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.
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 a 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 dis-
cussion 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 these 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.

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 the change (Δt, or dt), resulting in the quantity $\frac{dB}{dt}$. 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 $\frac{dB}{dt}$ 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 $\frac{dB}{dt}$. Current operating guidelines in the United States are based upon the threshold for sensation, rather than a specific numerical value for $\frac{dB}{dt}$. 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 $\frac{dB}{dt}$ 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 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.

$\frac{dB}{dt}$ 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.

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 heating. 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**


**Chapter References**


