3 MR Safety: Gradient Magnetic and Radiofrequency Fields

Gradient magnetic fields are used primarily for spatial encoding (localization) of the MR signal. Additional coils of wire located within the magnet bore (but underneath the plastic housing, and thus not visible to the patient or technologist) produce these fields. During scan acquisition, the current in the gradient coils is switched on and off rapidly, causing in turn quick changes in amplitude and polarity of the gradient magnetic fields. There are four primary performance-related characteristics that define a gradient system. These are slew rate (how fast one can drive a gradient to a specific amplitude, dB/dt), maximum amplitude (how high a gradient field one can actually achieve, regardless of how long it takes), spatial linearity (how far away from isocenter the gradient field reaches before its strength begins to fall off), and duty cycle (how often one can drive the gradient without failure). All four are very relevant to clinical performance. High slew rates permit shorter echo times (TEs) and echo spacing, improving the image quality of fast spin echo scans and contrast-enhanced MR angiography. High-amplitude gradients markedly improve diffusion-weighted scans.

Above a certain threshold in switching of the magnetic field gradients, peripheral nerve stimulation (with muscle twitching) and pain may occur. On modern MR systems, dB/dt values are calculated prior to scan execution and thus monitored to prevent initiation of a scan if safety standards are exceeded. One very noticeable result from the rapid switching of the gradient coils is acoustic noise. Pulsing the gradients creates a force (due to the change in the magnetic field created around the wires) that generates pressure waves and thus the audible sound (knocking). Generally speaking, higher magnetic fields, higher gradient amplitudes, and faster gradient ramping all increase the acoustic noise. Many strategies exist, and continue to be developed, to reduce the sound to acceptable limits, with the end result that some 3 T scanners today are quieter than older generation 1.5 T systems. For high-field MR systems, hearing protection is offered and encouraged for all patients and anyone in the scan room.

The radiofrequency (RF) field used in MRI is also referred to as the $B_1$ field. Its purpose is to excite the spins, creating an MR signal that can be detected by a receiver coil. The frequency at which the MR phenomenon can be induced is termed the Larmor frequency, which for protons (hydrogen nuclei) is 42.6 MHz/T, and thus 63 MHz at 1.5 T. The amount of RF power necessary for imaging is dependent on several factors. These include the size and type of RF coil used for transmission, the distance of the coil from the patient, the field strength ($B_0$), and the number and type of RF pulses in the imaging sequence. For example, a 180-degree RF pulse requires four times the RF power of a 90-degree pulse, if the waveforms used are identical.

The rate at which energy (RF) is deposited into the body is defined as the specific absorption rate (SAR), measured in watts per kilogram body weight. The most recent U.S. Food and Drug Administration (FDA) guidelines, from 2009, limit RF power deposition to 4 W/kg averaged over 15 minutes for the whole body, 3 W/kg over 10 minutes for the head, 8 W/kg over 5 minutes per gram of tissue for the head or torso, and 12 W/kg over 5 minutes per gram of tissue for the extremities. Body core temperature is not to increase beyond 1°C. Standards developed by the International Electrotechnical
Commission (IEC) differ. This organization comprises members from all over the world (including the United States) and is equivalent to the FDA in the rest of the world (for electrical, electronic, and related technologies). As with dB/dt, SAR is monitored by both software and hardware on current MR scanners, preventing the guidelines from being exceeded.

A major safety issue due to applied RF, mandating careful patient screening, is that metal, outside or inside the patient, may experience rapid and extreme heating under certain circumstances. Reported incidents include (up to) third-degree burns, coma, and death. Extreme care should be taken with any electrically conductive material that must remain within the bore of the MR scanner during imaging. Dangers exist due to contact of any conductive material with the patient, and leads or wires close to the wall of the magnet bore. Skin-to-skin contact points forming a closed loop can also allow current flow within the body with the risk of burns at contact points (e.g., when a patient forms a closed loop by touching his index fingers together). Detailed specific recommendations exist (and are beyond the scope of this book) and should be followed closely. The reader is referred to *The Reference Manual for Magnetic Resonance Safety, Implants, and Devices*, published annually. First- and second-degree burns have also been reported with decorative tattoos.

Deep brain stimulation systems (Fig. 3.2), like the majority of cardiac pacemakers (Fig. 3.1), also represent a contraindication to MRI. Although reports exist in the literature in which patients have been scanned safely with these and similar implanted electrical devices, this has been done under very closely controlled circumstances (and sometimes with complications, regardless). As such, it is important to monitor all patients during an MR exam: visually, verbally, and through the use of instruments such as a fiberoptic pulse oximeter. A new wave of MRI-safe cardiac pacemakers and implanted defibrillators are being developed, with some devices approved currently. Care must be taken to assure model type and specific magnetic field safety issues before scanning any patient with any type of implantable device.