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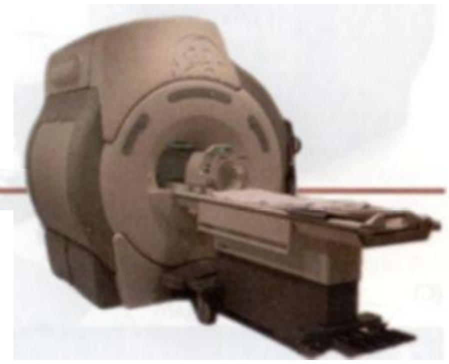
MRI Scanners



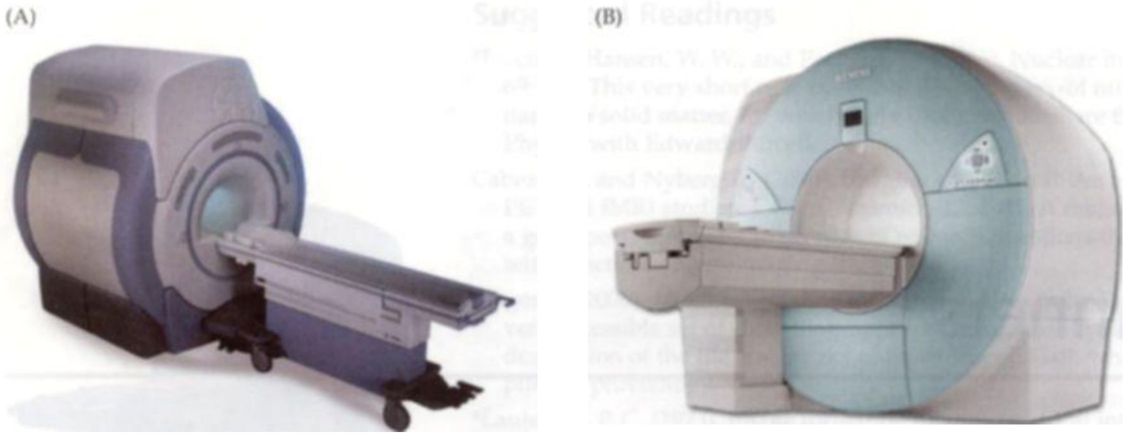
Since the beginning of MRI, technological advances have resulted in continual improvements in the speed at which data can be acquired, in the ability to localize signal in space, and in the types of contrast that can be measured. Consequently, the practice of MRI today differs drastically from that of the early pioneers, and modern MRI scanners (Figure 2.1 A-C) do not resemble the devices first used to detect nuclear magnetic resonance. However, the fundamental principles of MRI are unchanged. Just as Rabi used a strong magnetic field to measure spin properties of nuclei, today's MRI scanners use a strong magnetic field to induce changes in proton spin. Just as Bloch detected nuclear induction using transmitter and receiver coils, scanners now use similar coil systems to obtain MR signal. And just as Lauterbur manipulated magnetic field strength using changing gradient fields to create an image, every current MRI study relies on magnetic gradients for image acquisition. In this chapter, we identify the major components of MRI scanners, describe their use in practice, and discuss their safety implications.

How MRI Scanners Work

The three main components of an MRI scanner, as alluded to above, are the static magnetic field, radiofrequency coils, and gradient coils, which together allow collection of images. Yet these are not the only components important for fMRI. Also necessary are shimming coils, which ensure the homogeneity of the static magnetic field; specialized computer systems for controlling the scanner and the experimental task; and physiological monitoring equipment. This section introduces these components and their implementation on modern MRI scanners (Figure 2.2). We will return to a detailed discussion of how they are used to change the magnetic properties of atomic nuclei in Chapters 3 to 5.

Static Magnetic Field

The static magnetic field is an absolute necessity for MRI, providing the *magnetic* in magnetic resonance imaging. Magnetic fields were discovered in naturally occurring rocks, known as lodestones, by ancient Chinese almost 2000 years ago. By the eleventh century, the Chinese had recognized that the



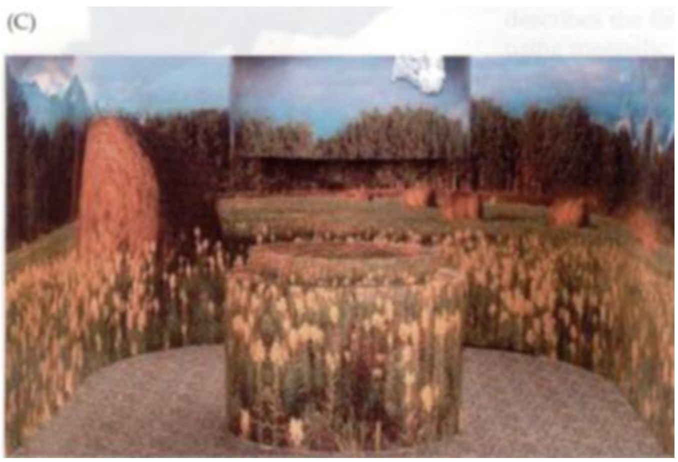


Figure **2.1** Examples of MRI scanners. Most MRI scanners use a closed-bore design, in which the patient/subject lies down on a table at the front of the scanner and then is moved back into the middle of the bore (i.e., central tube). Shown in (A) is a Signa series scanner from General Electric, and in (B) is a MAGNETOM Avanto scanner from Siemens. A small fraction of scanners use a more open design, such as FONAR's 360 Open Sky scanner, shown in (C). In an open scanner, the subject does not have to go into a tube, so the chance of a claustrophobic reaction is reduced. However, it is more difficult to maintain a strong homogeneous static magnetic field in an open scanner, and thus most scanners used for fMRI employ traditional closed-bore designs. (A courtesy of GE Medical Systems, Waukesha, Wisconsin; B courtesy of Siemans AG, Berlin, Germany; C courtesy of Fonar Corporation, Melville, New York.)

earth itself has a magnetic field, so that a magnet suspended in water will orient itself along the earth's magnetic field lines (i.e., from north to south). The eventual rediscovery of magnetism centuries later by European scientists proved invaluable for subsequent nautical exploration, as ships adopted magnetic compasses for directional guidance. MRI scanners use strong static magnetic fields to align certain nuclei within the human body (most commonly, hydrogen within water molecules) to allow mapping of tissue properties.

Some early MRI scanners used permanent magnets to generate the static magnetic fields used for imaging. Permanent magnets typically generate weak magnetic fields that are fixed by their material composition, and it is difficult to ensure that their magnetic fields are not distorted over space. Another way of generating a magnetic field was discovered by the Danish physicist Hans Oersted in 1820, when he demonstrated that a current-carrying wire influenced the direction of a compass needle below the wire, redirecting it perpendicularly to the direction of current. This relation was quantified later that year by the French physicists Jean-Baptiste Biot and Felix Savart, who discovered that magnetic field strength is in fact proportional to current strength, so that by adjusting the current in a wire (or sets of wires), one could precisely control field intensity. These findings led to the development of electromagnets, which generate their fields by passing current through tight coils of wire. Nearly all MRI scanners today create their static magnetic field through electromagnetism.

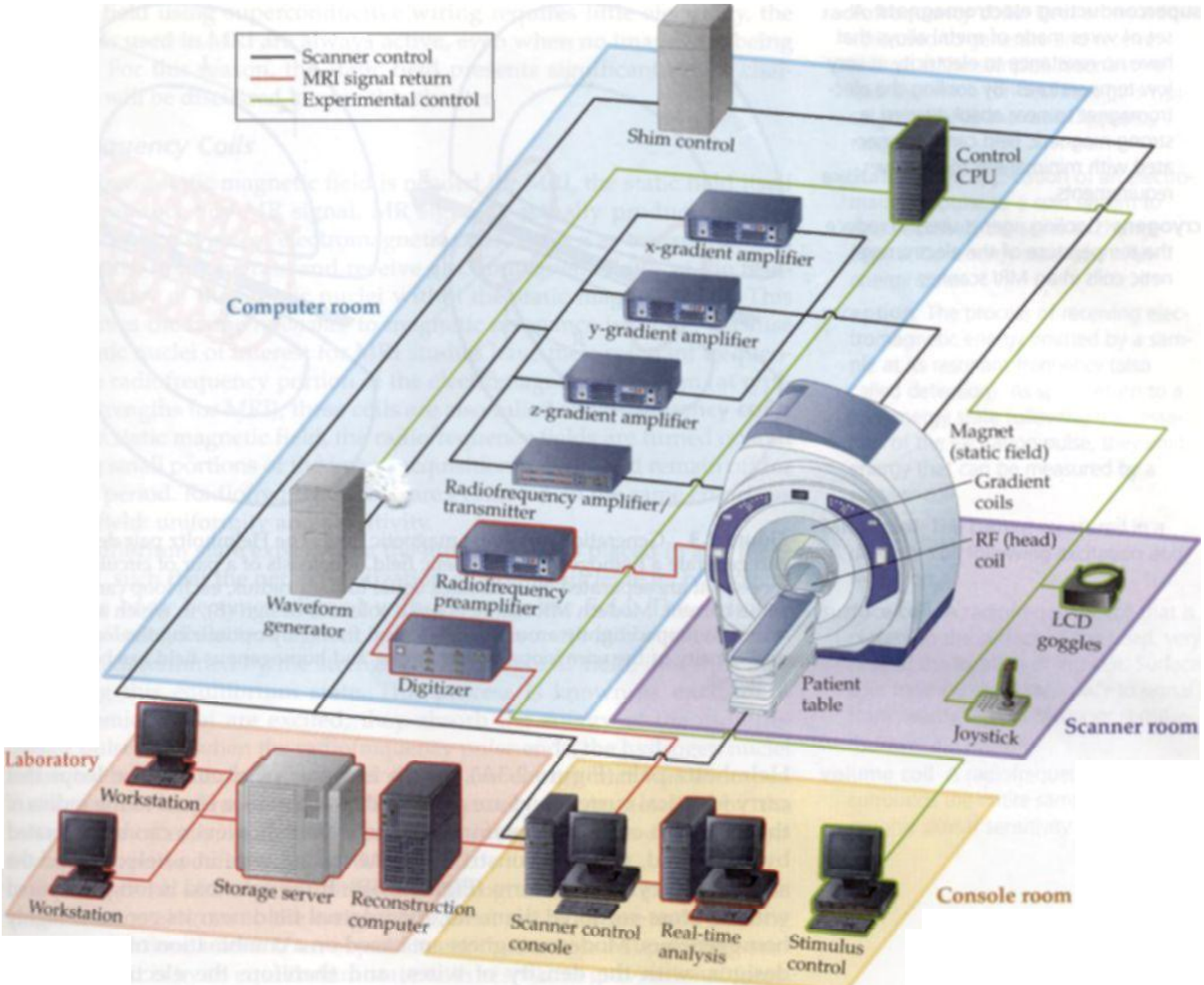


Figure 2.2 Schematic organization of the MRI scanner and computer control systems. Two systems are important for fMRI studies. The first is the hardware used for image acquisition, which in addition to the scanner itself consists of a series of amplifiers and transmitters responsible for creating gradients and pulse sequences (shown in black), as well as recorders of MR signal from the head coil (shown in red). The second system is responsible for controlling the experiment in which the subject participates and for recording behavioral and physiological data (shown in green).

There are, in general, two criteria for a suitable magnetic field in MRI. The first is uniformity (or **homogeneity**), and the second is strength. Uniformity is necessary in that we want to create images of the body that do not depend on which MRI scanner we are using or how the body is positioned in the field. If the magnetic field were inhomogeneous, the signal measured from a given part of the body would depend upon where it was located in the magnetic field. (In fact, MRI takes advantage of this effect by introducing controlled changes in magnetic field strength by adding magnetic field gradients.) A simple design for generating a homogeneous magnetic field is the

homogeneity Uniformity over space and time. In the context of MRI, a homogeneous magnetic field is one that has the same strength throughout a wide region near the center of the scanner bore.

superconducting electromagnets A set of wires made of metal alloys that have no resistance to electricity at very low temperatures. By cooling the electromagnet to near absolute zero, a strong magnetic field can be generated with minimal electrical power requirements.

cryogens Cooling agents used to reduce the temperature of the electromagnetic coils in an MRI scanner.

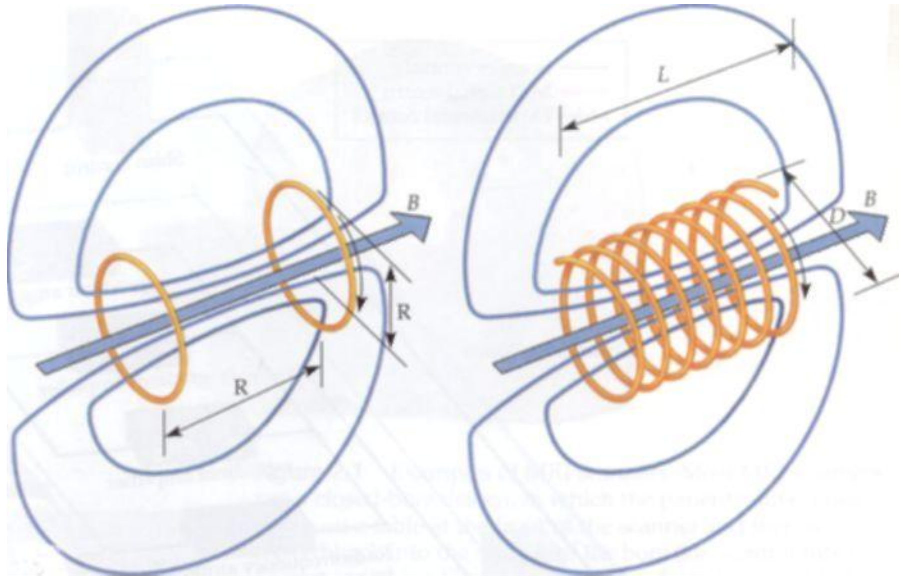


Figure 2.3 Generation of a static magnetic field. The Helmholtz pair design (A) can generate a homogeneous magnetic field. It consists of a pair of circular current loops that are separated by a distance equal to their radius; each loop carries the same current. Modern MR scanners use a solenoid design (B), in which a coil of wire is wrapped tightly around a cylindrical frame. By optimizing the locations and density of the wire loops, a very strong and homogenous field can be constructed.

Helmholtz pair (Figure 2.3A), which is a pair of circular wire loops that carry identical current and are separated by a distance equal to the radius of the loops. An even more uniform magnetic field, however, can be generated by a solenoid, which is constructed by winding wire in a helix around the surface of a cylindrical form (Figure 2.3B). If the solenoid is long compared with its cross-sectional diameter, the internal field near its center is highly homogeneous. Modern magnets are based on a combination of these classic designs, with the density of wires, and therefore the electrical current, numerically optimized to achieve a homogeneous magnetic field of the desired strength.

Field strength, in contrast to uniformity, requires force rather than finesse. To generate an extremely large magnetic field, one can inject a huge electric current into the loops of wire. For example, the very large electromagnets used to lift cars in junkyards have magnetic fields on the order of 1 T, similar to that in the center of some MRI scanners. To generate this field, they require enormous electrical power, and thus enormous expense. Modern MRI scanners use **superconducting electromagnets** whose wires are cooled by **cryogens** (e.g., liquid helium) to reduce their temperature to near absolute zero. Coil windings are typically made of metal alloys such as niobium-titanium, which when immersed in liquid helium reach temperatures of less than 12 K (-261° C). At this extremely low temperature, the resistance in the wires disappears, thereby enabling a strong and lasting electric current to be generated with no power requirements and minimal cost.

Combining the precision derived from numerical optimization of the magnetic coil design and the strength afforded by superconductivity, modern MRI scanners can have homogeneous and stable field strengths in the range of 1 to 9 T for human use and up to 20 T for animal use. Since maintaining a field using superconductive wiring requires little electricity, the static fields used in MRI are always active, even when no images are being collected. For this reason, the static field presents significant safety challenges, as will be discussed later in this chapter.

Radiofrequency Coils

While a strong static magnetic field is needed for MRI, the static field itself does not produce any MR signal. MR signal is actually produced by the clever use of two types of electromagnetic coils, known as transmitter and receiver coils, that generate and receive electromagnetic fields at the resonant frequency of the atomic nuclei within the static magnetic field. This process gives the name *resonance* to magnetic resonance imaging. Because most atomic nuclei of interest for MRI studies have their resonant frequencies in the radiofrequency portion of the electromagnetic spectrum (at typical field strengths for MRI), these coils are also called **radiofrequency coils**. Unlike the static magnetic field, the radiofrequency fields are turned on and off during small portions of the image acquisition process and remain off for any other period. Radiofrequency coils are evaluated on the same criteria as the static field: uniformity and sensitivity.

An equilibrium state exists when the human body is placed in any magnetic field, such that the net magnetization of atomic nuclei (e.g., hydrogen) within the body becomes aligned with the magnetic field. The radiofrequency coils send electromagnetic waves that resonate at a particular frequency, as determined by the strength of the magnetic field, into the body, perturbing this equilibrium state. This process is known as **excitation**. When atomic nuclei are excited, they absorb the energy of the radiofrequency pulse. But, when the radiofrequency pulse ends, the hydrogen nuclei return to the equilibrium state and release the energy that was absorbed during excitation. The resulting release of energy can be detected by the radiofrequency coils, in a process known as **reception**. This detected electromagnetic pulse defines the raw **MR signal**.

One can think of the measurement of MR signal through excitation and reception as analogous to the weighing of an object by lifting and releasing it in a gravitational field. If an object sits motionless on a supporting surface, so that it is in an equilibrium state with respect to gravitational force, we have no information about its weight. To weigh it, we first lift the object to give it potential energy and then release it so that it transfers that energy back into the environment. The amount of energy it releases, whether through impact against a surface or compression of a device like a spring (e.g., in a scale), provides an index of its weight. In the same way, we can perturb the magnetic properties of atomic nuclei (excitation) and then measure the amount of energy returned (reception) during their recovery to an equilibrium state.

The amount of energy that can be transmitted or received by a radiofrequency coil depends upon its distance from the sample being measured. In the case of fMRI, the radiofrequency coils are typically placed immediately around the head, either in a **surface coil** or **volume coil** arrangement (Figure 2.4). Surface coils are placed directly on the imaged sample, that is, adjacent to the surface of the scalp for functional imaging. The design of surface coils is based upon a single-loop inductor-capacitor (LC) circuit (Figure 2.4A). Within this circuit, the rapid charge and discharge of electricity between the inductor and capacitor generates an oscillating current that can be tuned to the frequency of interest. Because of their close spatial proximity to the brain, surface coils usually provide high imaging sensitivity and are often

radiofrequency coils Electromagnetic coils used to generate and receive energy at the sample's resonant frequency, which for field strengths typical to MRI is in the radiofrequency range.

excitation The application of an electromagnetic pulse to a spin system to cause some of the spins to change from a low-energy state to a high-energy state.

reception The process of receiving electromagnetic energy emitted by a sample at its resonant frequency (also called detection). As spins return to a low-energy state following the cessation of the excitation pulse, they emit energy that can be measured by a receiver coil.

MR signal The current measured in a detector coil following excitation and reception.

surface coil A radiofrequency coil that is placed on the surface of the head, very near to the location of interest. Surface coils have excellent sensitivity to signal from nearby regions but poor sensitivity to distant regions.

volume coil A radiofrequency coil that surrounds the entire sample, with roughly similar sensitivity throughout.

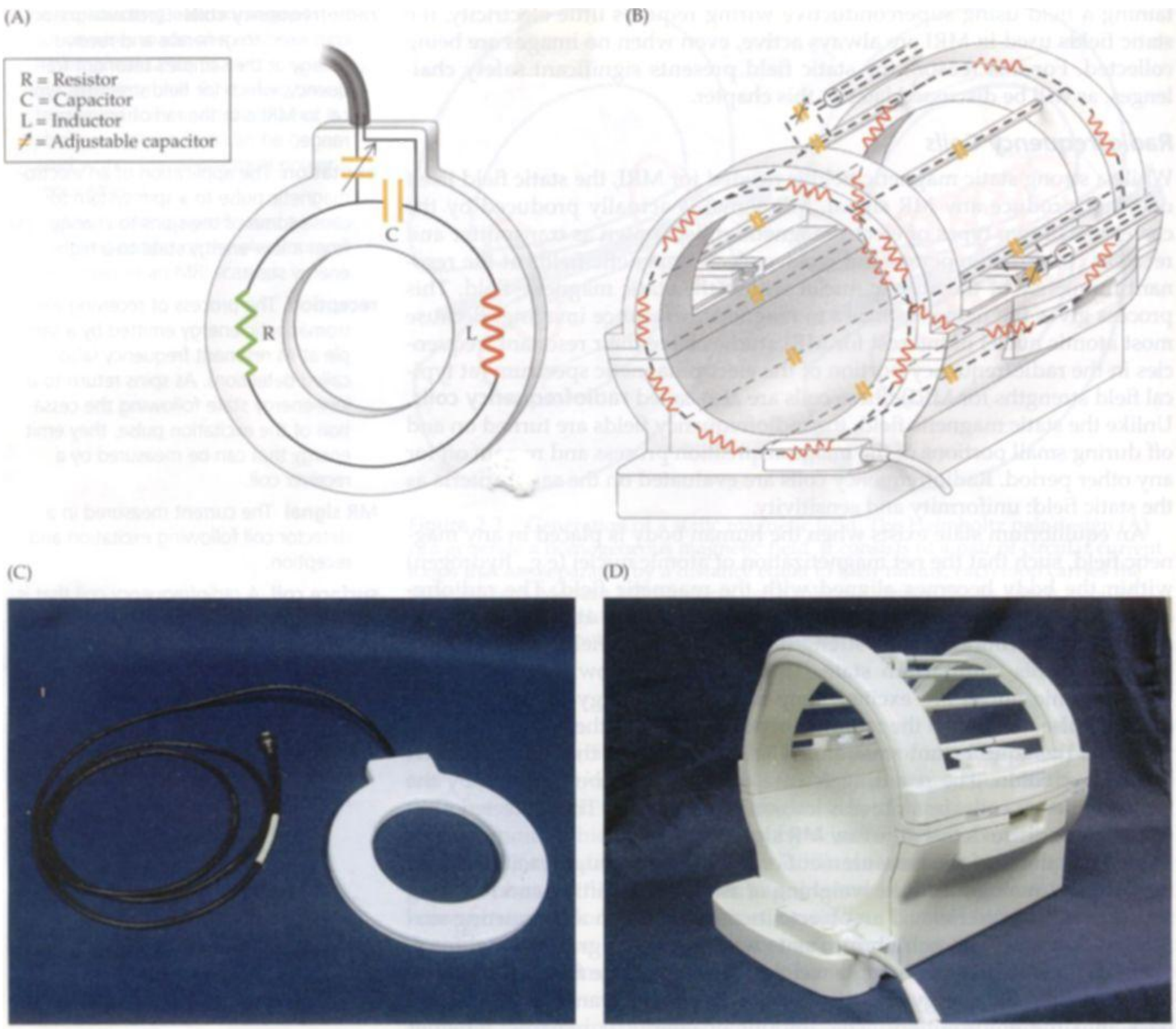


Figure 2.4 Surface and volume coils. (A) Surface coils consist of a simple inductor (L) -capacitor (C) circuit, with additional resistance (R) also present. The rapid charging and discharging of energy between the inductor and resistor generates an oscillating magnetic field. The signal from the surface coil is modulated by a variable capacitor (shown with the arrow). **(B)** Volume coils repeat the same LC circuit around the surface of a cylinder. This results in better spatial coverage than is provided by a surface coil, at the expense of reduced local sensitivity. (C) A typical surface coil, and (D) volume coil.

used for fMRI studies that are targeted toward one specific brain region, such as the visual cortex. The trade-off with high local sensitivity is poor global coverage. Since the amount of signal recovered from a given part of the brain depends on its distance from the surface coil, areas very near the coil provide a great deal of signal but areas far away provide very little (Figure 2.5A). Thus, the signal recovered by a surface coil is spatially inhomoge-

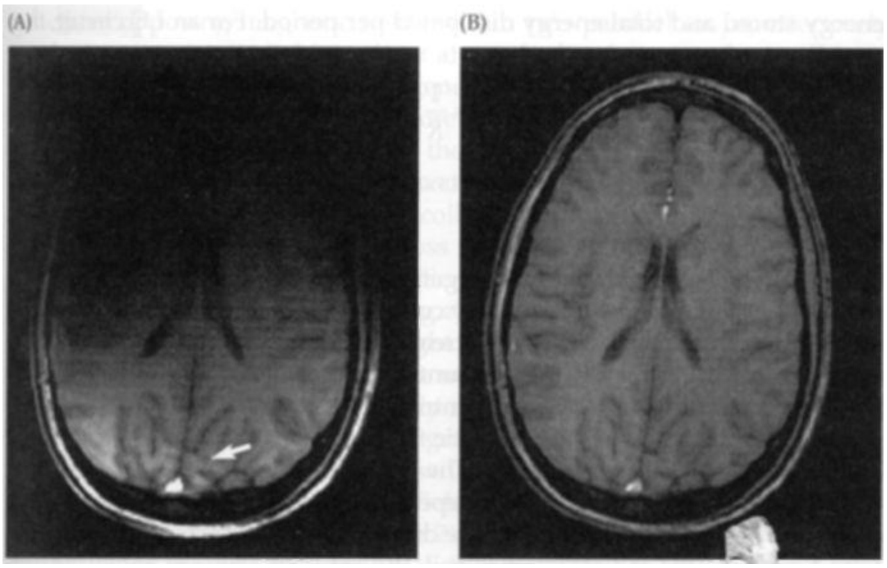


Figure 2.5 Signal recorded from surface and volume radiofrequency coils. The use of a receiver coil adjacent to the surface of the skull can increase signal-to-noise in nearby brain regions (visible here as reduced graininess, e.g., at arrowed location), but the recorded signal will drop off in intensity as the distance from the coil increases (A). Thus, the use of a single surface coil is more appropriate for fMRI studies that are targeted toward a single brain region. Volume coils have relatively similar signal sensitivity throughout the brain (B), so they are more appropriate for fMRI studies that need coverage of multiple brain regions.

phased array A method for arranging multiple surface detector coils to improve spatial coverage while maintaining high sensitivity.

neous, which makes a single surface coil inappropriate when whole-volume imaging is desired.

A second class of MR coil is the volume coil (Figure 2.4B), which provides uniform spatial coverage throughout a large volume. The basic element of the volume coil is the same LC circuit (described in the previous paragraph) for the surface coil. The LC circuit is replicated around a cylindrical surface to achieve uniform distribution of energy within the enclosed volume (Figure 2.5B). The arrangement resembles a birdcage, and thus a volume coil is sometimes referred to as a birdcage coil. Because the volume coil is farther from the head than a surface coil, it has less sensitivity to the MR signal but more even coverage across the brain.

A compromise approach that combines the best features of both coil types is to use a volume coil for exciting the imaging volume and a set of surface coils for receiving the MR signal. If multiple receiver coils are arranged in an overlapping pattern known as a **phased array**, the spatial coverage of a single coil can be increased considerably while the high sensitivity of the coils is maintained. Though sensitivity does change somewhat across the image, the use of multiple receiver coils is an increasingly important technique in fMRI.

The sensitivity of a radiofrequency coil is proportional to the strength of the magnetic field generated within the coil by a unit current. Thus, a coil that generates a strong magnetic field is also a sensitive receiver coil—an example of the principle of reciprocity. A stronger magnetic field can be generated by adding more wire loops to produce higher current density. Assuming that the coil resistance is not zero, because radiofrequency coils are not typically superconducting, some energy will be lost in the heat generation, which will hamper the coil sensitivity. To obtain a quantitative measure of the coil sensitivity, a quality factor is defined as the ratio of the maximum

gradient coils Electromagnetic coils that create controlled spatial variation in the strength of the magnetic field.

energy stored and total energy dissipated per period. For an LC circuit, that quantity can be represented as:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Minimizing resistance (R) thus boosts coil sensitivity.

Gradient Coils

The ultimate goal of MRI is image generation. The combination of a static magnetic field and a radiofrequency coil allows detection of MR signal, but MR signal alone cannot be used to create an image. The fundamental measurement in MRI is merely the amount of current through a coil, which in itself has no spatial information. By introducing magnetic gradients superimposed upon the strong static magnetic field, **gradient coils** provide the final component necessary for imaging. The purpose of a gradient coil is to cause the MR signal to become spatially dependent in a controlled fashion, so that different locations in space contribute differently to the measured signal over time. Similar to the radiofrequency coil, the gradient coils are only used during image acquisition, as they are typically turned on briefly after the excitation process to provide spatial encoding needed to resolve an image.

To make the recovery of spatial information as simple as possible, gradient coils are used to generate a magnetic field that increases in strength along one spatial direction. The spatial directions used are relative to the main magnetic field, with z going parallel to the main field and x and y going perpendicularly to the main field. Like the previously discussed components of the scanner, gradient coils are evaluated on two criteria: linearity (comparable to the uniformity measure for the main magnet and the radiofrequency coils) and field strength.

The simplest example of a linear gradient coil is a pair of loops with opposite currents, known as a Maxwell pair (Figure 2.6A). A Maxwell pair

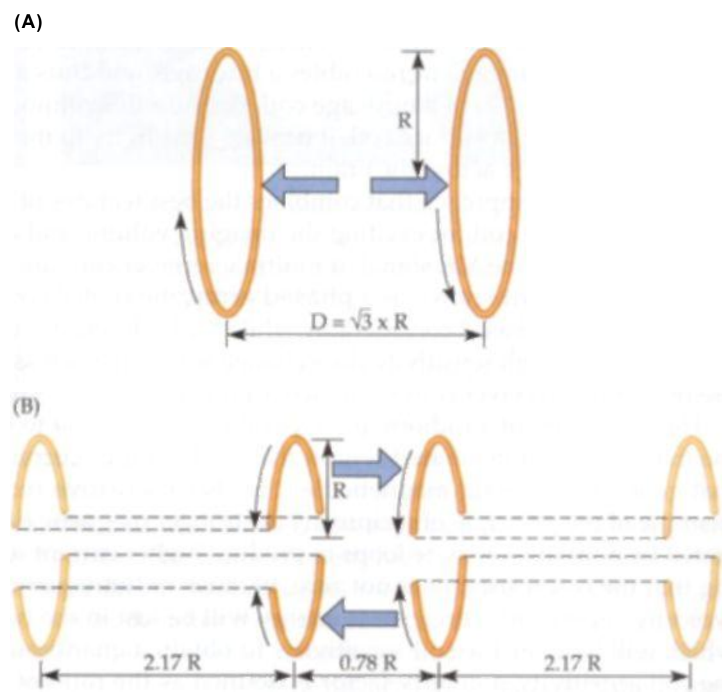


Figure 2.6 Coil arrangements for generating magnetic gradients. (A) Shows a Maxwell pair, two loops with opposing currents, which generates magnetic field gradients along the direction of the main magnetic fields. The configuration in (B) is known as a Golay pair. It allows generation of magnetic field gradients perpendicular to the main magnetic field.

generates opposing magnetic fields within two parallel loops, effectively producing a magnetic field gradient along the line between the two loops. This design, in fact, is the basis for generating the z-gradient used today. Of course, the z-gradient coils have a more complicated geometry than a simple pair, but the same concept underlies their design.

The x- and y-gradients, also known as transverse gradients, are both created in the same fashion, since the coils that wrap around the scanner are circular and thus symmetrical across those directions. It is important to understand that the transverse gradients change the intensity of the main magnetic field across space (i.e., along z); they do not introduce smaller magnetic fields along *x* and *y*, as one might suppose. That is, the introduction of an x-gradient, for example, makes the main magnetic field slightly weaker at negative values along *x* and slightly stronger at positive values along *x*. Therefore, to generate a transverse gradient, one cannot simply place the Maxwell pair along the *x* or *y* axis (which would generate a magnetic field pointing perpendicular to the main field). Instead, scanners use a configuration similar to that shown in Figure 2.6B to generate these gradients. This slightly more complicated double-saddle geometry is known as a Golay pair. The final geometry that actually produces the x- or y-gradient field is numerically optimized and contains many more windings than the simple saddle coil shown here. Figure 2.7 illustrates the different patterns of coil windings used for the magnetic gradients and the static magnetic field.

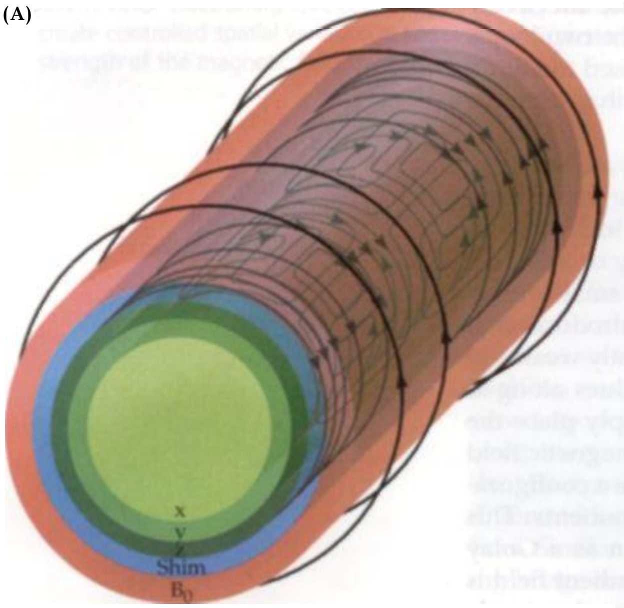
The strength of the gradient coil is a function of both the current density and the physical size of the coil. Increasing the current density by increasing the electrical power supplied to the coil produces a stronger gradient field. Reducing the size of the coil, so that a given current travels through a smaller area, also produces a stronger gradient field. The trade-off between held strength, size, and power is not linear. In fact, as the bore size increases, the power required for generating a gradient of the same strength increases with the 5^{th} power of the bore size. The implications of this fact can be appreciated in a simple example. Consider that a physicist wants to increase the bore size of a scanner by a factor of 2, while maintaining the same gradient strength. Although the bore size is only doubled, the power requirements increase by a factor of 2^5, or 32. This constraint imposes a practical limitation on the bore size of an MRI scanner.

Thought Question

Some manufacturers have begun developing "head-only" MRI scanners for clinical and functional studies of the brain. Based upon what you know so far, what would be the advantages of such scanners?

Shimming Coils

In an ideal MR scanner, the main magnet would be perfectly homogeneous and the gradient coils would be perfectly linear. This is hardly the case in reality, as the authors (and everyone who has ever conducted fMRI studies!) can attest. MRI scanners must correct for inhomogeneities in the static magnetic field; in some locations the field may be too strong, in others too weak. This process is analogous to what we do when a table is rocking—we simply put a wedge under one of the uneven legs to make it stable. This wedge is called a shim. In the scanner, additional coils generate high-order compensatory magnetic fields (like the analogous wedges) that correct for the inho-



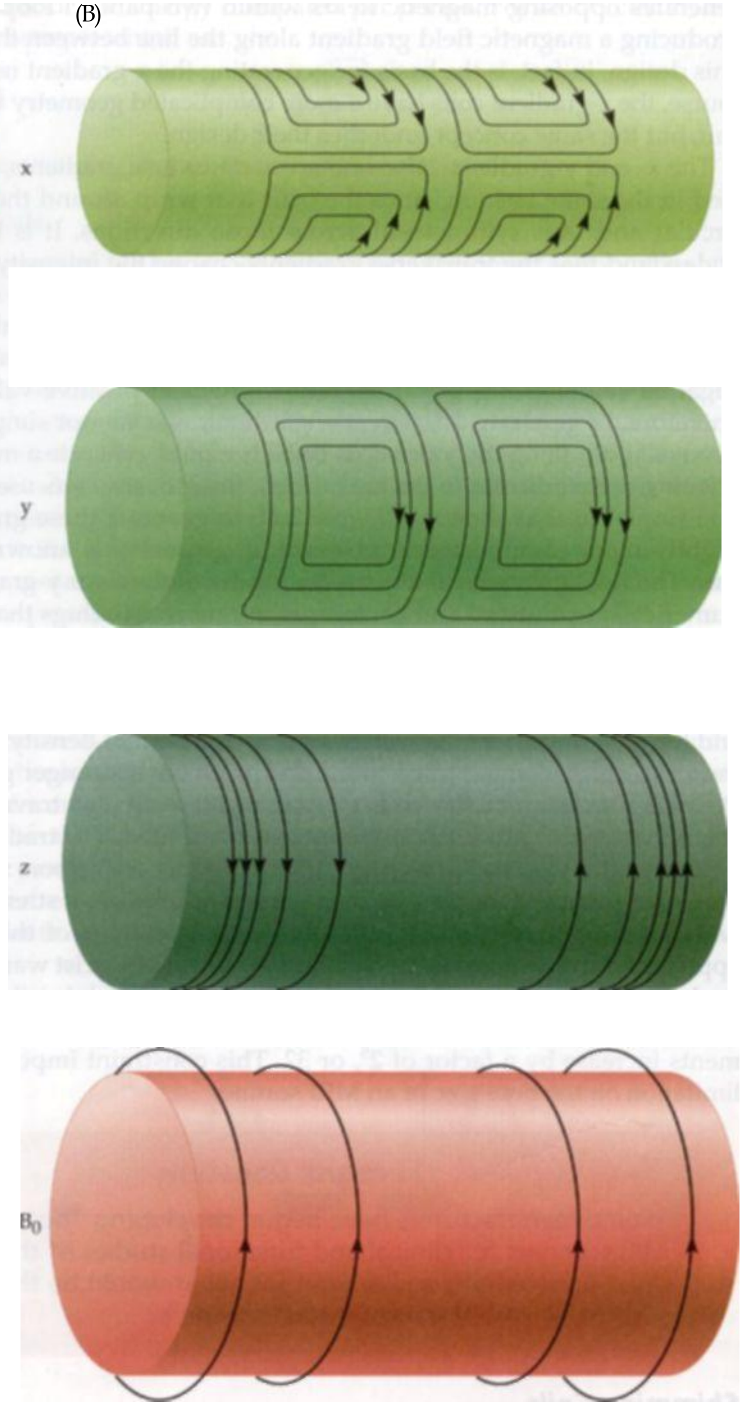


Figure 2.7 Generation of x-, y-, and z-gradients and the static magnetic field (B_0). (A) A number of different electromagnetic coils are used within a single MRI scanner. (B) The coils are arranged as a series of concentric circles, beginning with the gradient coils at the interior and followed by the shimming coils and then the static field coils. The x- and y-gradients are generated using the Golay pair arrangement, and the only difference between them is that one is rotated 90° from the other. The z-gradient is generated using the Maxwell pair arrangement. The shimming coils are not shown here due to their complexity; as discussed in the text, there may be many different coil types depending on the scanner. Finally, the static field is generated using a series of Helmholtz pairs, with the distance between the pairs corresponding to their radius.

shimming coils Electromagnetic coils that compensate for inhomogeneities in the static magnetic field.

mogeneity of the magnetic field. These coils, intuitively, are named **shimming coils**.

Typically, shimming coils can produce first-, second-, or even third-order magnetic fields. For example, an x-shimming coil would generate a magnetic field that depends on position along the x-axis (first-order), while an x^3-shimming coil could generate a magnetic field that depends upon the cube of the *x* position (third-order). Combinations of these high-order magnetic fields can usually correct for the inhomogeneity of a typical magnet so that the magnetic field is uniform to roughly 0.1 part per million (ppm) over a spherical volume of 20-cm diameter. For a 1.5-T magnet, this represents a deviation of only 0.00000015 Tesla.

Unlike the other magnetic fields, the shim fields are adjusted for each subject. For fMRI studies, each person's head distorts the magnetic field slightly differently. Shimming procedures used in fMRI thus account for the size and shape of the subject's head so that the uniformity of the magnetic field can be optimized over the brain. Also unlike the radiofrequency and gradient coils, which are turned on and off throughout the imaging session, the shimming coils are usually adjusted once and then left on for the duration of the session.

pulse sequence A series of changing magnetic field gradients and oscillating electromagnetic fields that allows the **MRI** scanner to create images sensitive to a particular physical property.

Computer Hardware and Software

Digitizing, decoding, and displaying MR images require a considerable amount of computer processing power. All MRI scanners are equipped with at least one central computer to coordinate all hardware components (e.g., gradient coils, radiofrequency coils, digitizers), and often multiple computers are used to control separate hardware clusters. The computer type, processor, and operating system vary greatly across scanner manufacturers. In addition to the hardware requirements, two types of specialized software are needed for fMRI. The first type of software sends a series of instructions to the scanner hardware so that images can be acquired. These programs, often called **pulse sequences,** coordinate a series of commands to turn on or off certain hardware at certain times. The type of pulse sequence used determines which kind of images are acquired. Usually the selection of parameters for a pulse sequence is done via a graphic user interface (Figure 2.8). The second type of software is the reconstruction and analysis package to create, display, and analyze the images. Creation of many images, especially anatomical, is done online at the scanner, but often images are sent to other more powerful computers for reconstruction and/or analysis. We will discuss the principles of image formation and pulse sequence generation in Chapters 4 and 5.

Experimental Control System

To induce changes in brain function in response to task manipulations, an experimental control system is necessary. Although the particular hardware and software used will differ across laboratories, there are three basic components. First, the control system must generate the experimental stimuli, which may include pictures or words that subjects see, sounds that subjects hear, or even taps on the skin that subjects feel. Since normal computer monitors cannot go into the strong magnetic field of the scanner, visual stimuli are often shown to the subject by custom virtual-reality goggles that are MR compatible or by projecting an image onto a screen in the bore of the scanner. Second, the control system must record behavioral responses made by the subject, such as pressing a button or moving a joystick. Usually, both the timing and the accuracy of the response are measured. Third, the presentation of stimuli and recording of responses must be synchronized to the timing of image acquisition, so that the experimental paradigm can be matched to the fMRI data. This may be done through direct electrical connection of the scanner hardware and experimental control system, so that starting the scanner sends an electrical pulse to the control system that triggers the start of the experiment as well. Specialized software packages are often used for the experimental control system in conjunction with standard personal computers. The

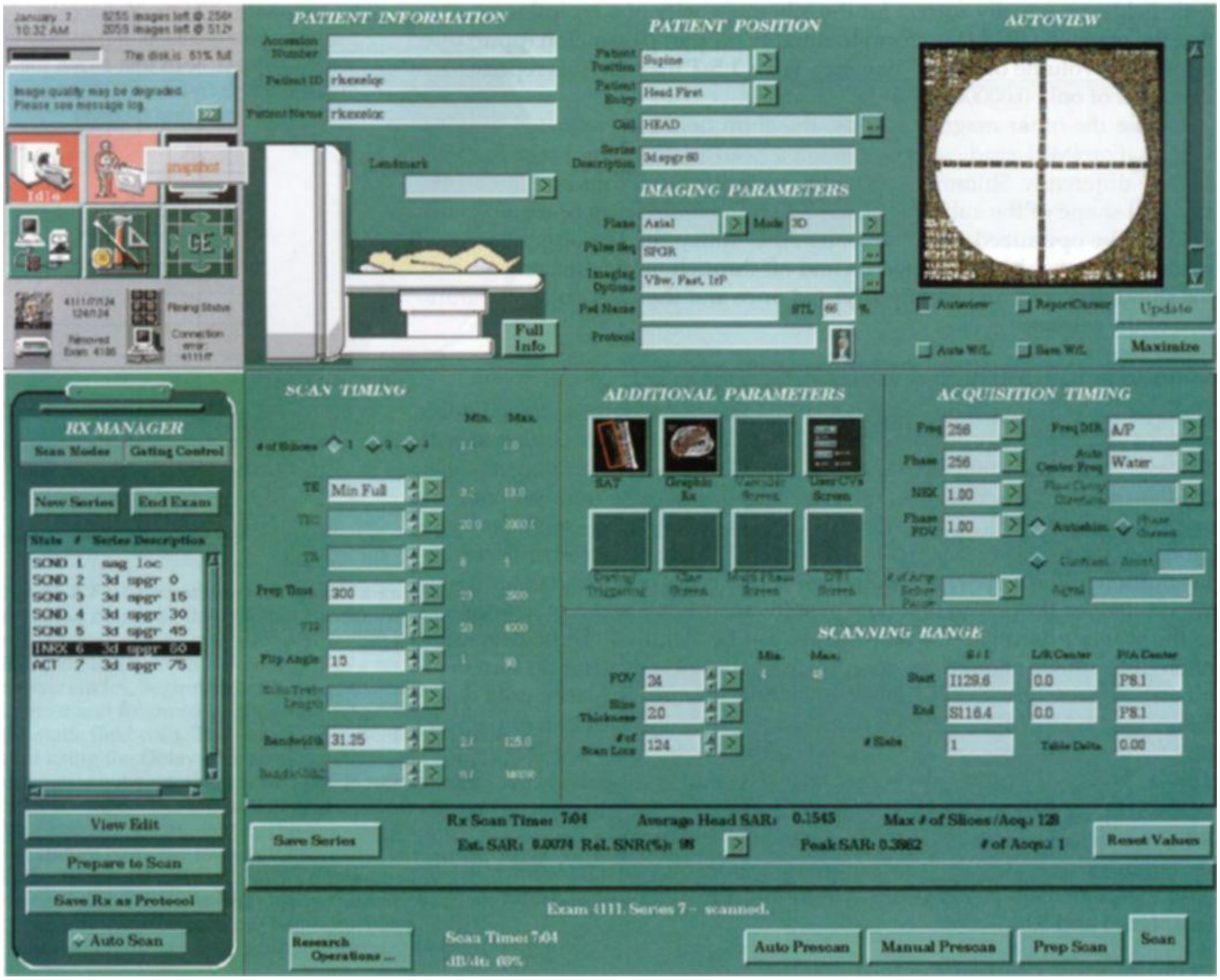


Figure 2.8 A graphic user interface used to control an MRI scanner. The operator of an MRI scanner will use an interface similar to this one to select the pulse sequence parameters for a given study. (Courtesy of General Electric Medical Systems, Waukesha, Wisconsin.)

key challenge for any experimental setup is to ensure that the equipment used in the scanner room, such as display devices or joysticks, is not attracted by the strong magnetic fields and does not interfere with imaging.

Physiological Monitoring Equipment

Many MRI scanners have equipment dedicated to recording physiological measures like heart rate, respiratory rate, exhaled CO_2, and skin conductance. In clinical studies, such equipment allows attending physicians to monitor patients' vital signs. If a patient has trouble breathing or has heart problems during the scanning session, a doctor may choose to remove the individual from the scanner. Physiological monitoring is especially important for patients who may be uncomfortable within the MRI environment, including the elderly, the severely ill, or young children. In functional MRI experiments, research subjects are often healthy young adults, and as such they have little risk of clinical problems. Physiological monitoring in fMRI studies, therefore, often has a different goal: to identify changes over time that may contaminate the quality of the functional images. Each time the heart beats or the lungs inhale, for example, the brain moves slightly. Also, changes in the air volume of the lungs can affect the stability of the magnetic field across the brain. By recording the pattern of physiological changes over time, researchers can later compensate, at least partially, for some of the variability in fMRI data (see Chapter 10).

A second reason to record physiological data during fMRI sessions lies in the relation between physiology and cognition. Many physiological measures can be used as indices for particular cognitive processes. For example, the diameter of the pupil can be used as an index of arousal, in terms of both alertness and amount of cognitive processing. If the size of the pupils increases more in response to one photograph than to another, a researcher may conclude that the former picture is more arousing than the latter. Skin electrical conductance provides another indicator of arousal. Additionally, the position of the eyes can be used as an obvious indicator of the focus of a subject's attention. By examining the sequence of a subject's eye movements across a visual scene, a researcher may discover which objects are most important, due to the increased visual dwell time on them, and which are least important or ignored. Physiological monitoring thus has two primary purposes for fMRI studies: to improve the quality of the images and to provide additional information about subjects' mental states.

MRI Safety

Since the inception of clinical MRI testing in the early 1980s, more than 200 million MRI scans have been performed, with an additional 50,000 scans performed each day. The vast majority of these scans are performed without incident, confirming the safety of MRI as an imaging technique. However, the very serious exceptions to this generalization should give pause. The static magnetic field of an MRI scanner is strong enough to pick up even heavy ferromagnetic objects, like oxygen canisters, and pull them toward the scanner bore at great speed. Implanted metal objects, like aneurysm clips or pacemakers, may move or malfunction within the magnetic field. Only through constant vigilance and strict adherence to safety procedures can serious accidents be avoided.

Effects of Static Magnetic Fields upon Human Physiology

The overriding risks for any MRI study result from the use of extremely strong static magnetic fields. The magnetic field generated by an MRI scanner is sufficiently strong to pick up heavy objects and pull them toward the scanner at very high velocity. This motion of objects is known as a **projectile effect**. Given the dramatic influence of the MRI static field on metal objects, it is not surprising that many people assume that magnetic fields themselves have substantial biological effects. However, this is a misconception. Static magnetic fields, even the extremely strong fields used in MRI, have no known long-term deleterious effects on biological tissue.

projectile effect The movement of an untethered ferromagnetic object through the air toward the bore of the MRI scanner.

BOX 2.1 Outline of an fMRI Experiment

A biology major at college, Emily has always been interested in the brain. One day, while walking back from class, she saw a flyer advertising a "Functional Neuroimaging Study" that used MRI to study the brain. The flyer said that the study would last about two hours, she would be compensated for her time, and she would be able to see pictures of her own brain. The study sounded intriguing, and she called the laboratory to get more information.

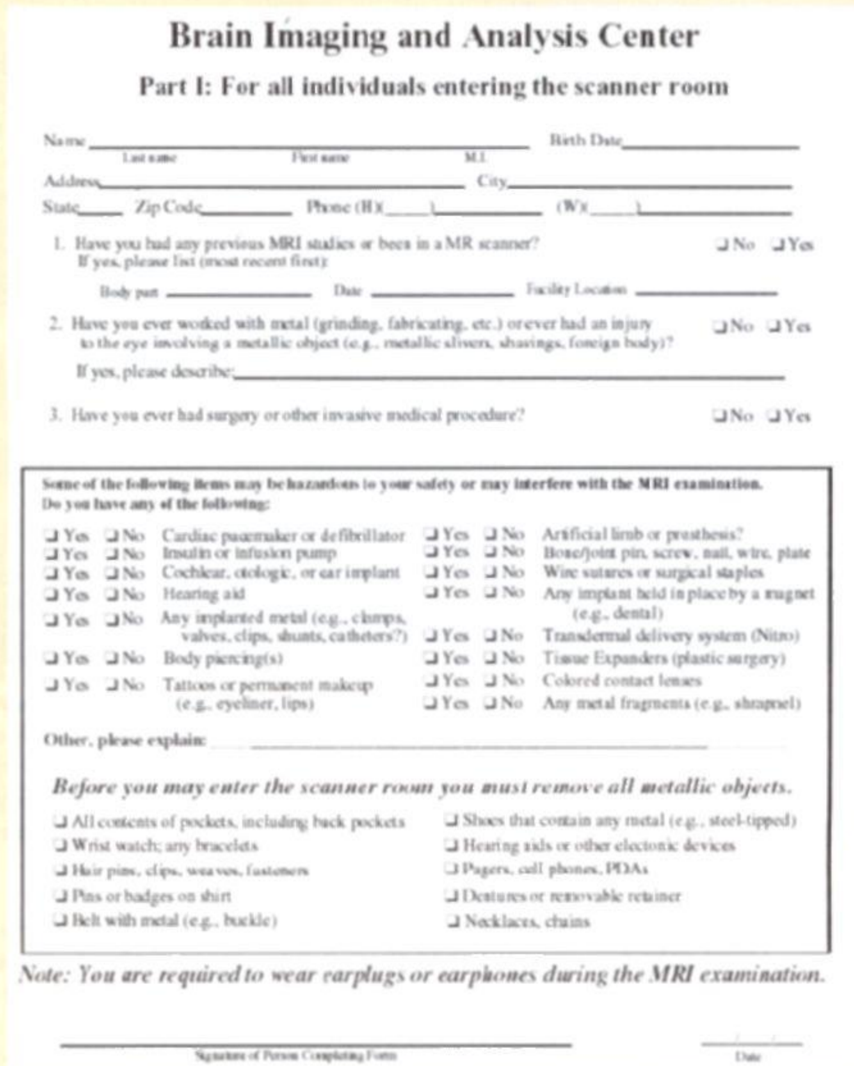
Before the Experiment

When she called the laboratory, Emily was nervous. She didn't know very much about MRI, and she wanted to learn more about the technique. The researcher on the phone told her about what would happen in the study. The primary goal of this research, he said, was to investigate which parts of the brain were responsible for working memory, the ability to actively maintain information over time. During the experiment, she would lie in the MRI scanner and watch a series of shapes presented one after another. Whenever she saw a particular shape, she would press a button on a joystick. The MRI scanner would then measure the changes in her brain that occurred each time she pressed the button. The experiment sounded interesting to Emily, and she told the researcher that she wanted to participate.

The researcher then told Emily that he would need to ask her a set of questions to determine whether she was eligible to participate in the study. He asked her whether she had any metal in her body, like a pacemaker or aneurysm clip; whether she had any nonremovable body piercings; and whether she was claustrophobic. Emily did not have any medical condition that prevented her from participating, so she passed this screening test. The researcher then scheduled Emily for an fMRI session the following week.

Setting Up the Subject

On the day of the fMRI session, Emily was only slightly apprehensive. She was prepared for the scanning when she arrived at the hospital MRI center, having left her wallet, jewelry, and book bag in her dorm room. She had also worn clothing without any metal, as she had been instructed. She was greeted at the entrance by a graduate student, who escorted her to the MR console room. There she met an MR technologist, whose job it was to run the MR scanner. The console room was large and contained several computers.



Brain Imaging and Analysis Center

Part I: For all individuals entering the scanner room

Name ______ (Last name, First name, M.I.) Birth Date ______

Address ______ City ______

State ____ Zip Code ______ Phone (H)(____)______ (W)(____)______

1. Have you had any previous MRI studies or been in a MR scanner? ❑ No ❑ Yes
   If yes, please list (most recent first):
   Body part ______ Date ______ Facility Location ______
2. Have you ever worked with metal (grinding, fabricating, etc.) or ever had an injury to the eye involving a metallic object (e.g., metallic slivers, shavings, foreign body)? ❑ No ❑ Yes
   If yes, please describe: ______
3. Have you ever had surgery or other invasive medical procedure? ❑ No ❑ Yes

Some of the following items may be hazardous to your safety or may interfere with the MRI examination. Do you have any of the following:

❑ Yes ❑ No Cardiac pacemaker or defibrillator
❑ Yes ❑ No Insulin or infusion pump
❑ Yes ❑ No Cochlear, otologic, or ear implant
❑ Yes ❑ No Hearing aid
❑ Yes ❑ No Any implanted metal (e.g., clamps, valves, clips, shunts, catheters?)
❑ Yes ❑ No Body piercing(s)
❑ Yes ❑ No Tattoos or permanent makeup (e.g., eyeliner, lips)
❑ Yes ❑ No Artificial limb or prosthesis?
❑ Yes ❑ No Bone/joint pin, screw, nail, wire, plate
❑ Yes ❑ No Wire sutures or surgical staples
❑ Yes ❑ No Any implant held in place by a magnet (e.g., dental)
❑ Yes ❑ No Transdermal delivery system (Nitro)
❑ Yes ❑ No Tissue Expanders (plastic surgery)
❑ Yes ❑ No Colored contact lenses
❑ Yes ❑ No Any metal fragments (e.g., shrapnel)

Other, please explain: ______

Before you may enter the scanner room you must remove all metallic objects.

❑ All contents of pockets, including back pockets
❑ Wrist watch; any bracelets
❑ Hair pins, clips, weaves, fasteners
❑ Pins or badges on shirt
❑ Belt with metal (e.g., buckle)
❑ Shoes that contain any metal (e.g., steel-tipped)
❑ Hearing aids or other electonic devices
❑ Pagers, cell phones, PDAs
❑ Dentures or removable retainer
❑ Necklaces, chains

Note: You are required to wear earplugs or earphones during the MRI examination.

______ Signature of Person Completing Form ______ Date

Figure 2.9 A sample screening form used for functional MRI studies. This form would be filled out by a prospective subject before a research study. The experimenter would then examine the form to make sure that the subject has no condition (e.g., ferrous metal in the body) that would preclude participation in the study.

BOX 2.1 *(continued)*

Through a window, she saw the MR scanner, which was behind a locked door. The graduate student gave her several pieces of paperwork to fill out, including a consent form that described the study and a screening form that asked her questions about metal, medical conditions, and medications (Figure 2.9). The graduate student explained that Emily was participating in this experiment as a research volunteer, so she could quit the study at any time for any reason. Emily was also told that the experimenters would talk with her throughout the experiment to make sure that she was not having any problems. After Emily read and signed the consent and screening forms, she was ready to begin the study.

The technologist looked over Emily's forms to verify that she could participate and then asked her whether she had anything in her pockets or in her hair. At first, Emily thought that this was a strange question, but the technologist quickly explained that they wanted to make sure that people did not bring any metal with them into the scanner room. When Emily checked, she realized that she had left her keys in her pocket, and she placed them on a table. Once Emily made sure that she had no metal on her, the technologist unlocked the scanner room and escorted her inside. Emily sat down on the table at the front of the scanner, and the technologist handed her some earplugs. As Emily put the earplugs in, the technologist explained that the scanner would be loud and that the earplugs would reduce the noise to a comfortable level. Emily then lay down on the table. The technologist handed her a joystick and placed a pair of goggles over her eyes. The goggles had tiny computer screens inside! The technologist also gave her a squeeze ball that was connected to an alarm in the console room. If Emily became uncomfortable or needed help immediately, she could squeeze the ball to summon the technologist.

Although she couldn't see the scanner room anymore, due to the goggles, she could feel a pillow being wrapped around the sides of her head. The technologist told her that this was a vacuum pack that would support her head and help keep her from moving during the experiment; after a few seconds, Emily heard a hissing sound and the pillow hardened to form a solid cushion. A plastic cylinder called a volume coil then slid around her head (Figure 2.10). The technologist then told her that she was about to go into the scanner, and Emily found herself slowly moving back into the bore.

Structural and Functional Scanning

The technologist returned to the control room and then asked Emily over an intercom how she was feeling. Emily said that she was doing fine; her nervousness had worn off, and she was pretty comfortable in the scanner. The technologist then told her that she would hear some knocking noises while the scanner took pictures, called structural images, of her brain anatomy. The first knocking noise startled her, because she had expected the scanner to be quiet, like an X-ray machine. After the initial shock wore off, she ignored the noise and just thought about the scanner session. She looked forward to seeing pictures of her brain and wondered whether it was normal. The structural images took about 10 minutes, and then the technologist told her that it was time for the experiment to begin. The graduate student had previously explained that she was supposed to watch for circles to be presented on the screen. Whenever she saw a circle,

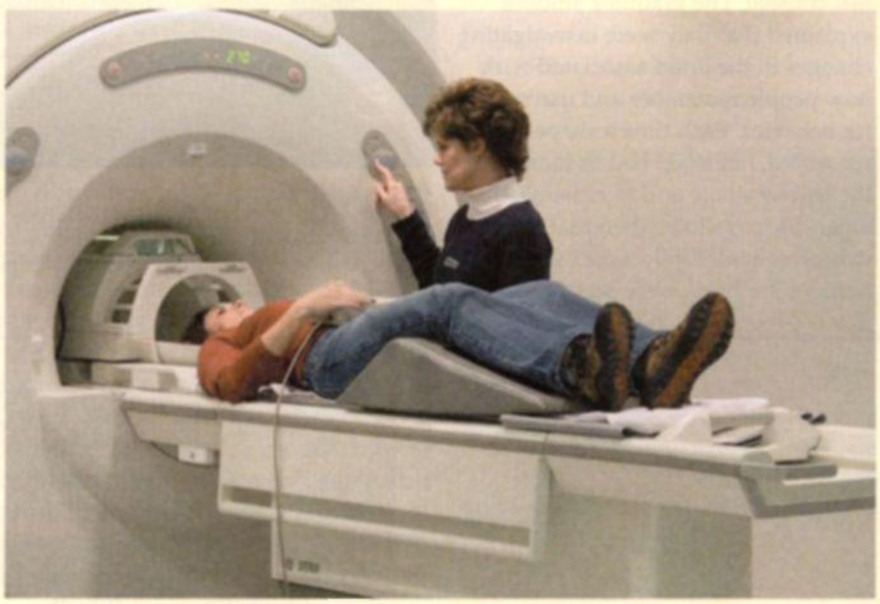


Figure 2.10 Setting up a subject in the scanner. The experimental subject is being positioned in the scanner before a research study. She is holding a joystick in her right hand that will be used for recording behavioral responses. The technologist standing next to the scanner is moving the table so that the subject's head is in a particular position. Once the subject is positioned properly, the technologist will move the volume radiofrequency coil forward so that it fits around the subject's head and then send her into the bore of the scanner.

BOX 2.1 *(continued)*

she was supposed to press a button on the joystick. Emily told the technologist that she was ready to begin.

The experiment was broken into a series of 6-minute runs. In each run, Emily saw **.1** large number of different shapes. Each time she saw a circle she pressed the button. Once or twice, she was trying so hard to look for the circles that she pressed the button for another shape. Overall, though, she made very few mistakes. Between the runs, the technologist talked to her to see how she was doing. After about **10** runs, the experiment was finished and the technologist came into the room to bring her out of the scanner. Emily was a little tired from concentrating for an hour, but she had still enjoyed the experiment and she wanted to see the pictures of her brain.

After the Experiment

Emily sat down in a chair next to the **MR** console. The graduate student explained that they were investigating changes in the brain associated with how people remember and use rules for behavior. Each time a shape was presented, her brain had to identify the correct shape and to remember what rule to follow when that shape was presented. Emily asked which areas of her brain were active during the experiment, and the graduate student told her that her data would have to be analyzed by computer programs back in the laboratory before they could answer that. They could, however, show her the structural images they had collected. The graduate student loaded the structural images onto the scanner console (Figure 2.11). They had collected two sets of structural images: a set of sagittal images that showed a side view of her brain and a set of axial images that showed a bottom-up view of her brain. After Emily was finished asking questions, she picked up her keys from the table, and the graduate student walked her back to the entrance to the scanner. Emily said she would be happy to participate in another session in the future, and then she went back to her dorm to rest.

Figure 2.11 Reviewing the anatomical MR images after the experiment. The graduate student who ran the experiment explains the nature and purpose of the experiment. She shows the subject pictures of her brain and discusses the goals of the research.

Thought Question

Why do you think that belief in the biological effects of magnetic fields has persisted, in the absence of strong evidence in support of such effects?

The study of the health effects of magnetic fields long predates MRI. In the 1920s, the prevalence of large industrial magnets in the factories of the day prompted the physiologists Drinker and Thompson to study the effects of magnetic fields upon both cells and animals. No health effects were found. Yet by the 1980s and 1990s, the possible health consequences of magnetic fields reemerged into public awareness, as people worried about exposure to power lines, cellular telephones, and MRI scanners. While a full discussion of the history of magnetic field safety is beyond the scope of this book, the outcome of a century of research can be stated succinctly: No replicable experimental protocol has ever been developed that demonstrates a long-term negative effect of magnetic fields upon human or animal tissue. Where plausible mechanisms for biological effects of magnetic fields have been postulated, they involve very high magnetic field strengths that are greater than those typically used in MRI—and orders of magnitude greater than those generated by power lines, cellular telephones, or other common sources. We refer the interested student to the comprehensive reviews cited in the references for fuller treatments of this issue.

There have been anecdotal reports of minor and short-lived effects associated with static field strengths greater than 2 T. These include reports of visual disturbances known as phosphenes, metallic taste sensations, sensations in teeth fillings, vertigo, nausea, and headaches. These sensations happen infrequently, but appear to occur when the subject's head is moved quickly within the static field. It is believed that some of these effects—particularly vertigo, nausea, and phosphenes—may be related to magnetohydrodynamic phenomena. When an electrically conductive fluid, such as blood, flows within a magnetic field, an electric current is produced, as is a force opposing the flow. In the case of blood flow, magnetohydrodynamic forces are resisted by an increase in blood pressure. However, this effect is negligible, requiring a field strength of 18 T to generate a change of 1 mm Hg in blood pressure. These resistive forces could, however, impose torque upon the hair cells in the semicircular canals of the inner ear, causing vertigo and nausea, or upon the rods or cones in the retina, causing the sensation of phosphenes. We emphasize that these latter effects are likely to occur only during quick movements of the head within the field. Moving the subject slowly in and out of the scanner and restricting head movement should eliminate these sensations.

Given the paucity of evidence in support of magnetism-induced health risks, as well as the absence of any plausible mechanism for such effects, why have magnetic fields engendered such concern? We speculate that the issue of magnetic field safety is symptomatic of two larger problems in public understanding and evaluation of scientific findings. First, magnetic fields and electric currents are mysterious to most nonphysicists, acting invisibly and over large distances. Surely a force powerful enough to lift a car or pull an oxygen canister across the room must have some effect upon the human body! The mysterious nature of magnetic fields makes any consequence of exposure plausible, from the threat of cancer by prolonged exposure to power lines to the circulatory improvements of magnetic bracelets, even if those consequences are themselves contradictory. Indeed, some data suggest that the experiences related to magnetic field exposure may partially result from psychological suggestion. A group of researchers at the University of Minnesota put subjects into the bore of a 4-T scanner and found that 45% reported unusual sensations. The researchers noted that this high rate of self-reported effects was interesting, given that the magnet had been powered down for repair and there was no magnetic field present at the time of the study.

Second, people, even many scientists, tend to select evidence in support of a preconceived viewpoint and reject evidence that refutes their ideas. While the vast majority of studies (and all replicated studies) show absolutely no health risks for magnetic fields less than 2 T, there remain a few studies that have claimed specific consequences of exposure. Even

translation The movement of an object along an axis in space (in the absence of rotation).

though these results have failed under replication, they plant a seed of doubt that grows in the minds of believers. In closing, we note that the efforts to demonstrate health consequences, either positive or negative, from magnetic fields fall perilously close to what has been called "pathological" or "voodoo" science: a conjecture for which, despite more and more studies, the evidence never gets any stronger.

Translation and Torsion

The primary risk of the static field used in MRI results not from the field itself but instead from the field's effects on metal objects. Objects that are constructed in part or whole with ferromagnetic materials (iron, nickel, cobalt, and the rare earth elements chromium, gadolinium, and dysprosium) are strongly influenced by magnetic fields. Steel objects are highly ferromagnetic, and even some medical grades of stainless steel are ferromagnetic. Metals such as aluminum, tin, titanium, and lead are not ferromagnetic, but objects are rarely made of a single metal. For example, ferromagnetic steel screws may secure titanium frames for glasses.

The most dramatic risks with a strong magnetic field are projectile effects that result in the **translation,** or movement, and subsequent acceleration of a ferromagnetic object toward the scanner bore. The magnetic pull on an object can increase dramatically as it nears the scanner. A movement of just a few inches toward the bore of the magnet can exponentially increase the force experienced by the object, making it impossible for a person to hold on to a ferromagnetic object such as a wrench or screwdriver. Similarly, a pager may stay clipped to a belt at the doorway to the magnet room, but become propelled into the magnet bore at 20 to 40 mph when the wearer takes a few steps forward. Projectile injuries have resulted from a number of metal objects, including scissors, IV-drip poles, and oxygen canisters (Figure 2.12).

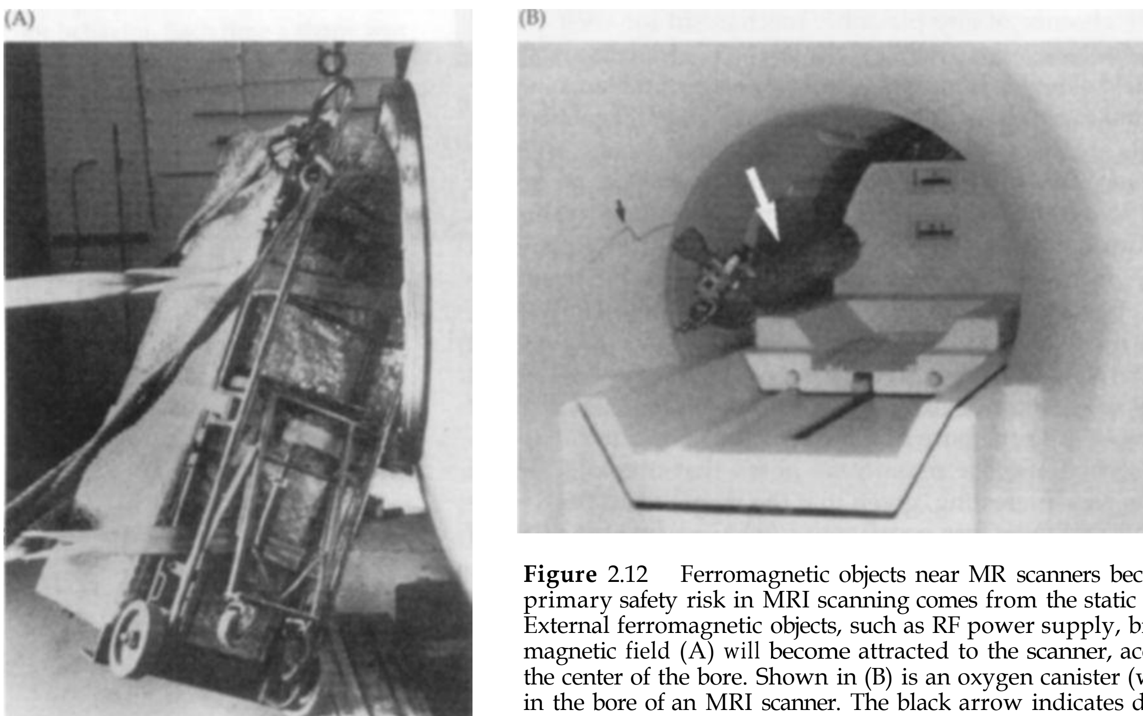


Figure 2.12 Ferromagnetic objects near MR scanners become projectiles. The primary safety risk in MRI scanning comes from the static magnetic field. External ferromagnetic objects, such as RF power supply, brought within the magnetic field (A) will become attracted to the scanner, accelerating toward the center of the bore. Shown in (B) is an oxygen canister (white arrow) lodged in the bore of an MRI scanner. The black arrow indicates damage to the scanner casing. Projectiles present a severe risk to subjects within the bore. (A from Schenck, 2000; B from Chaljub et al., 2001.)

In a tragic example of the danger of projectile effects, a 6-year-old boy was killed in 2001 when a ferromagnetic oxygen canister was brought into the MRI scanner room to compensate for a defective oxygen supply system.

Even if unable to translate toward the scanner center, ferromagnetic devices and debris will attempt to align parallel with the static magnetic field. This alignment process is known as **torsion.** Torsion poses an enormous risk for individuals with implanted metal in their bodies. In 1992 a patient with an implanted aneurysm clip died when the clip rotated in the magnetic field, resulting in severe internal bleeding. Another potential problem is metal within the eyes, as may be present in someone who suffered an injury while working with metal shavings. If lodged in the vitreous portion of the eye, the metal may have no ill effects upon vision. Yet exposure to a strong magnetic field may dislodge such fragments, blinding the patient. Torsion effects have also been used to explain the swelling and/or irritation that have been reported for subjects with tattoos and wearing certain makeup—particularly mascara and eyeliner. The pigments in tattoos and makeup may contain iron oxide particles in irregular shapes that attempt to align with the magnetic field, producing local tissue irritation.

torsion A rotation (twisting) of an object. Even if the motion of objects is restricted so that they cannot translate, a strong magnetic field will still exert a torque that may cause them to rotate so that they become aligned with the magnetic field.

dB/dt The change in magnetic field strength (dB) over time (dt).

The cardinal rule of MRI safety is that no ferromagnetic metal should enter the scanner room. All participants and medical personnel should remove any ferromagnetic objects, such as pagers, PDAs, cell phones, stethoscopes, pens, watches, paper clips, and hairpins, prior to entering the scanner room. Once the scanner is ramped to its full field strength, the magnetic field is always present, even if no one is in the scanner and no images are being acquired. For this reason, it is the responsibility of all MRI researchers and technicians to be ever vigilant for metal entering the scanner room.

Gradient Magnetic Field Effects

The main safety risk from the gradient magnetic fields is the generation of electric currents within the body. Because the gradient magnetic fields are much weaker than the static magnetic field, typically changing the overall magnetic field by a few thousandths of a Tesla (mT) per meter, they do not cause translation or torsion. However, they change rapidly over time. The effect of a gradient is calculated by dividing the change in magnetic field strength (ΔB, or dB) by the time required for that change (Δt, or dt), resulting in the quantity **dB/dt.** Since the human body is a conductor, gradient switching can generate small currents that have the potential to stimulate nerves and muscles as well as to alter the function of implanted medical devices.

Currents induced in the body by dB/dt can cause peripheral nerve or muscle stimulation. This stimulation may result in a slight tingling sensation or a brief muscle twitch that may startle the subject, but it is not recognized as a significant health risk. Threshold sensations such as these should not be ignored, however, because this sensation may become unpleasant or painful at higher levels of dB/dt. Current operating guidelines in the United States are based upon the threshold for sensation, rather than a specific numerical value for dB/dt. To prevent peripheral nerve stimulation, subjects should be instructed not to clasp their hands or cross their legs during scanning; these actions create conductive loops that may potentiate dB/dt effects. Subjects should also be instructed to report any tingling, muscle twitching, or painful sensations that occur during scanning.

Gradient field changes can also induce currents in medical devices or in implanted control wires that remain after device removal. If a patient with a pacemaker were to be scanned, gradient field effects might induce voltages in the pacemaker that in turn could cause rapid myocardial contraction. This

specific absorption rate (SAR) A quantity that describes how much electromagnetic energy is absorbed by the body over time.

uncontrolled contraction due to electrical malfunction, not the translation or torsion of the pacemaker, appears to be the primary cause of pacemaker-related fatalities in the MRI setting. At least six individuals with pacemakers have died as a result of MRI sessions, and clinical or research centers do not allow patients with pacemakers to enter MRI scanners. Other implanted devices, such as cochlear implants, also pose risks for MRI participation, and patients with those devices should be excluded from research studies. To minimize the risks of gradient field effects, researchers should carefully screen potential subjects and exclude any subject who has an implanted medical device.

Radiofrequency Field Effects

Electromagnetic energy from the radiofrequency coils is absorbed by protons in the brain and then re-emitted for measurement. While this emitted energy forms the basis for MRI, not all of the energy is re-emitted. Excess energy becomes absorbed by the body's tissues and is dissipated in the form of heat—through convection, conduction, radiation, or evaporation. Thus, a potential concern in MRI is the heating of the body during image acquisition. The specific absorption rate (SAR) determines how much electromagnetic energy is absorbed by the body, and is typically expressed in units of watts per kilogram, or W/kg. SAR depends upon the pulse sequence and the size, geometry, and conductivity of the absorbing object. Because the resonant frequency of atomic nuclei increases with increasing field strength, and higher frequencies are more energetic than lower frequencies, there is a greater potential for heating at higher static field strengths. As will be discussed in Chapter 5, larger-flip-angle pulses (180°) deposit more energy than smaller-flip-angle pulses (90°), and SAR is greater for pulse sequences that employ many pulses per unit time (such as fast spin echo) than those that employ fewer (such as gradient-echo echo-planar imaging).

To ensure participant safety, SAR is limited in MRI studies to minimize body temperature increases. Accurately determining SAR is difficult; it depends upon heat conduction and body geometry as well as upon the weight of the subject. Subjects regulate heat dissipation through perspiration and blood flow changes, so researchers should attend to patient comfort throughout a session. Thermoregulation is impaired in patients with fevers, cardiocirculatory problems, cerebral vascular disease, or diabetes, and thus SAR thresholds should also be lowered for these individuals.

Metal devices and wires also absorb radiofrequency energy and may become hotter than the surrounding tissue. The most common source of heating results from looped wires, such as electroencephalogram or electrocardiogram leads, that act as antennae and focus energy to a small locus. Metal necklaces can also focus radiofrequency energy and cause irritation or burning. Thus, the most significant safety risk caused by the radiofrequency fields used in MRI is local burning. Note that induced currents in conductors and loops due to time-varying magnetic fields associated with gradient coils can also result in heating, through a different mechanism (described in the previous section).

To prevent radiofrequency heating, researchers should (1) screen subjects to exclude those who have metal devices or wires implanted within their bodies; (2) ensure that subjects remove all metal prior to entering the scanner—including nonferromagnetic jewelry such as necklaces, piercings, and earrings; and (3) make certain that any wire leads are not looped and that wires are not run over bare skin.

Claustrophobia

The most common risk from participation in an fMRI study is claustrophobia. Most participants find the physical confinement of the MRI bore only somewhat uncomfortable, and any concern passes within a few moments. For some subjects, however, confinement results in persistent anxiety and, in the extreme, panic. Roughly 10% of all patients experience claustrophobia during clinical MRI scans. This percentage is much lower for research studies, in our experience about 1 to 3%, as research subjects are generally younger and healthier than their clinical counterparts, and people who know that they are claustrophobic are unlikely to volunteer for research studies.

There is no simple solution to the problem of claustrophobia. Subjects who state that they are claustrophobic during a pre-experiment screening should be excluded from study. Anxiety in the scanner can be reduced by talking with subjects frequently throughout the scan, particularly at its onset; by directing air flow through the bore to reduce heat and eliminate any fear of suffocation; and by providing the subject with an emergency panic device. If subjects know that assistance is immediately available, and that they can quit the study at any time, they will feel in control of the session. For first-time subjects, an experimenter should explain that the sounds they will hear are a normal part of scanning. Subjects should also be told that mild apprehension in enclosed spaces is a normal reaction, but if they feel increasingly anxious, they can ask to stop the scan. An experimenter must listen for telltale signs of growing anxiety or discomfort, such as the subject repeatedly asking how much longer the scan will last. Taking a few minutes to enter the scanner room and reassure a subject may help avoid an escalation of anxiety. However, if a subject appears to be more than mildly anxious or declares himself or herself to be anxious, then the experimenter must remove the subject from the scanner immediately.

Thought Question

Under some conditions, clinical patients may have MRI scans even if they have some contraindication (e.g., an implanted device, claustrophobia) that would preclude their participation in a research study. Why should there be different standards for clinical patients and research subjects?

Acoustic Noise

The rapid changes of current in the gradient coils induce Lorentz forces, physical displacement of wires due to electric current, which in turn cause vibrations in the coils or their mountings. To the subject, the vibrations sound like knocking or tapping noises. The parameters of the noise depend on the particular pulse sequence used, but during functional scanning sequences, which make up the bulk of any fMRI session, the noises are often very loud (>95 dB) and of high frequency (1000 to 4000 Hz). In general, fast sequences, such as echo-planar imaging, and sequences that tax the gradient coils, like diffusion-weighted imaging, are louder than conventional sequences. Without some protection, temporary hearing loss could result from the extended 1- to 2-hour exposure of a typical fMRI study. To reduce acoustic noise, fMRI participants should always wear ear protection in the form of earplugs and/or headphones. Researchers should check the fit of the protective devices to ensure their effectiveness.

Summary

The basic parts of most MRI scanners include a superconducting magnet to generate the static field, radiofrequency coils (transmitter and receiver) to collect MR signal, gradient coils to provide spatial information in the MR signal, and shimming coils to ensure the uniformity of the magnetic field. Additional computer systems control the hardware and software of the scanner, present experimental stimuli and record behavioral responses, and monitor physiological changes.

Although fMRI is a noninvasive imaging technique, these hardware components do have associated safety concerns. Most important are issues related to the very strong static field, which can cause translation or torsion effects in ferromagnetic objects near the scanner. The changing gradients and radiofrequency pulses can also cause problems if researchers do not follow standard safety precautions. Some subjects report brief claustrophobic reactions upon entering the scanner, although for most people these feelings fade within a few minutes. Since these risks can be minimized for most subjects, fMRI has become an extraordinarily important research technique for modern cognitive neuroscience.

Suggested Readings

Kanal, E., Borgstede, J. P., Barkovich, A. J., Bell, C, Bradley, W. G., Felmlee, J. P., Froelich, J. W., Kaminski, E. M., Keeler, E. K., Lester, J. W., Scoumis, E. A., Zaremba, L. A., and Zinninger, M. D. (2002). American College of Radiology White Paper on MR safety. *Am.* J. *Radiol,* 178: 1333-1347. A report from leading experts on MR safety about recommended procedures in the MRI environment.

Schenck, J. F. (2000). Safety of strong, static magnetic fields. *J. Magn. Reson. Imaging,* 12: 2-19. This journal article provides a scholarly and comprehensive introduction to the effects of magnetic fields on biological tissue.

Shellock, F. G., and Crues, J. V. (2002). Commentary: MR safety and the American College of Radiology White Paper. *Am. J. Radiol.,* 178: 1349-1352. This short commentary provides additional interpretation, and in some cases rebuttal, of the report authored by Kanal and colleagues.

Chapter References

Chaljub, G., Kramer, L. A., Johnson, R. F, Johnson, R. F., Singh, H., and Crow, W. N. (2001). Projectile cylinder accidents resulting from the presence of ferromagnetic nitrous oxide or oxygen tanks in the MR suite. *Am. J. Roentgenol.,* 177: 27-30.

Drinker, C. K., and Thomson, R. M. (1921). Does the magnetic field constitute an industrial hazard? *J. Ind. Hyg.,* 3:117-129.

Guidance for Industry and FDA Staff: Criteria for Significant Risk Investigations of Magnetic Resonance Diagnostic Devices. (2003). U.S. Food and Drug Administration, http://www.fda.gov/cdrh/ode/guidance/793.pdf

Reilly, J. P. (1998). Maximum pulsed electromagnetic field limits based on peripheral nerve stimulation. *IEEE Trans. Biomed. Eng.,* 45: 137-141.