter how small will have a north and a south pole. North and south poles attract each other while similar poles repel each other. A magnetic pole is the name we use to describe the location on the magnet that has these magnetic properties. You can not see a magnetic pole. Magnetism is different than electricity in that you can not have just a north pole or just a south pole. They always come in pairs, while it is possible to have just positive or negative electricity.

MAGNETS ALWAYS HAVE A NORTH AND A SOUTH POLE

If you break a magnet in half, it will have a north pole on one end and a south pole on the other end. This can be repeated until you have a microscopic magnet, still with a north and a south pole. If you have a simple bar magnet, one pole is on each end. Let's paint the north pole blue and the south pole red. If you have two such bar magnets and bring them near each other you discover that ends with the same color do not like (repel) each other. However, opposite poles have a strong attraction for each other, sticking together with considerable force.

MAGNETISM IS CAUSED BY ELECTRIC CURRENT, EVEN IN ATOMS

Early in the last century it was discovered that electric currents produce magnetic fields, which led to the invention of electromagnets. Late in the last century Ampere proposed that all magnetic fields are due to the motion of electric charge, or electric current.

You may remember from grade school that all atoms are made up of electric charges. You should not be surprized to learn that atoms have magnetic properties. I don't want to lose you in details but we have to go one step further. All the components of atoms are made up of spinning subatomic particles. In the nucleus of the atom the heavy particles called protons have one unit of positive charge. As they spin, the rotating charge produces a very weak magnetic field. This magnetic field plays an important role in MRI.

The magnetic field of a single proton cannot be observed directly. It is much too weak. If a nucleus has an even number of protons, they combine in pairs to greatly reduce the net magnetic field outside the nucleus. For MRI it is best to look for nuclei composed of single protons or an odd number of protons. Nearly all MRI studies take advantage of the single proton found as the nucleus of the hydrogen atom.

HYDROGEN IS OUR MOST COMMON ELEMENT

Nature has been kind to us by providing a great abundance of hydrogen atoms. Hydrogen is the most common element in nature and in our bodies. You probably know that the body contains a lot of water. Every water molecule has two hydrogen atoms combined with one oxygen atom. In addition, fat contains hydrogen as a major component. Bone has much less hydrogen than other parts of the body. The body is made up of a huge number of very small magnets--the nuclei of hydrogen atoms or protons. They are pointing in random directions so the little magnets do not combine to produce a magnetic field from our body. There are some very weak detectable magnetic fields from the currents flowing in our nerves and muscles. These magnetic fields are millions or billions of times weaker than the earth's magnetic field.

RESONANCE IS "GETTING TUNED IN"

Now let's talk about "resonance"--the "R" of MRI. Resonance has several definitions. We will use the definition used in physics: "The state of a system in which an abnormally large vibration is produced in response to an external stimulus, occurring when the frequency of the stimulus is the same, or nearly the same as the original frequency of the system." Resonance is a very common phenomenon in nature. It is an important characteristic of all musical instruments. For example, the string of a violin or guitar has a resonant frequency or resonance at which it will vibrate. If that frequency is produced by another instrument it will cause the string to vibrate. When we tune a violin we change this resonant frequency. When you tune your radio to a station, the frequency of the radio waves from that station is at the resonant frequency of the circuit in your receiver. The resonant frequency, produces a big effect compared to frequencies higher or lower than it. Resonance is a common phenomenon in our lives from pushing a child on a swing to tuning our radio or TV set.

PROTONS' RESONANT FREQUENCY DEPENDS ON MAGNETIC FIELD

Protons in a strong magnetic field have resonant frequencies in the frequency range between the AM and FM bands on your radio. For example, in a 1.5 Tesla field the resonant frequency of protons is 64 MHz, while the FM band extends from 88 to 108 MHz. The resonant frequency of protons is very dependent on the strength of the magnet field; the stronger the magnetic field, the higher the resonant frequency. Similarly, the resonant frequency of a violin string increases as the string is stretched tighter. The resonant frequency for protons is called the Larmor frequency, named after the scientist who discovered the effect. In MRI we communicate with trillions of protons in your body using radio waves tuned to their resonant frequency. We can think of each proton as a microscopic radio receiver. It also acts as a microscopic radio transmitter when it emits a radiowave.

MRI UNITS HAVE FEW MOVING PARTS

The only moving part on an MRI unit is the rolling platform that moves the patient to the proper position in the donut shaped magnet (Fig. 1). There are only a few basic components of an MRI unit: a strong uniform magnetic field; coils to produce pulsed magnetic fields, and a special radio frequency broadcasting system and an equally special radio receiver to pick up the signals "broadcast" by the protons. There are, of course, lots of other auxiliary components needed for an MRI unit to produce an image of the inside of the body. You can be sure it uses a powerful computer to collect and store millions of pieces of data. The computer also does the many millions of calculations necessary to convert

: information into a picture. The details of this ocess are complex, but you don't have to know out them, anymore than you have to know how : film in your camera produces the picture.

Although it is not important to the patient, the RI room has special shielding to avoid the radio-quency energy escaping from the room and inter-ing with communication equipment. The large ignets are designed to minimize the magnet fields the surrounding rooms.

The number of hydrogen nuclei (protons) in ur body is enormous. Most of us can't grasp large mbers like the national debt. A single cell of our dy will contain about eight trillion hydrogen nu-:i or protons. An MRI scan depends on the com-ned effects of an unbelievably large number of otons in the body. The magnetic field from a sin-: proton is negligible. It is analogous to adding e penny to the national debt. However, when bil-ms of pennys are added to the debt it begins to nount to real money! It is the combined effect from llions upon billions of protons that makes MRI ssible.

IE MRI UNIT CAN ERASE CREDIT CARDS

We are now ready to explain how MRI orks. The patient is brought into the MRI suite and ecked to make sure she or he has no magnetic ma-rials on their clothing or in their body. The MRI erator wants to make sure that no magnetic materi-s are brought near the powerful magnet of the MRI iit. The magnetic field is typically thousands of nes larger than the earth's magnetic field. If a odern credit card is brought near it, all of the infor-ation on the card is erased. If you bring an iron rench near the MRI unit, the large magnetic force ill pull the wrench out of your hand, propelling it e a bullet to the magnet. The magnetic force hold-g the wrench is so great that it is necessary to turn f the magnet to release it.

The MRI unit looks much like a Computerized omographic (CT) unit (Fig. 1.). The patient is mpletely unaware of the strong magnetic field. lagnetic fields are not detected by our senses.

RODUCING THE MAGNETIC FIELD

The magnetic field in an MRI unit can be pro-ced by three methods: a superconductive current, hich is always left on; a current in a resistive coil, hich is turned off only at night; or by the use a per-anent magnet. The larger the magnetic field, the ster the image is produced. The most powerful agnetic fields are produced by large electric currents in superconducting coils. Certain alloys have the interesting characteristic that when they are cooled to extremely low temperatures they loose all of their resistance to the flow of electric current. This is called superconductivity. This permits the magnet to have very large currents, which produce very large magnetic fields. However, it is necessary to keep the magnet extremely cold using liquid helium. A superconducting magnet alone may cost a half-million dollars. The liquid helium costs thousands of dollars per year.

The magnetic field must be very uniform for the technique to work. The strong magnetic field makes the hydrogen nuclei--(little magnets) in the body "sit up and pay attention." That is, there is a magnetic force that tries to align them with the magnetic field, somewhat the way a compass needle is aligned by the force of the earth's magnetic field.

PROTONS IN YOUR BODY ARE ALIGNED BY THE MAGNETIC FIELD

The atoms and molecules in our body are continually in motion due to their heat energy. The orientation of the protons is random. When a strong magnetic field is turned on about half of the protons will have their north poles roughly aligned with the field and the remainder have their north poles in the opposite direction. Fortunately, it isn't a perfect division. One direction is slightly preferred over the other. This slight difference is determined by nature and nature tries to keep this difference constant. If the distribution is changed artificially by human interference, nature will try to get it back to its original condition. This tendency of the protons to return to their natural condition is fundamental in the operation of an MRI unit. The technical term to describe protons returning to their natural distribution is "relaxation." More about that later.

There is a very slight energy difference between protons pointed with the field and those pointed in the other direction. This energy difference is trivial from a human standpoint. It is even trivial compared to the energy used by a single cell of our body. However, the right amount of energy can be provided by a radio frequency wave at the resonant frequency of the proton. This frequency depends on the magnetic field. The MRI unit has a radio broadcast antenna (see Fig. 1) and broadcasts a pulse of radiofrequency energy at the body. It's like a radio station broadcasting to a radio receiver that has been already tuned to a particular frequency. If the broadcast frequency is the same as the resonant frequency of the receiver, the signal is received.

THE PROTONS ACT LIKE LITTLE WALKIE-TALKIE RADIOS

Some of the protons absorb the radio frequency energy and reverse their orientation. The natural distribution is thus disturbed. Nature starts immediately to get things back to the natural distribution. As the protons return to the preferred distribution they give up energy. You guessed it, they give up the same radio frequency that they originally absorbed. The antenna picks up the weak signal and amplifies it and stores the information about the signal in the memory of the computer. This information is used later for constructing a picture of the body part.

Now you can see why the energy was sent in as a short pulse. We need to listen between the pulses for the radiowaves being sent back by the protons as they "relax" back to their preferred distribution. The length of the radio frequency pulse and how often it is sent out depends on the type of MRI study. The patient does not feel the radiofrequency pulses but will hear the clicking sound produced by the equipment that controls the magnetic fields.

Actually, the MRI unit looks at the strength of the returning signal from a selected slice of tissue at a preselected time (a fraction of a second) after the pulse that disturbed the equilibrium. This time is very important and is selected by the operator to maximize the image quality. The time depends on the type of MRI study. This process is repeated many times to get enough information to produce an image. There are some tricks to speed up the process that we won't discuss.

MRI PICTURES ARE TRICKY TO MAKE

Although much of your body may be inside the magnet, only a limited part of it is being studied. It doesn't make an image of your whole body. The part being studied is centered in the very uniform central part of the magnet. If another part is to be studied it will be moved to the central area.

The optimum time to look for the relaxation signal depends on the tissues and the medical problem. If an inappropriate time is chosen, the resulting MRI picture may be of little use for diagnostic purposes. Let's say that the time is chosen such that signals from protons in tumor tissue look like the signals from protons in the surrounding normal tissue. That would be a real "no show" for the tumor. Figure 2 shows three images from the same section of the head at three different delay times. Note that in the middle picture the two different tissues are about the same shade of grey and are difficult to distinguish. Note also that the shades of grey in Fig. 2a are reversed from those in Fig. 2c. In this case it is not a question of detecting a tumor, but distinguishing two adjoining tissues. Figure 3 shows that some diseases can only be seen under appropriate time sequences.

The characteristics of the returned signal give information about the tissues in a particular small volume of the body, called a voxel. If the relaxation is faster or slower from a certain voxel than from voxels in the surrounding tissues, it means the protons live in a different chemical or physical neighborhood than do the normal tissues. This could indicate that a disease, such as cancer, has invaded these tissues.

MRI, like Computerized Tomography (CT) and other devices to make pictures of our insides does not itself make a diagnosis of cancer or any other disease. It produces an image that must me interpreted by a medical specialist (radiologist). The radiologist is an M.D. who has spent four years beyond medical school studying the interpretation of these type of images. In addition to the image, other studies are often needed to make the final diagnosis.

THREE FACTORS HAVE A BIG EFFECT ON THE MRI PICTURE

There are three factors that affect the returning signal. One is the number (or density) of protons in the volume being studied. Some tissues have a greater percentage of water than other tissues, thus they send back a stronger signal due to the greater number of protons present.

The other two important imaging factors have the scientific names "spin-lattice relaxation time" or T1, and "spin-spin relaxation time" or T2. The relaxation time is a measure of how long it takes for the protons to return to their natural distribution. It is very difficult to measure T1 and T2 independent of each other. However, some MRI images will show the effect of one more than the other. These will be referred to as a "T1 weighted" image or a "T2 weighted" image.

Because of the relatively weak signal that must be detected and the large number of combinations of settings that can be varied for a given MRI study, it generally takes longer to do an MRI study than to do a comparable x-ray study. However, you should not think that MRI will eliminate the need for x-rays. There are still many situations, such as problems involving the bones, where x-rays are the best diagnostic tool.

A MRI unit looks somewhat like a CT x-ray unit in that it is shaped somewhat like a donut. In addition, the images often look quite similar. However, a MRI image gives very different information from a CT or x-ray image. The most striking part of an x-ray image is usually the bones. The calcium in the bones absorbs most of the x-rays causing the bones to show up clearly on the film. In the case of MRI, bone is practically invisible because it has relatively little water in it. The MRI picture does show the marrow on the inside of the bones. In some cases the lack of a bone image makes it easier to see disease in the adjoining areas, such as the cartilage of the knee. You can also see why MRI might be preferred to x-rays for studying the brain which is surrounded by the skull. MRI is used for other parts of the body, as well as the brain. It can be used for looking for diseases in your muscles and heart. The decision on whether to use the MRI or CT unit for a given study will depend on a number of factors. Each imaging device has its own advantages.

HOW THE MRI UNIT SORTS OUT ALL THE INFORMATION

You might wonder how the MRI equipment sorts out the different parts of the body. Aren't all the protons sending signals at the same time? That would be like having all the phones in the country hooked up together at one time. Information from any one phone couldn't be sorted out from all the other conversations.

As you might guess the engineers and physicists have solved the problem in a very clever way. Remember earlier I told you that the resonant frequency depends on the strength of the magnetic field. Even a very small change in the field will change the resonant frequency and the protons will not respond. The MRI unit is designed such that only a thin slice of the body has the proper resonant (Larmor) frequency at the instant the pulse of radiofrequency energy is sent out. While the energy is being emitted from the protons the magnetic field over the slice being imaged is varied using "gradient coils". The protons in different magnetic field strengths then broadcast at different frequencies. Like a radio that can tune in different stations, the MRI unit can detect the different frequencies and know where each frequency came from, thus identifying the location and characteristics of each small volume of tissue.

It is considerably more complex than this brief description indicates but I hope you get the general idea. If you want to know more you can read one of the reference books listed at the end.

DOES AN MRI STUDY HURT?

A potential patient having an MRI probably wants to know how much it hurts and whether it is safe. The patient is able to communicate with the MRI staff at all times through a microphone and intercom. Since the body cannot feel magnetic fields or radio waves, there is no direct pain from the MRI procedure. There may be some incidental pain from lying stationary during the study. Some patients may be bothered by being confined inside the machine. There is some noise associated with the operation of the MRI unit but this is usually not objectionable. In some procedures "surface coils" are placed near the part of the body being studied. They can detect weaker radio signals from the tissues. There is no hazard from these coils as they are used to pick up signals from the body.

ADVANTAGES OF MRI vs CT

The MRI unit has several advantages over a CT unit. Because of the way the MRI unit collects the information about the body, it is able to produce pictures of slices in any direction, for example, along the axis of the body, rather than just across the body as is the case for the usual CT unit. The radiologist can select what slice to look at to get the best information. The MRI unit can be adjusted to give better detail for some organs, such as the blood vessels. In an x-ray or CT study it is necessary to inject a dye into the blood to make the arteries visible. Because bone does not appear in the MRI image, it often shows some parts of the body more clearly, such as the spinal cord. In general, each medical imaging system has its own unique advantages. It is a primary role of the radiologist to choose the best device for the particular medical problem. It is often necessary to use several imaging systems since they give different types of information.

WHAT ARE THE RISKS OF AN MRI STUDY?

There appear to be no significant risks from an MRI study. MRI does not use any ionizing radiation such as x-rays or radioactive materials. Thus there is no risk similar to that from an x-ray or a nuclear medicine study. The high magnetic fields seem to have no biological effects, good or bad. No hazard has been attributed to the radiofrequencies used in MRI, however, the strong magnetic field may adversely affect a heart pacemaker. Also, some types of metal, such as iron, are moved by strong magnetic fields. Thus there is a slight risk to a patient who has a piece of magnetic material in the body from earlier surgery, such as blood vessel clips or a cochlear (ear) implant. Also, some artificial hips are made of magnetic materials. Sometimes a metal

worker will have a sliver of metal in the eye from an industrial accident. The strong magnetic field may cause the metal to move and produce internal damage. If the metal is non-magnetic it poses no hazard but it will show up on the MRI image.

The major negative aspect of MRI is the high cost of the equipment and its operation. This translates into higher health care costs. An MRI unit typically costs about twice as much to buy and operate as a Computerized Tomographic (CT) unit. One way to cut the large equipment cost is for several hospitals to share the cost. There are MRI units mounted in large semi-trailers that can be taken from one hospital to another.

WHAT ABOUT THE FUTURE OF MRI?

During the past year there has been startling scientific news about new materials that may make MRI superconducting magnets less expensive. Undoubtedly new uses will be found for MRI. It already is considered the best way to do some diagnostic studies. Even though it has nothing to do with x-rays, you will find the MRI equipment in the x-ray or radiology department. Ultrasound, another non-radiation medical imaging technique is also found in the x-ray department. As a result some x-ray departments are using a new name- The Medical Imaging Department.

This discussion was not intended to tell you all the facts about MRI. If you want to learn more about this new medical tool take a look at some of the books listed below.

A Non-Mathematical Approach To Basic MRI by H-J. Smith, published by MPPC in May 1988. This book is used to teach physicians how MRI works.

An Introduction to Pulse NMR Spectroscopy by T. C. Farrar, 1987. Available from MPPC. This book is very technical.