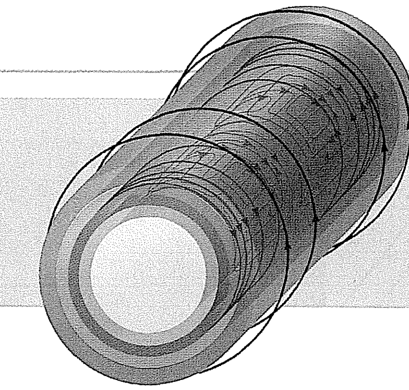
Chapter 2

MRI Scanners



Modern MRI scanners do not resemble the devices used by Rabi, Bloch, Lauterbur, and other early pioneers. They are no longer blocky and kludgy masses of electronics that would be at home in a theoretical physics laboratory. Instead, as MRI has become an increasingly important—and standard—part of medical practice, MRI scanners have become more ergonomic and patient-friendly (Figure 2.1). Continual technological improvements make modern scanners far superior to their predecessors: in the ability to localize signals in space, in the rate of data acquisition, and in the flexibility with which they can acquire different types of images. Yet the fundamental principles underlying MRI have not changed. 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 signals. And just as Lauterbur manipulated the 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

An MRI scanner has three main components, as mentioned above, whose purposes can be easily remembered using the mnemonic M-R-I. The "M" represents the main static magnetic field, which is generated by a series of electromagnetic coils that carry very large currents around the bore of the scanner. The "R" refers to the delivery of energy at the resonance frequency of the targeted atomic nuclei. The "I" refers to image formation, which requires alteration of the magnetic field strength over space by turning on and off the magnetic gradient coils.

These are not the only components important for fMRI. Also necessary are the shimming coils, that 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 all of these components and their implementation in modern MRI scan-

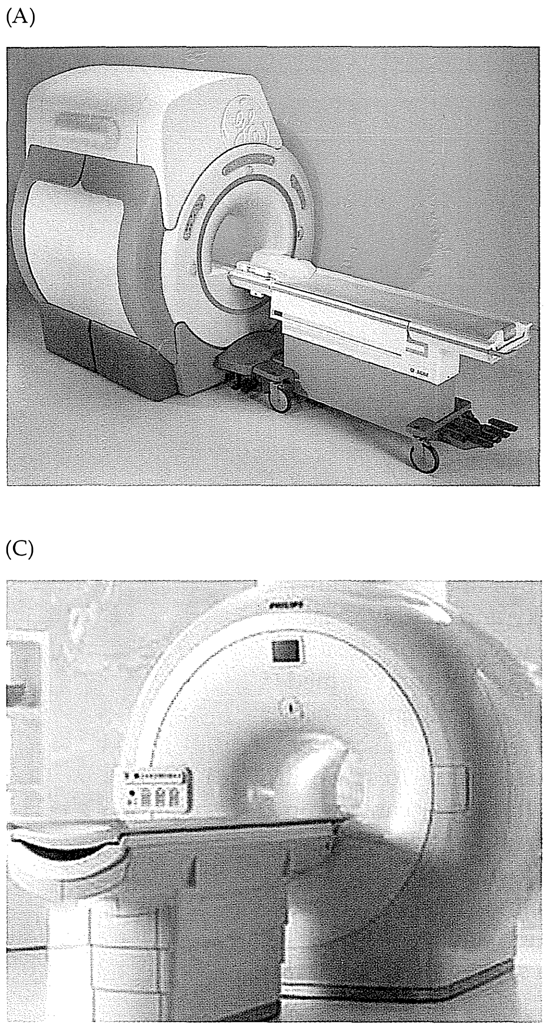


Figure 2.1 Examples of MRI scanners. Most MRI scanners use a closed-bore design, in which the patient or subject lies down on a table at the front of the scanner and then is moved back into the middle of the bore (i.e., central tube). Shown in (A) is a Signa series scanner from General Electric, in (B) is a MAGNETOM Avanto Scanner from Siemens, and in (C) is an Achieva scanner from Philips. (A courtesy of GE Healthcare, Waukesha, WI; B courtesy of Siemans Medical Solutions, Erlangen, Germany; C courtesy of Philips Medical Systems, Andover, MA.)

ners (Figure 2.2). We will return to a detailed discussion of how these hardware components 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, in China almost 2000 years ago. By the eleventh century, the Chinese had recognized that the 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 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 for the mapping of tissue properties.

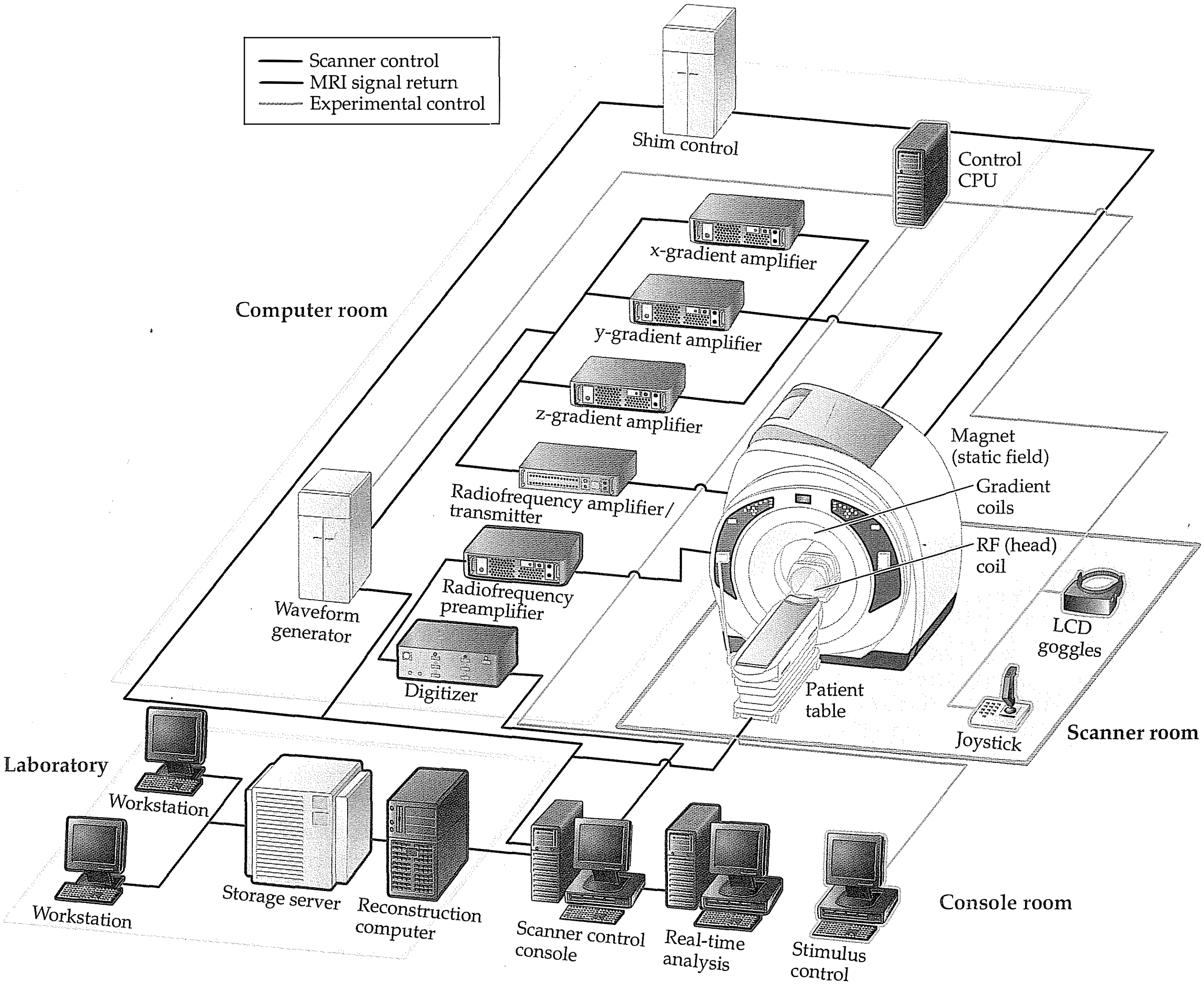


Figure 2.2 Schematic organization of the fMRI scanner and computer control systems. Two systems are important for fMRI studies. The first is the hardware used for image acquisition. In addition to the scanner itself, this hardware consists of a series of amplifiers and transmitters responsible for creating the gradients and pulse sequences (shown in black), and recorders of the 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).

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 the fields are not distorted over space. Another method 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 placed below the wire, redirecting it perpendicularly to the direction of the current. This relationship was quantified later that

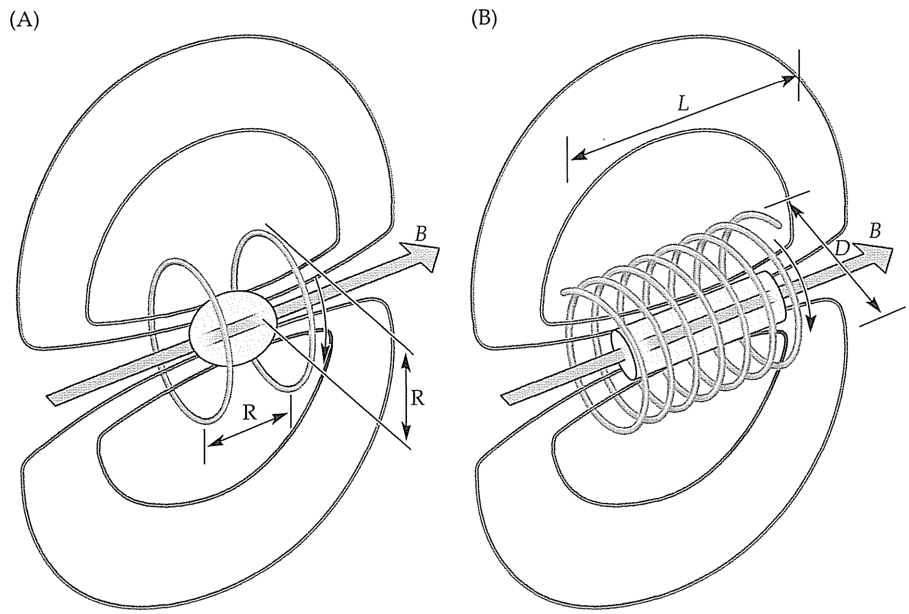


Figure 2.3 Generation of a static magnetic field. (A) The Helmholtz pair design can generate a homogeneous magnetic field. It consists of a pair of circular current loops that are separated by a distance equal to their radius (R); each loop carries the same current. (B) Modern MR scanners use a solenoid design, 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 (B) can be constructed. The green surfaces inside the coils indicate the approximate areas of maximum uniformity.

year by the French physicists Jean-Baptiste Biot and Félix Savart, who discovered that magnetic field strength is in fact proportional to current strength, so that by adjusting the current in a wire (or set of wires), one could precisely control the intensity of the magnetic field. 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 fields through electromagnetism.

In general there are two criteria for a suitable magnetic field in MRI. The first is **field uniformity** (or **homogeneity**), and the second is **field strength**. Making the magnetic field uniform over both space and time is necessary so that we can 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 is not homogeneous, the signal measured from a given part of the body could change unexpectedly, depending on where it is located in the magnetic field. (In practice, MRI takes advantage of this effect by introducing controlled changes in the magnetic field to produce gradients.) A simple design for generating a homogeneous magnetic field is the Helmholtz pair (Figure 2.3A), which is a pair of circular wire loops of the same size that carry identical currents and are separated by a distance equal to the radius of each loop. 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 (L) compared with its cross-sectional diameter (D), 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, optimized by computers to achieve a homogeneous magnetic field of the desired strength.

Whereas field uniformity requires finesse, field strength requires force. To generate an extremely large magnetic field, a huge electric current must be injected 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 these fields, the magnets require enormous

field uniformity In the context of MRI, a uniform magnetic field is one that has a constant strength throughout a wide region near the center of the scanner bore.

homogeneity Uniformity over space and time.

field strength The magnitude of the static magnetic field generated by a scanner, typically expressed in units of Tesla.

electrical power, and thus enormous expense. Modern MRI scanners use superconducting electromagnets whose wires are cooled to temperatures near absolute zero. Most MRI scanners use multiple cooling agents, or cryogens. The coil windings used to generate the static field 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 these extremely low temperatures, the resistance in the wires disappears, thereby creating a strong, stable, and lasting electric current that can be maintained with no power requirements and at minimal cost. Liquid nitrogen is sometimes used as an insulator to minimize loss of the much more expensive helium.

By combining the precision derived from numerical optimization of the magnetic coil design with the strength afforded by superconductivity, modern MRI scanners can have homogeneous and stable field strengths in the range 1.5 to 11 T for human use, and up to 24 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. The MR signal is actually produced by the clever use of electromagnetic coils that generate and receive electromagnetic fields at the resonant frequencies 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 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 during small portions of the image acquisition process, and remain off the rest of the time. The radiofrequency fields are evaluated using similar criteria as the static field: uniformity (i.e., homogeneity over space and time) and sensitivity (i.e., the relative strength of the signal that can be emitted or detected).

After a human body is placed into a strong magnetic field, an equilibrium state is reached in which the magnetic moments of atomic nuclei (e.g., hydrogen) within the body become aligned with the magnetic field. The radiofrequency coils then send electromagnetic waves that resonate at a particular frequency (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. When the radiofrequency pulse ends, the atomic 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. The processes of excitation and reception will be covered in detail in Chapter 3.

One can think of the measurement of an 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 the 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

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.

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 process of sending electromagnetic energy to a sample at its resonant frequency (also called transmission). The application of an excitation pulse to a spin system causes 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 nuclei 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 close to the location of interest. Surface coils have excellent sensitivity to the signal from nearby regions but poor sensitivity to signal from distant regions.

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

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

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 on its distance from the sample being measured. In the case of fMRI, the radiofrequency coils are typically placed immediately around the head. There are three main ways to arrange radiofrequency coils: surface coils, volume coils, and phased arrays (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 a surface coil is based on a single-loop inductor–capacitor (LC) circuit (Figure 2.4A). Within this circuit, the rapid charge and discharge of electricity between the inductor and

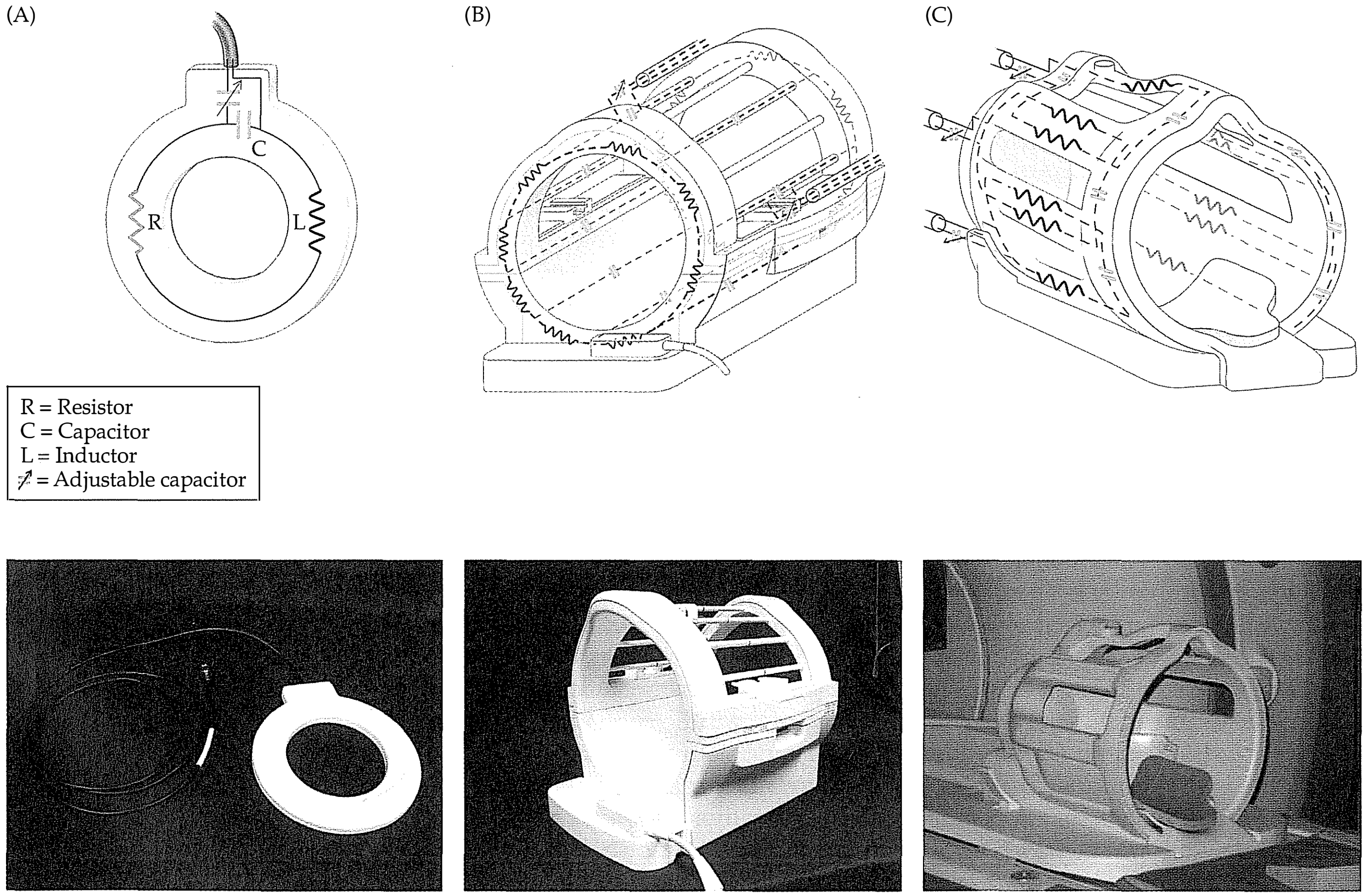


Figure 2.4 Surface, volume, and phased array coils. (A) Surface coils consist of a simple inductor (L) –capacitor (C) circuit, with additional resistance (R) also present. The rapid charging and discharging of energy between the inductor and capacitor generates an oscillating magnetic field. The signal from the surface coil is modulated by a variable capacitor (shown by 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) Phased-array coils combine multiple surface coils in an arrangement intended to give roughly equal spatial sensitivity. These can provide the best combination of spatial uniformity and signal strength.

(A) (B) (C)

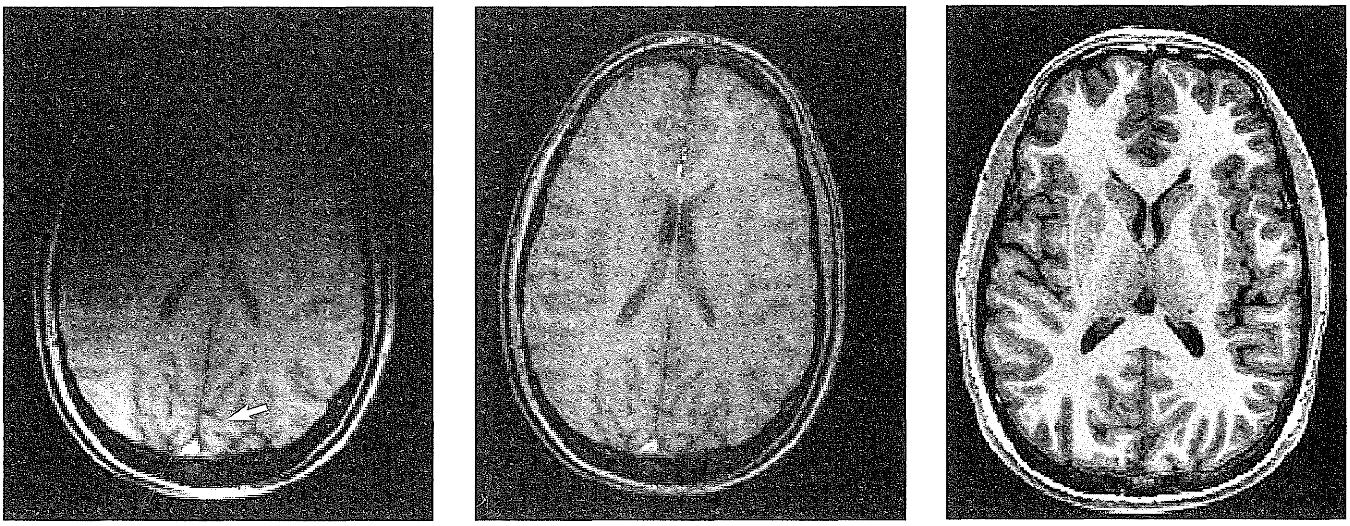


Figure 2.5 Signals recorded from surface, volume, and phased-array radiofrequency coils. (A) The use of a receiver coil adjacent to the surface of the skull can increase the signal-to-noise ratio in nearby brain regions (visible here as reduced graininess in the area indicated by the arrow), but the recorded signal will drop off in intensity as the distance from the coil increases. Thus, the use of a single surface coil is more appropriate for fMRI studies that are targeted toward a single brain region. (B) Volume coils have relatively similar signal sensitivity throughout the brain, so they are more appropriate for fMRI studies that need coverage of multiple brain regions. (C) Phased-array coils can be a good compromise between the sensitivity of a surface coil and the coverage of a volume coil.

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 used for fMRI studies that are targeted toward one specific brain region, such as the visual cortex. The trade-off for 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 near the coil provide a great deal of signal but areas further away provide very little (Figure 2.5A). Thus, the signal recovered by a surface coil is spatially inhomogeneous, 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 as is used in the surface coil. The LC circuit is replicated around a cylindrical surface to achieve a uniform distribution of energy within the enclosed volume. This 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 a more even coverage across the brain (Figure 2.5B).

A compromise approach that combines the best features of both the surface and the volume coils 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 (Figure 2.4C), the spatial coverage can be increased considerably while maintaining

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

high sensitivity. Although the sensitivity does change somewhat across the image, the use of multiple receiver coils is an increasingly important technique in fMRI (Figure 2.5C).

The sensitivity of a radiofrequency coil is proportional to the strength of the magnetic field generated within the coil by the 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 a 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 generation of heat, which will reduce the coil's sensitivity. To obtain a quantitative measure of the coil sensitivity, a sensitivity factor (known as the *Q-value* to reflect "quality") is defined as the ratio of the maximum energy stored and total energy dissipated per time period. For an LC circuit, that quantity can be represented as:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{2.1}$$

Thus, minimizing the resistance (R) boosts the coil sensitivity (Q).

Gradient coils

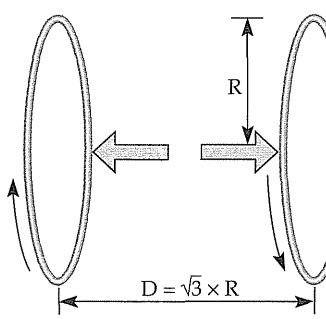
The ultimate goal of MRI is image formation. By placing an object in a strong static magnetic field and exciting its atomic nuclei using radiofrequency pulses, current can be detected in surrounding receiver coils. This current, which is the MR signal, has no spatial information and thus cannot be used to create an image by itself. By introducing magnetic gradients superimposed on 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. Like the radiofrequency coils, the gradient coils are only used during image acquisition. They are typically turned on briefly after the excitation process to provide the spatial encoding needed to resolve an image.

To make the recovery of spatial information as simple as possible, separate gradient coils are used to modify the strength of the magnetic field so that it increases or decreases along specific directions. Three gradient coils are typically oriented along the cardinal directions relative to the static magnetic field. The direction represented by z is parallel to the main field, while x and y are perpendicular to the main field and to each other. Like the previously-discussed components of the scanner, gradient coils are evaluated based on two criteria: linearity (which is comparable to the uniformity measure used 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 generates opposing magnetic fields within two parallel loops, effectively producing a magnetic field gradient along the line between the two loops. This design is the basis for generating the z-gradients used today, although modern z-gradient coils have a more complicated design. The change in the magnetic field that is generated by the gradient coils is orders of magnitude smaller than that of the static magnetic field. The gradients used in modern scanners typically alter field strengths by a few tens of milliteslas per meter.

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

(A)



(B)

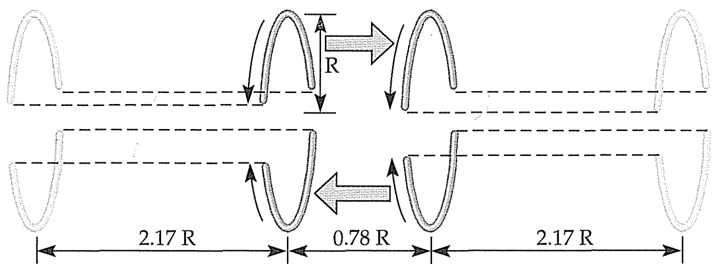


Figure 2.6 Coil arrangements for generating magnetic gradients. (A) A Maxwell pair, two loops with opposing currents, which generate magnetic field gradients along the direction of the main magnetic field. (B) The configuration known as a Golay pair. It allows generation of magnetic field gradients perpendicular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

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 a positive 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 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. Note that the gradient coils are relatively small compared with those generating the main magnetic field. In a typical scanner, the gradient coils may weigh about 2 tons, while the main magnet coils could weigh between 10 and 30 tons.

The strength of a gradient coil is a function of both the current density and the bore 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 bore size and electrical power in generating field strength is not linear. In fact, as the bore size increases, the amount of power required for generating a gradient of the same strength increases with the fifth 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 two, while maintaining the same gradient strength. Although the bore size is only doubled, the

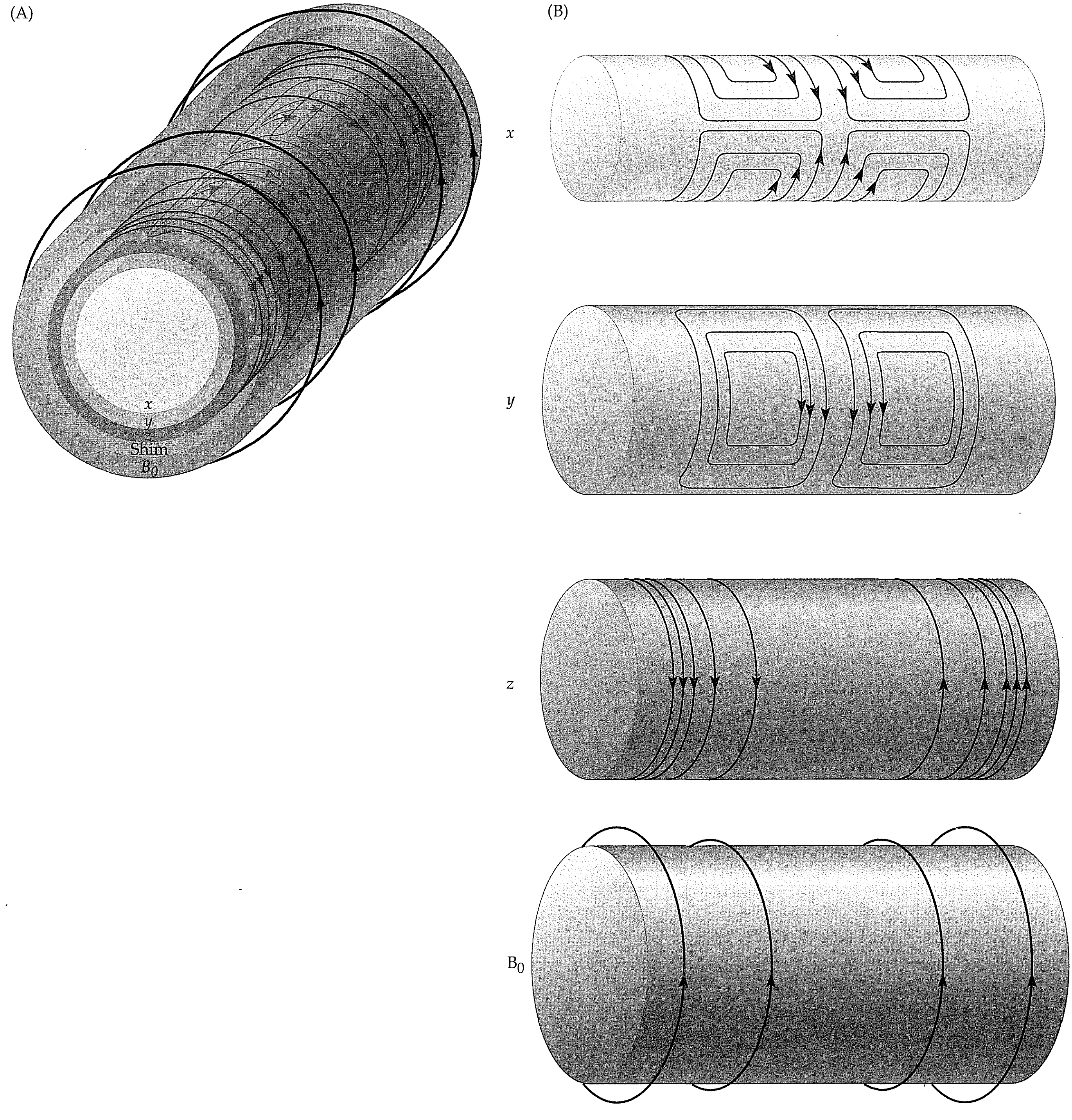


Figure 2.7 Generation of x-, y-, and z-gradients and the static magnetic field (B_0). (A) A number of different electromagnetic coils are used within a single MRI scanner. (B) The coils are arranged as a series of concentric circles, beginning with the gradient coils at the interior, followed by the 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.

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.

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

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 anyone who has ever conducted an fMRI study) 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 of adjustment is analogous to what we do when a table is rocking because one leg is shorter than the others—we simply put a wedge under one of the uneven legs to make it stable. This wedge is called a shim. In a scanner, some shimming is done passively, when first setting up the scanner, by positioning pieces of iron or small magnets within the scanner itself. Other, active shimming uses additional coils that generate compensatory magnetic fields that correct for the inhomogeneity in the static magnetic field. These are aptly 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 the position along the x-axis (first-order), while an x^3-shimming coil would generate a magnetic field that depends on the cube of the x position (third-order). These high-order magnetic fields are used in combination to correct for the inhomogeneities in the static magnetic field. Typically this results in a magnetic field that is uniform to roughly 0.1 part per million over a spherical volume with a diameter of 20 cm. For a 3.0 T magnet, this represents a deviation of only 0.0000003 Tesla.

Unlike the other magnetic fields, the shimming coils can be adjusted for each subject. In fMRI studies, each person's head distorts the magnetic field slightly differently. Thus, the shimming procedures used in fMRI 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. 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.

Thought Question

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

Computer hardware and software

Digitizing, decoding, and displaying MR images requires 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 among scanner manufacturers. In addition to the hardware requirements, two categories of specialized software are needed for fMRI. The first category sends a series of instructions to the scanner hardware so that

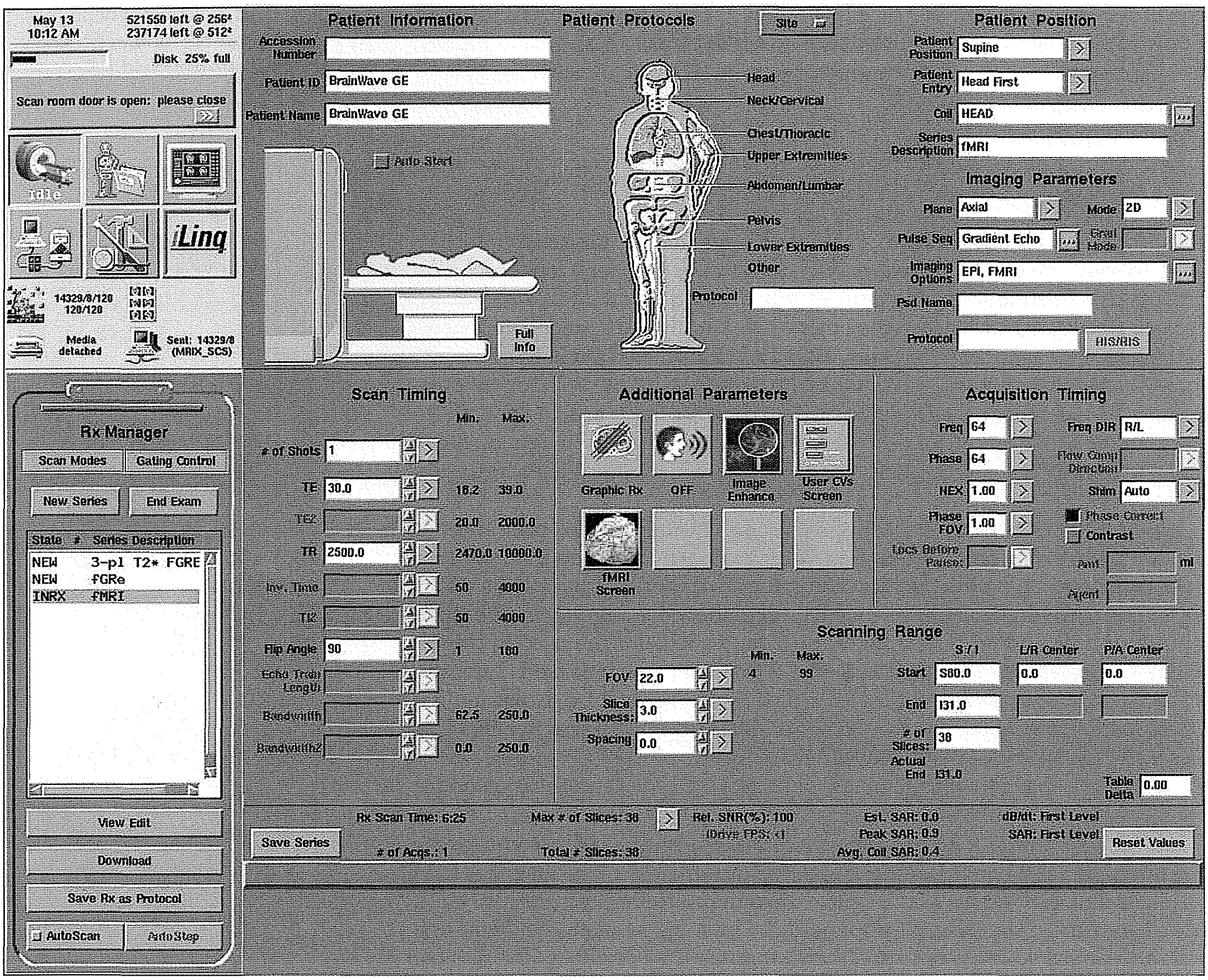


Figure 2.8 A graphic user interface used to control an MRI scanner. The operator of an fMRI scanner will use an interface similar to this one to select the pulse sequence parameters for a given study. (Courtesy of GE Healthcare, Waukesha, WI, and Dr. X. Joe Zhou, University of Illinois, Chicago.)

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 pulse sequence determines which kind of image is acquired. Usually the selection of parameters for a pulse sequence is done via a graphic user interface (Figure 2.8). The second category of software includes reconstruction and analysis packages that create, display, and analyze the images. Many types of images, especially those showing anatomical detail, are created online at the scanner. Often the large number of images collected, even in a short fMRI experiment, are sent to other more powerful computers for reconstruction and/or analysis. We will discuss the principles of image formation and pulse sequence selection in Chapters 4 and 5.

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.

Experimental control system

To induce changes in brain function in response to task manipulations, researchers use computer systems to control their experiments. Although the particular hardware and software used will differ between 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 using 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 design can be matched with the fMRI data. This may be done through a direct electrical connection between the scanner hardware and the experimental control system, so that starting the scanner sends an electrical pulse to the control system, triggering the start of the experiment. The experimental control system often consists of specialized software packages designed for standard personal computers. The key challenge for any experimental setup is to ensure that the equipment used in the scanner room, such as a display device or joystick, 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 in 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. Therefore, physiological monitoring in fMRI studies often has a different goal: to identify changes over time that may influence 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 8).

A second reason to record physiological data during fMRI sessions is to better understand the relationship between physiology and cognition. Many physiological measures can be used as indicators of particular cognitive processes. For example, the diameter of the pupil can be used as an index of arousal, in terms of both alertness and the amount of cognitive processing. If the size of the pupil 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. The position of the eyes can be used to indicate the focus of a subject's attention. By examining the sequence of a subject's eye movements across a visual scene, a

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

researcher may discover which objects are most important to the subject. The eyes would dwell on important objects, and skip over or ignore unimportant objects. Physiological monitoring thus has two primary purposes for fMRI studies: to improve the quality of the images, and to provide additional information about the subjects' mental states.

It is clear from the above discussion that the design of an fMRI experiment is complex, involving multiple components. Box 2.1 describes a typical fMRI experiment, and explains what the experience is like for both the researcher and the subject.

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 (i.e., objects containing iron, nickel, cobalt, or one of the rare earth elements chromium, gadolinium, and dysprosium), 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.

Perhaps even more worrisome is that ignorance of the basic principles of MRI can lead to misconceptions about its effects on human tissue. This can influence policy makers and alter regulations. In 2005, the European Union proposed a new law, whose primary goal was to ensure that industrial workers were not exposed to excessive magnetic fields and electromagnetic radiation. One (perhaps unintended) consequence of the law was to preclude MR technologists (or other medical personnel) from remaining next to the scanner while images were being recorded. An estimated 30% of all MRI sessions, mainly those involving children or sedated patients, could be prohibited under this law. Reaction from the medical and scientific communities was swift and critical. Leading MRI experts, including Peter Mansfield (see Chapter 1), condemned the law as introducing unnecessary restrictions—and directly harming patients by restricting needed medical tests—without supporting scientific evidence. This debate has not yet been resolved, and demonstrates how scientific data—or the lack thereof—can influence public policy and, in turn, clinical applications.

Effects of static magnetic fields on human physiology

The overriding risks in 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 is known as the **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 tissues.

BOX 2.1 Outline of an fMRI Experiment

To some readers of this textbook, running an fMRI study may seem commonplace or routine. Yet all of us, even veteran researchers who have completed dozens of fMRI experiments, began as inexperienced novices who were nervous about their first fMRI sessions. One of the authors can remember several aspects of the first time he participated in an fMRI session: the noise and vibration, the confinement of the scanner bore, and (most vividly) his uncertainty about what fMRI actually measured. Can the experimenters see my thoughts? Will it be obvious when I'm distracted and not doing the task? What can the experimenters tell about my brain? Participating in an fMRI experiment is very different, in unexpected and important ways, from participating in other behavioral or even medical experiments. Here in this box (and in the textbook, more generally), we plan to give you a sense of what an fMRI experiment entails, from the viewpoint of both the experimenter and the participant.

Preparing for the Experiment

Ava came to the laboratory with a sense of excitement—today she was running her first subject in *her* fMRI experiment. As a second-year graduate student in the cognitive neuroscience program, she had previously tagged along with more senior graduate students to watch their studies. She had even helped with the data analysis on a study that would be presented at a conference next month. But now she was finally running a study that she had designed herself (with guidance from her advisor, of course).

Two weeks ago, she had placed advertisements for a "Functional neuroimaging study of decision making" around campus. The advertisements contained a short description of the study, details about the payment that subjects would receive, the Institutional Review Board protocol that covered the experiment, and Ava's contact information. While Ava knew that many potential participants would be most interested in the money they could earn, she was hopeful that others would be interested in helping science or seeing images of their own brain.

Her first potential participant, Owen, had called the laboratory the next day. He was very interested in the study—in part because he was a biology and psychology double major—but he was also a bit nervous because he did not know much about fMRI. To allay his concerns, Ava described what would happen in the study. The primary goal of this research, she said, was to investigate how activation of a particular brain region—something called the prefrontal cortex—differed depending on what information people used when making a decision. When he came in for the experiment, Owen would lie in the MRI scanner and read a series of ethical dilemmas. Ava emphasized that there was no right answer for any of these problems and that Owen could decide to agree or disagree with the proposed solution to each dilemma by pressing one of two buttons on a joystick. The MRI scanner would then measure the changes in his brain that occurred each time he made a decision. The experiment sounded interesting to Owen, and he agreed to participate. But, before he could be scheduled for a session, he needed to answer a series of MRI safety questions: whether he had any metal in his body, such as a pacemaker or aneurysm clip; whether he had any non-removable body piercings; and whether he was claustrophobic. Owen did not have these conditions, nor any other that would prevent him from participating, so he was scheduled for the fMRI session.

Now, Ava waited at the MR center entrance for her subject to arrive. She had tested the experimental protocol the night before; the computers, MR-compatible goggles, and joystick all worked fine. She had even sent a reminder to Owen the night before. A post-doc in the laboratory had joked with her that she was worrying too much about the study, before smiling and congratulating her on being organized. That reassured her, but she still knew that she'd feel better *after* the session ended successfully.

Setting Up the Subject

Owen arrived at the MRI center thirty minutes early, as instructed. He came prepared for going into the scanner: wearing no metal on his clothing nor any jewelry or watch, and leaving his book bag in his dorm room. Ava greeted him at the entrance and walked him to the MR console room. The only other person in the room was the MR technologist whose job was to run the MR scanner. The console room was large and contained several computers. Through an observation window, they could see the MR scanner, which was behind a locked door.

Ava pulled several forms from a folder she carried: a consent form that described the study, an instruction sheet for the experiment, and a screening form that asked questions about metal, medical conditions, and medications (Figure 1). Ava went over the consent form in detail, explaining that Owen was participating in this experiment as

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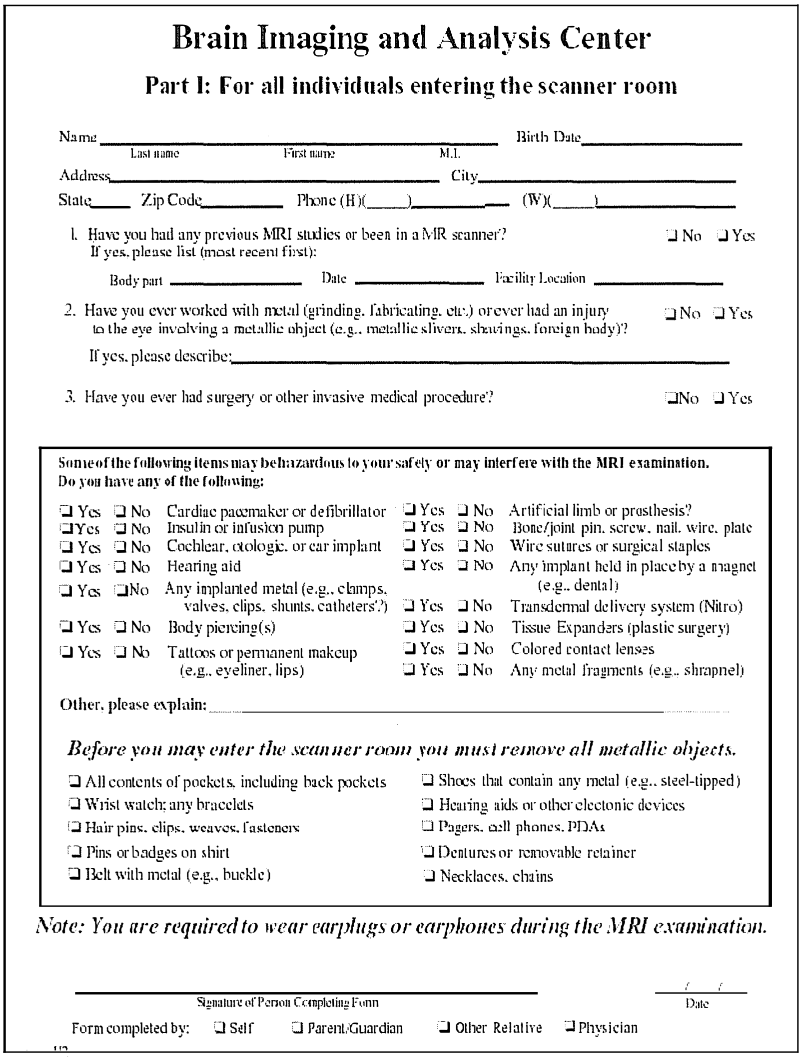
BOX 2.1 *(continued)*



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

Form completed by: ❑ Self ❑ Parent/Guardian ❑ Other Relative ❑ Physician

Figure 1 A sample screening form used for fMRI 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.

a research volunteer, so he could quit the study at any time for any reason. One section of the consent form covered something called an "incidental finding." Even though the images were not the same as those used for clinical scanning, one of the scientists might see something abnormal in Owen's brain. If so, the MR images would be evaluated by a neuroradiologist who would then decide whether to contact Owen with more information. This seemed reasonable to Owen, so he signed the forms and was ready to begin the study.

As Owen walked to the scanner room door, the technologist asked him whether he had anything in his pockets or in his hair. At first, Owen 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 Owen checked, he realized that he had his keys in his pocket, and he placed them on a table. Only then did the technologist unlock the scanner room and escort him inside. Owen hopped up onto a bed at the front of the scanner, and the technologist handed him some earplugs. As Owen 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. Owen then lay down on the table. The technologist handed him a joystick, a pair of goggles with tiny LCD screens inside, and a squeeze ball that was connected to an alarm in the console room. If Owen became uncomfortable or needed help immediately, he could squeeze the ball to summon the technologist.

Although he couldn't see the scanner room anymore, due to the goggles, Owen could feel a pillow being wrapped around the sides of his head. The technologist said that this was a vacuum pack that would support his head and keep it still during the experiment. After a few seconds, Owen heard a hissing sound and the pillow hardened to form a solid cushion. A plastic cylinder called a volume coil was then placed around his head (Figure 2). The technologist pressed a button on the scanner, and Owen found himself slowly moving back into the bore. The technologist returned to the control room and asked Owen over an intercom how he was feeling. Owen said that he was doing fine; any anxiety had worn off, and he was pretty comfortable in the scanner. This

BOX 2.1 *(continued)*

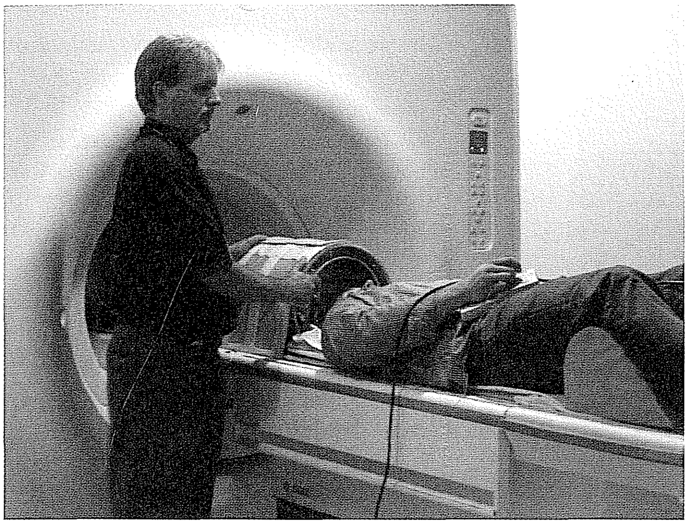


Figure 2 Setting up a subject in the scanner. The experimental subject is being positioned in the scanner before a research study. He is holding a joystick in his right hand that will be used for recording behavioral responses. The technologist standing next to the scanner is moving the table so that 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 him into the bore of the scanner.

reassured Ava greatly—she was more nervous than her subject, it seemed!

Structural and Functional Scanning

The first part of the session involved the collection of high-resolution anatomical images. Even though he had been warned (and had earplugs), Owen was still startled by that first knocking noise. He had expected the scanner to be quiet, like an X-ray machine. The structural images took about ten minutes, and then Ava came on the intercom to tell him that the experiment was about to begin. The experiment was broken into a series of six-minute runs. In each run, Owen read about many different ethical dilemmas. Some of the solutions seemed completely obvious, allowing him to press the joystick button right away. Others were much more challenging—it took him a few seconds to deliberate and respond, and even then he sometimes regretted his choice.

Ava followed the experiment and Owen's choices on the computers in the console room. His decisions in the first few experimental trials matched those of pilot subjects she had recently tested outside the scanner. In these trials, where the solution was made completely obvious, Owen always responded quickly and accurately. Ava could even get a rough idea of Owen's head movements using the real-time tracking program on the scanner's reconstruction computer. So far, he was performing the task well. Between the runs, Ava used the intercom to ask Owen how he was doing, and each time he reported that he was doing well. Forty-five minutes (and six runs) later, the experiment was finished and the technologist brought Owen out of the scanner. He was a little tired from concentrating for an hour, but had still enjoyed the experiment and wanted to see the pictures of his brain.

After the Experiment

Owen re-entered the MR console room and sat down in front of a computer monitor. Ava gave him a short document called a debriefing statement; it explained the basic goals of the experiment and what Ava and her colleagues were hoping to discover. The basic idea, as Ava explained it, seemed simple. Previous researchers in Ava's laboratory had identified areas in the brain associated with making specific types of ethical decisions, but those researchers had only used one type of ethical decision. Ava and her advisor had hypothesized that a slightly different set of regions in the medial prefrontal cortex, would be involved when the ethical decisions were about specified individuals. This made sense to Owen because, in thinking back to the experiment he'd just completed, he remembered having the most difficulty making decisions when the dilemmas concerned a particular person. Owen asked if those areas were active in his brain during the experiment, but Ava told him they would not know anything about his brain function until the data were analyzed by computer programs back in the laboratory.

She could, however, show him the structural images they had collected (Figure 3): a set of sagittal images that showed a side view of his brain, and two sets of horizontal images that showed bottom-up views of his brain. Owen immediately asked whether his brain looked normal. Ava reminded him that this was only a research study and that the images were optimized for research purposes, but not for clinical evaluation. Owen told Ava that she or others in her

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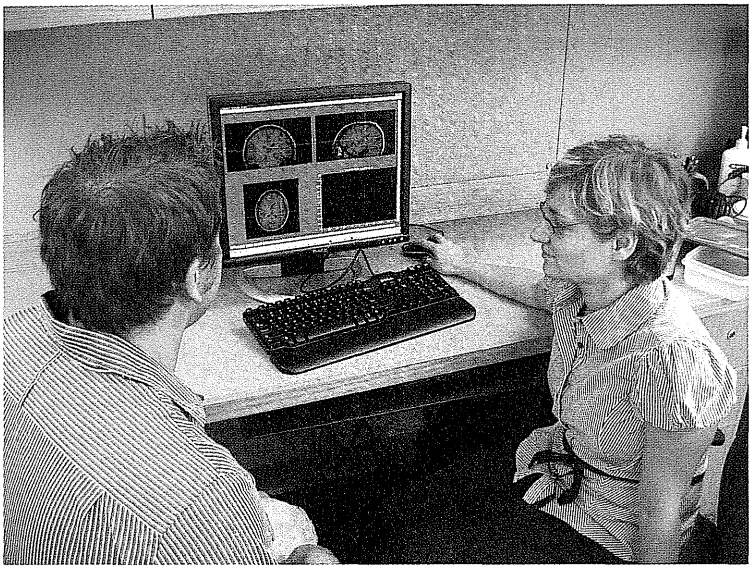


Figure 3 Reviewing the anatomical MR images after the experiment. The graduate student who ran the experiment explains the nature and purpose of the experiment. She shows the subject pictures of his brain and discusses the goals of the research.

center were welcome to contact him for more studies, especially if they involved interesting questions like this one. Then he went back to his dorm to rest.

Ava returned to the console room and flopped down in a chair next to the technologist. The session had gone as well as she had hoped. The subject had finished the entire experiment, had kept his head reasonably still, and had answered all of the questions without any problems. No technical problems with the scanner had affected the data collection; in fact, the data were already being transferred back to her laboratory. All in all, everything had gone smoothly and safely.

Thought Question

Why do you think that a 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 factories prompted the physiologists Drinker and Thompson to study the effects of magnetic fields on both cells and animals. No health effects were found. Yet by the 1980s and 1990s, concerns about magnetic fields (sometimes confused with concern about electromagnetic radiation) reemerged into public awareness, as people worried about exposure to power lines, cellular telephones, and MRI scanners. A full discussion of the history of magnetic field safety is beyond the scope of this book. However, the outcome of a century of research can be summarized as follows: no replicable experiment has ever demonstrated a long-term negative effect of magnetic fields on 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.

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 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 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 lack of evidence for magnetism-induced health risks, as well as the absence of any plausible mechanism for such effects, why have magnetic fields generated such concern? We speculate that the issue of magnetic field safety is symptomatic of two larger problems in the public understanding and evaluation of scientific findings. First, magnetic fields and electric currents are mysterious to most non-physicists, 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 effect seem plausible, from the threat of cancer by prolonged exposure to power lines to the promised health benefits of magnetic bracelets, even if those effects are contradictory. Indeed, some data suggest that the experiences related to magnetic field exposure may, at least partially, result from psychological suggestion. For example, a group of researchers at the University of Minnesota put subjects into the bore of a 4-T scanner and found that 45% of the subjects reported unusual sensations. This high rate of self-reported effects was interesting, given that the magnet had been powered down and there was no magnetic field present at the time of the study.

A second problem with the public evaluation of scientific findings is that many people (including 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 the studies whose findings have been replicated) show absolutely no health risks for magnetic fields of less than 2 T, there remain a few studies that have claimed specific effects of exposure. Even though attempts to replicate these results have failed, the results can be used as evidence by people who believe that magnetic fields must have some effect on health. 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. Despite increasing numbers of these studies, the evidence for long-term health effects has not become stronger. For more information on this issue, see the references at the end of this chapter.

Translation and torsion

The primary risk of the static field used in MRI results from the field's effect on metal objects. Objects that are constructed in part or wholly from ferromagnetic materials are strongly influenced by magnetic fields. Steel objects, and even some medical grades of stainless steel are ferromagnetic. Metals such as

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

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

aluminum, tin, titanium, and lead are not ferromagnetic, but objects are rarely made of a single metal. For example, ferromagnetic steel screws may be used to secure titanium frames for eyeglasses.

The most dramatic risk in a strong magnetic field is the projectile effect that results in the **translation**, or movement, of a ferromagnetic object toward the scanner bore. The magnetic pull on an object can increase dramatically as it nears the scanner, causing its movement to accelerate. A movement of just a few inches toward the bore of the magnet can exponentially increase the magnetic pull, 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 if 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, that were brought too close to an MRI scanner (Figure 2.9). In a tragic example of the danger of projectile effects, a six-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.

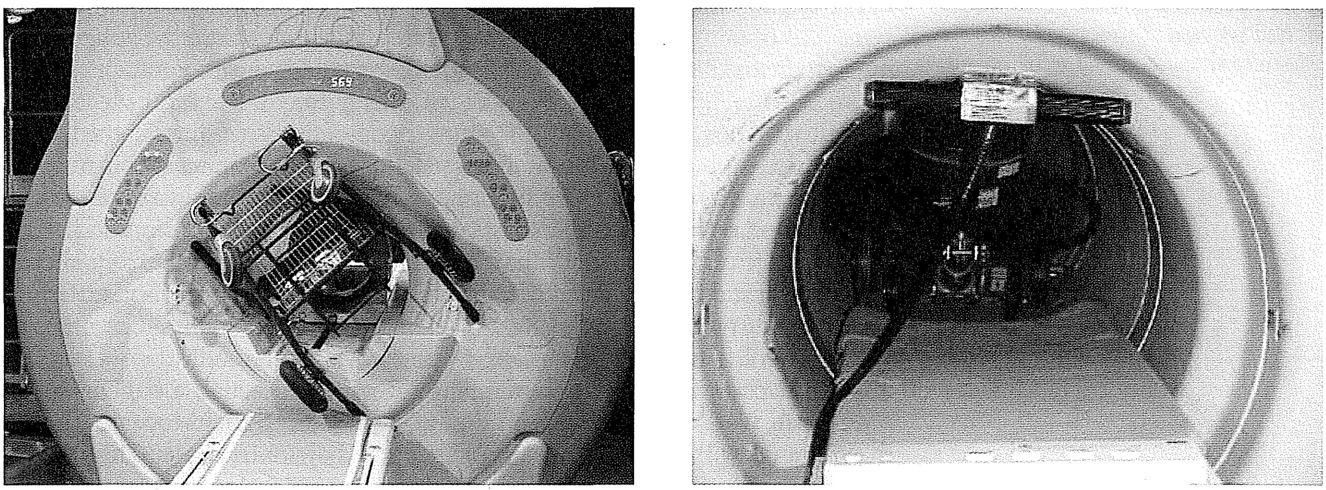
Even if they are unable to translate toward the scanner center, ferromagnetic devices and debris will be subject to a force that will cause them to re-align so that they are parallel with the static magnetic field. This alignment process is known as **torsion**. Torsion poses an enormous risk for individuals 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, which 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. But exposure to a strong magnetic field may dislodge the fragments, blinding the patient. Torsion effects may also explain the swelling and/or irritation that have been reported for some subjects with tattoos or wearing certain makeup—particularly mascara and eyeliner. The pigments in tattoos and makeup may contain iron oxide particles with sharp edges or irregular shapes. If these particles move in an attempt to align with the magnetic field, they may produce local tissue irritation.

The cardinal rule of MRI safety is that no ferromagnetic metal should enter the scanner room. All participants and medical personnel should remove any objects that contain metal, such as pagers, PDAs, cell phones, stethoscopes, pens, watches, paper clips, and hairpins, prior to entering the 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 constantly vigilant to prevent metal from entering the scanner room.

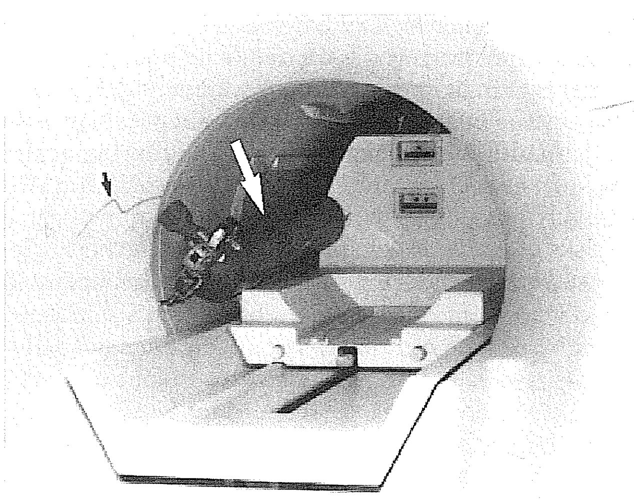
Gradient magnetic field effects

The main safety risk from the gradient magnetic fields is the generation of electric currents within the body. The gradient magnetic fields are much weaker than the static magnetic field, typically changing the overall strength of the field by only a few thousandths of a Tesla (mT) per meter. Therefore, they do not alter the translation or torsion effects on objects. However, the gradient magnetic fields 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

(A) (B)



(C) (D)



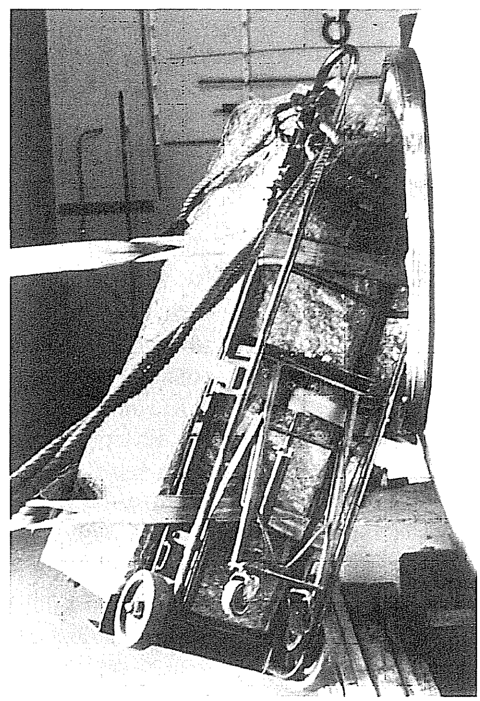


Figure 2.9 Ferromagnetic objects near MR scanners become projectiles. The primary safety risk in MRI scanning comes from the static magnetic field. External ferromagnetic objects brought within the magnetic field will become attracted to the scanner, accelerating toward the center of the bore. Shown are examples of a chair (A), floor buffer (B), oxygen canister (white arrow; C), and power supply (D), all lodged in the bores of MRI scanners. Projectiles present a severe risk to subjects within the scanner bore. (A,B courtesy of Dr. Moriel NessAiver; C from Chaljub et al., 2001; D from Schenck, 2000.)

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 electric currents that have the potential to stimulate nerves and muscles, or to alter the functions of implanted medical devices.

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

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

Currents induced in the body by gradient switching can cause peripheral nerve or muscle stimulation. This stimulation may result in a slight tingling sensation or a brief muscle twitch. Although this may startle the subject, it is not recognized as a significant health risk. Threshold sensations such as these should not be ignored, however, because they may become unpleasant or painful at higher levels of dB/dt. The current operating guidelines in the United States are based on 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 enhance 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 could cause rapid myocardial contractions. This type of electrical malfunction, rather than 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, and clinical or research centers no longer allow patients with pacemakers to enter MRI scanners. Recent studies, however, have demonstrated that under appropriate conditions patients with pacemakers can be scanned safely at field strengths of up to 1.5 T. Because of the increasing prevalence of pacemakers in an aging population, further studies of pacemaker safety will be necessary. 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, fMRI researchers carefully screen potential subjects and exclude any subject who has an implanted medical device.

Radiofrequency field effects

Recall from our discussion of the scanner hardware that the radiofrequency coils send energy, in the form of electromagnetic radiation, into the body. Because the energy is in the radiofrequency range, the radiation is not ionizing (i.e., it does not break molecular bonds). Yet it still can influence biological tissue. While the re-emission of some of the radiofrequency energy forms the basis for MRI, not all of the energy is re-emitted. Excess energy is absorbed by the body's tissues and 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 on the pulse sequence and the size, geometry, and conductivity of the absorbing object. Because the difference between low- and high-energy states increases with increasing field strength, there is a corresponding increase in the resonant frequency of the energy required to change atomic nuclei between those states. Furthermore, those higher frequencies are more energetic than lower frequencies, resulting in 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 or echo-planar imaging). Also, SAR increases with scanner field strength, making it more of a concern for high-field fMRI studies.

To ensure participant safety, SAR in MRI studies is limited to minimize body temperature increases. Accurately determining SAR is difficult; it depends on 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 small areas. Metal necklaces, other jewelry, and even some tattoos 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 the induced currents caused by gradient field effects can also result in heating, through a different mechanism (described in the previous section).

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

mock scanner A device that simulates a real MRI scanner, usually by reproducing the scanner bore, the bed that the subjects lie on, and the sounds made during scanning.

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. However for some subjects, confinement results in persistent anxiety, and in extreme cases, panic. Roughly ten percent of all patients experience claustrophobia during clinical MRI scans. This percentage is much lower for research studies, because 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. In our experience, only about one to three percent of research subjects suffer from claustrophobia during fMRI experiments.

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. Researchers with access to a mock scanner, which is a simulated scanner without a static magnetic field, can put prospective subjects in that device before the real fMRI sessions. 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 subjects 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 contraindications (e.g., implanted devices, 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, or physical displacement of the wires, which in turn cause vibrations in the coils and their mountings. To the subject, the vibrations sound like knocking or tapping noises. The quality of the noise depends 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 (greater than 95 dB) and of high frequency (1000 to 4000 Hz). In general, fast sequences, such as in 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 one- to two-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 the 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.

REFER TO THE
fMRI
COMPANION WEBSITE AT
www.sinauer.com/fmri2e
for study questions and Web links.

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.*

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Drinker, C. K., and Thomson, R. M. (1921). Does the magnetic field constitute an industrial hazard? *J. Ind. Hug.*, 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. www.fda.gov/cdrh/ode/guidance/793.pdf

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

Shellock, F. G. (2000). Radiofrequency energy-induced heating during MR procedures: a review. *J. Magn. Reson. Imaging*, 12: 30–36.