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CHAPTER ONE

General Approach to Body MRI

After completing this chapter, the reader will be able to:

- **Identify the major challenges of body MRI**
- **Identify methods for reducing or eliminating artifacts seen in body MRI**
- **Demonstrate proper coil usage and positioning**

Body magnetic resonance imaging (MRI) has enjoyed its greatest relative growth in the number of procedures performed in recent years compared to neurological and musculoskeletal MRI applications. This growth is attributed to numerous factors, including significant advances in MR hardware and software.

OVERVIEW

Previously most MR systems were unable to acquire images in the body rapidly enough to eliminate artifacts associated with respiration and other physiologic motion. With state-of-the-art scanners and scanning techniques, the acquisition time of most body sequences are sufficiently short to be performed during a single breath hold, eliminating most motion artifacts. As a result, the majority of streamlined body MR protocols can be completed in less than 30 minutes.

For the purposes of this module, Body MRI will refer to any MR imaging in the torso not related to neuro-anatomical or musculoskeletal applications.

POINTS FOR PRACTICE

1. What are the pros and cons of MRI body applications as compared to CT and US?
2. Name several strategies for reducing or eliminating respiratory motion artifact.
3. What two strategies can be used to suppress signal from subcutaneous fat?
4. What are common causes of magnetic susceptibility? How can these best be managed?
5. Why do the vast majority of body MRI applications use a combination of GRE and FSE/TSE sequences?
6. What are methods used to reduce the effects of echo spacing in FSE/TSE and EPI-based pulse sequences? What are the disadvantages of these methods?
7. What is the most important parameter for producing high-quality images?
8. Why have phased-array coils become a standard part of the MRI system?

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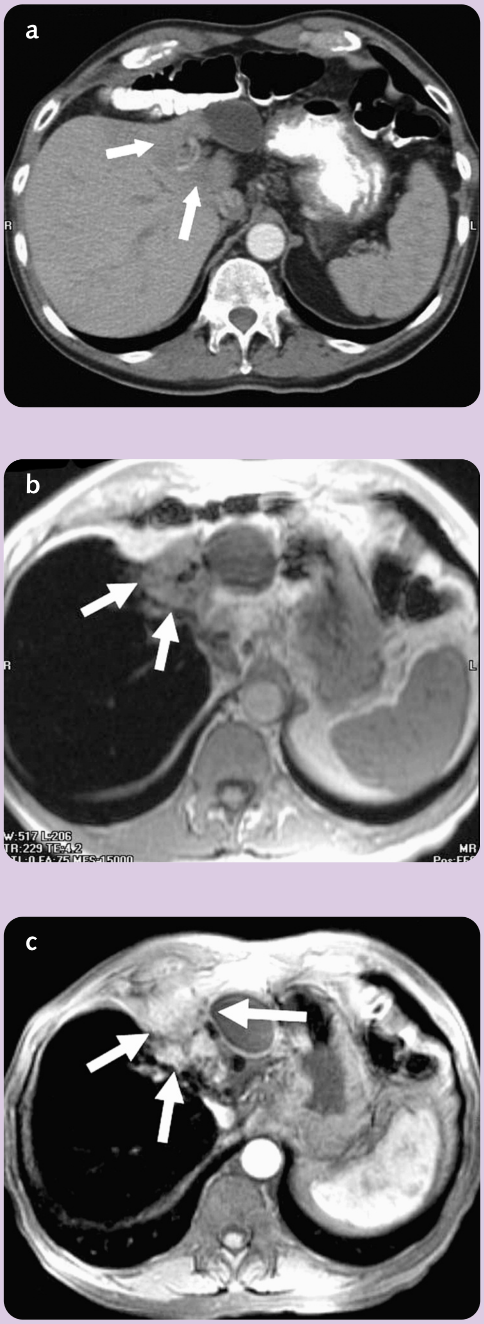

Figure 1. (a) Contrast-enhanced liver CT depicts a subtle abnormality of the medial segment of the left lobe of the liver (arrows). T1-weighted gradient-echo MRI performed. (b) Pregadolinium administration. (c) Postgadolinium administration depicts a malignant cholangiocarcinoma (arrows).

Benefits and Challenges of Using MRI

Although computed tomography (CT) and ultrasound (US) have benefited from technological advances over the last several years, in many spheres of diagnosis, body MRI remains the most sensitive and specific diagnostic imaging tool available (Figure 1). Patients undergoing CT or US exams may require a more definitive study, and MRI is increasingly used as first-line imaging.

Body MRI generally requires more time than most other imaging modalities. Because of the nature of collecting MR data, it has been difficult to acquire a diagnostic image in what might be considered a "fast" imaging time. In the early days of MRI, obtaining a single image in less than a minute was considered a marvel, despite the severely compromised image quality. These long imaging times, for example, six to eight minutes to acquire axial images of the entire brain, could be tolerated for many applications because the patient had only to lie still for a painless, albeit long and noisy, imaging exam. Body applications, however, were altogether different.

For many years, MRI body imaging suffered from challenges typically not problematic for other areas of the body. Because of respiratory, cardiac, and bowel motion, MR systems lacked the hardware and software to scan rapidly enough to acquire meaningful images. Much of MR body imaging was of poor quality, requiring patients to remain in the magnet bore for excessively long periods, even by MR standards. With the addition of gadolinium-based contrast sequences, the exam became intolerably long. Respiratory artifacts, referred to as **ghosts**, severely affected images. Compromises in imaging matrix, slice thickness, and signal-to-noise ratio (**SNR**) in favor of speed left images pixilated with noise and low in spatial resolution. As a result, MRI, for all its promise in other

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applications, was not valued as a diagnostic tool in body applications until the mid-1990s when high-speed gradients and advanced pulse sequences were developed.

ADVANCES IN GRADIENT SPEED AND PULSE SEQUENCING

Gradient Speed

High **slew rate** gradients allow more slices per repetition time (**TR**), resulting in shortened acquisition times. High slew rate gradients also reduce echo spacing in fast spin-echo or turbo spin-echo sequences, improving image quality.

Advanced Pulse Sequences

New pulse sequences (pulse sequence database or **PSDs**) collect MR data quickly, reducing acquisition times so that breath-hold 3D imaging is now routine. Other pulse sequences provide effective methods of reducing or even eliminating breathing artifacts, and these are discussed later in detail.

Phased-Array Technology

High-channel phased-array coils specifically designed for chest, abdominal, and pelvic imaging yield high SNR and coverage that free the user from performing in-room coil repositioning.

Today most MRI body applications are optimized so that only two or three pre-contrast pulse sequences are required. These are typically breath-held sequences. Post-contrast imaging can be sufficiently rapid to acquire dynamic contrast uptake images with high temporal resolution in a 3D acquisition. While not all body applications require post-contrast imaging, its use is no longer an impediment to successful body imaging.

In the sections to follow, typical pulse sequences are presented for their use and special characteristics. The newest technologies in body imaging, such as parallel imaging and fast steady-state techniques, ultrafast T2 techniques, and fast 3D T1 methods are discussed. Individual applications and protocols also are included, using image examples and anatomical references. The areas of MR body imaging included in this module are:

- Breast
- Hepatobiliary System
- Adrenal Glands and Kidneys
- Female Pelvis
- Prostate
- Rectal Cancer

ISSUES UNIQUE TO BODY MRI

As previously mentioned, body MRI presents unique challenges as compared to other MRI applications. These challenges include respiratory and cardiac motion, peristalsis, and susceptibility effects of tissue-air interfaces. Each of these challenges affects the images differently, but each can be minimized or resolved using artifact-reduction methods.

RESPIRATORY MOTION ARTIFACTS

It is well recognized that any motion of imaged anatomy invariably contains a cascading artifact known as a **ghost** across the image. Motion artifacts occur in any MR image when the position of protons changes relative to the gradient field from one phase-encoding step to the next. The resulting phase-encoding errors cause misplaced signal in the phase-encoding direction. Respiratory motion usually presents the most visible of motion ghosts, since it regularly occurs throughout the imaging process, as compared to jerk motion, which occurs sporadically. Moreover, respiratory motion artifacts are

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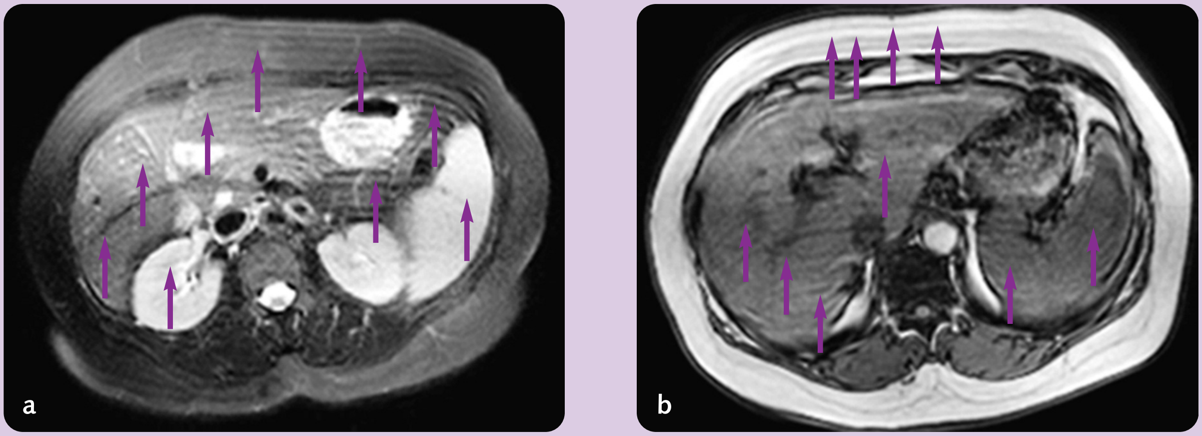

Figure 2. **53-year-old female patient with a limited ability to breath hold during liver imaging. (a) Axial T2-weighted fat suppression. (b) Axial T1-weighted spoiled gradient echo. Total breath-hold time was 0:22 and 0:26 seconds, respectively. Arrows indicate excessive respiratory motion artifacts through each image.**

compounded by changes in breathing depth and rate (Figure 2). While it is optimal to eliminate respiratory motion artifacts completely via suspension of breathing, there are beneficial pulses with a duration longer than a breath hold. Fortunately, several strategies exist to reduce or eliminate respiratory motion.

STRATEGIES TO REDUCE OR ELIMINATE RESPIRATORY MOTION

Respiratory Ordered Phase Encoding

With respiratory ordered phase encoding, respiratory bellows are placed around the patient's abdomen to record the patient's respiratory waveform (Figure 3). The waveform information includes the breathing rate and depth of inspiration/expiration. For each phase-encoding step, the respiratory position is recorded. After the scan is completed, the data are shuffled to correspond as closely as possible to the position of the abdomen. This "respiratory compensation method" reduces the number and intensity of respiratory ghosts without increasing scan time. While this method is only somewhat effective, it represents one of the earliest advances in body imaging.

Increasing Signal Averaging

Because they are random, respiratory ghosts can be treated as noise rather than as true signal. One method for reducing noise is to

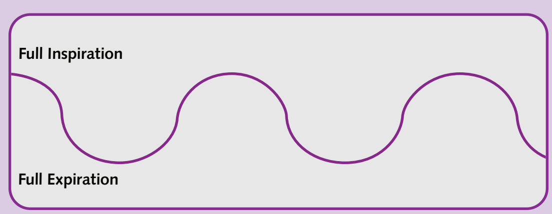

Figure 3. **Respiratory waveform generated by the expansion and contraction of respiratory bellows placed around the patient's abdomen.**

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significantly increase the SNR by increasing the number of signal averages, effectively decreasing the intensity of the respiratory ghosts into the noise floor of the image. The obvious downside to this method is greatly increased scan times.

Fat Suppression and Fat Saturation Techniques

Respiratory ghosts are highly visible because they arise from the bright signal of subcutaneous fat, primarily located in the anterior abdominal wall (Figure 2). Ghosts from tissue of very low signal intensities are typically not visible because their lower signal intensity falls below the noise floor. Therefore, if the high-intensity fat signal is suppressed, the ghosts can be converted to low-signal intensity and fall below the noise floor, becoming less disturbing.

One method for suppressing fat signal is to place **pre-saturation pulses** into the anterior abdominal wall, the largest contributor of respiratory ghosts. However, the pre-saturation bands must be carefully placed as to not saturate important structures. Moreover, pre-saturation bands cannot be shaped to the curvature of a patient's abdomen or be used to suppress fat signal deeper in the abdomen. Finally, pre-saturation pulses increase **SAR**, which can reduce the numbers of slices per TR and ultimately increase scan time.

Chemical saturation is the other method of fat suppression. Protons of fat are excited just prior to slice excitation, saturating the fat signal throughout the entire image. While this method is effective in reducing the intensity of respiratory ghosts, it also reduces the overall SNR on the image. However, high-intensity "non-fat tissues" can still exhibit ghosting. Alternatively, chemical fat saturation also increases SAR and ultimately scan time.

Gradient Reorientation

Like any motion artifact, respiratory ghosts run in the phase-encoding direction (Figure 2). In an axial body image, the anterior-to-posterior direction is a default direction for phase encoding. Thus, the ghosts appear to cascade through the image in that direction. Re-orienting or "swapping" the phase-encoding and frequency-encoding directions (so that phase runs in the right-to-left direction) forces the ghosts to run in that direction. It should be noted that this method does not reduce the number or intensity of the respiratory ghosts, rather only changes their direction.

Respiratory Triggering

As in respiratory ordered phase encoding method, **respiratory triggering** also employs bellows, although the data collection scheme is vastly different and far more effective. In respiratory triggering, which uses a fast or turbo spin-echo (**FSE/TSE**) pulse sequence, a respiratory waveform is generated. However, instead of noting the most active part of the respiratory cycle, as in respiratory ordered phase encoding, the system registers the most **quiescent** part of the respiratory cycle

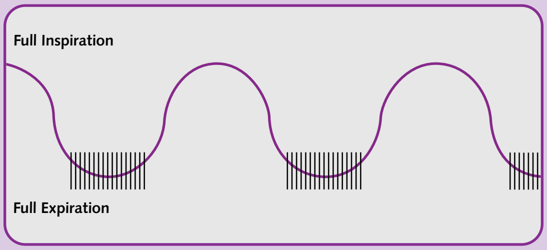

Figure 4. **Respiratory waveform monitored by the MR system uses the most quiescent period of the respiratory cycle to trigger and launch data acquisition.**

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(**endexpiratory phase**). During this period of the cycle, the system collects numerous lines of ***k*-space** (Figure 4). During the rest of the cycle, when there is maximum abdominal motion, no data are collected. In respiratory triggering, it is essential that the patient breathes at a consistent rate. The effective TR is determined by the patient's respiratory rate; therefore, the effective TR is always relatively high, making T1-weighted imaging impractical using this method. For non-breath-held methods, respiratory triggering is nonetheless a highly effective method for near-elimination of respiratory ghosts. Recently, **navigator**-based sequences have been developed that track the motion of the diaphragm, allowing data acquisition during the endexpiratory phase without the use of abdominal bellows.

SUSCEPTIBILITY EFFECTS

Magnetic susceptibility refers to the ability of a material to become magnetized. Interfaces between tissue and air and the presence of metal can generate magnetic field gradients, significantly altering the local magnetic field. The change in magnetic field alters the resonant frequency, leading to dephasing of spins. In regions of altered magnetic susceptibility, the net effect causes dephasing of spins, yielding significant signal loss and dropout. The field gradients that may be set up can also result in geometric distortions in the images.

Primary sources of magnetic susceptibility effects in the body include tissue-air interfaces near the diaphragm and compact bone-tissue interfaces. Excessive susceptibility in these areas can lead to image distortion near the

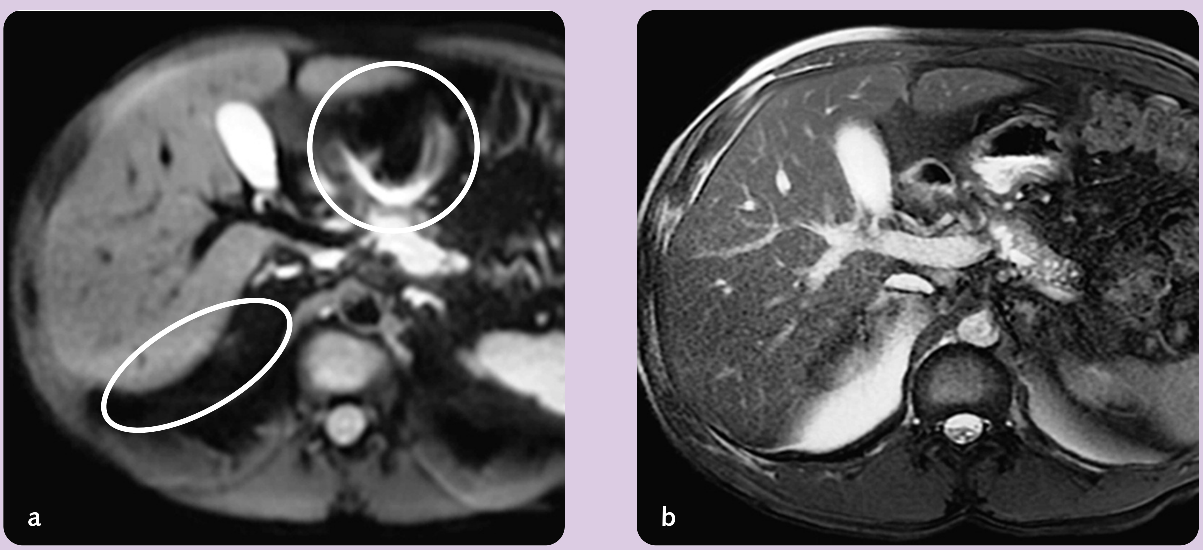

Figure 5. Axial images of the liver of a 43-year-old male. (a) Single-shot echo planar imaging diffusion-weighted image with a b-value of 20. (b) Same location using FIESTA. Note the amount of image distortion (circles) in the DWI image. This distortion (referred to as geometric distortion) is an example of the sensitivity of EPI to magnetic susceptibility effects, such as by tissue-air interfaces, compact bone-tissue interfaces, or metal cause susceptibility effects. In EPI and gradient-echo imaging techniques, these areas of large differences in magnetic susceptibility cause high degrees of dephasing and image "bending" or distortion. Nevertheless, DWI of the liver can be highly sensitive to liver pathologies and motion-free due to the ultrafast imaging speed of EPI.

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interface and increased signal dephasing that results in very low SNR in that area. These distortions and areas of signal loss are exacerbated by higher field strengths, lower slew rate gradients (which result in longer echo times), and the widespread use of gradient echo (**GRE**) and diffusion-weighted imaging (**DWI**) pulse sequences (Figure 5).

Methods for reducing magnetic susceptibility effects in body MRI are limited. Because the technologist has no control over the field strength of the system, one must turn to pulse sequence manipulation to balance the reduction of susceptibility effects with the contrast, resolution, and SNR requirements of the exam.

Echo Spacing

In an echo-train type pulse sequence, for example, fast spin echo or turbo spin echo, as well as echo planar imaging (**EPI**), the time between successive echo read-out gradient pulses is termed **echo spacing** (**ESP**). The duration may be milliseconds or microseconds, depending on the sequence. Regardless of the sequence, any increase in ESP increases the variance of T2 decay within *k*-space. This increased variance results in several predictable effects. In FSE/TSE, blurring will be increased. In an EPI sequence, such as DWI, an increase in ESP results in greater geometric distortion (Figure 6). In both sequences where there is a tissue-air interface, the area of susceptibility effect is greatly increased.

Reducing the ESP can be accomplished by increasing the receiver bandwidth (**RBW**), reducing frequency-encoding steps and, to some extent, increasing field-of-view (**FOV**). Associated disadvantages are decreased SNR when increasing RBW and decreased spatial

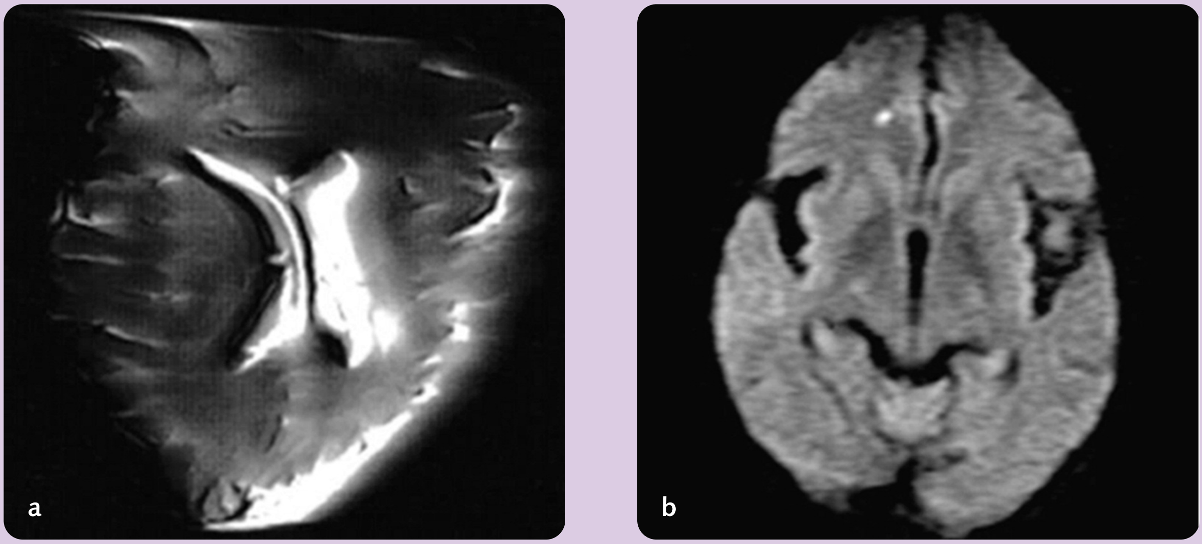

Figure 6. Examples of how reducing echo spacing can reduce geometric image distortion. (a) Axial single-shot echo planar imaging of the brain. The extreme distortion in the image is due to parameters that greatly increased the ESP. These parameters include low slew rate gradients, high spatial matrix, small field-of-view, and narrow receive bandwidths. (b) Axial SS-EPI image of the brain that demonstrates greatly reduced geometric distortion due to reductions in ESP.

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resolution when decreasing frequency encoding and increasing FOV. Nonetheless, effective balancing of the advantages and disadvantages are attainable as demonstrated in the protocol tables for body applications at the end of Chapter 2.

Gradient Echo vs SE/FSE/TSE Sequences

Spin-echo–based sequences are less affected by susceptibility artifacts because the dephasing effects of the field changes are rephased by 180° radiofrequency refocusing pulses. By contrast, GRE and echo planar sequences may experience large areas of signal loss and dropout from the field changes and dephasing effects because of their use of gradient-echo refocusing pulses. In rare instances, these sequences may be completely unusable. Therefore, it might appear to be a disadvantage to use GRE or EPI sequences in body imaging, but this is not the case.

GRE and EPI sequences have been some of the most effective methods for obtaining fast (in a breath-hold time) abdominal imaging. They very quickly provide the requisite SNR, contrast, and spatial resolution. The vast majority of body MRI applications employ an effective combination of GRE and FSE/TSE sequences.

Effective Use of Local Gradient Shimming

There is no single, more important parameter for producing high image quality than magnetic field homogeneity. Even if all the other components of the MRI system are optimized, their value is negated if the homogeneity is poor. Therefore it is essential that the user make judicious use of local gradient shimming in any body imaging. Shimming further reduces susceptibility effects and maximizes the SNR for any given pulse sequence and its parameters.

SURFACE COIL SELECTION AND USE

The surface coil is a well known and commonplace accessory in MRI. A surface coil in MR is nothing more than a receiving antenna that collects the signal from excited protons and

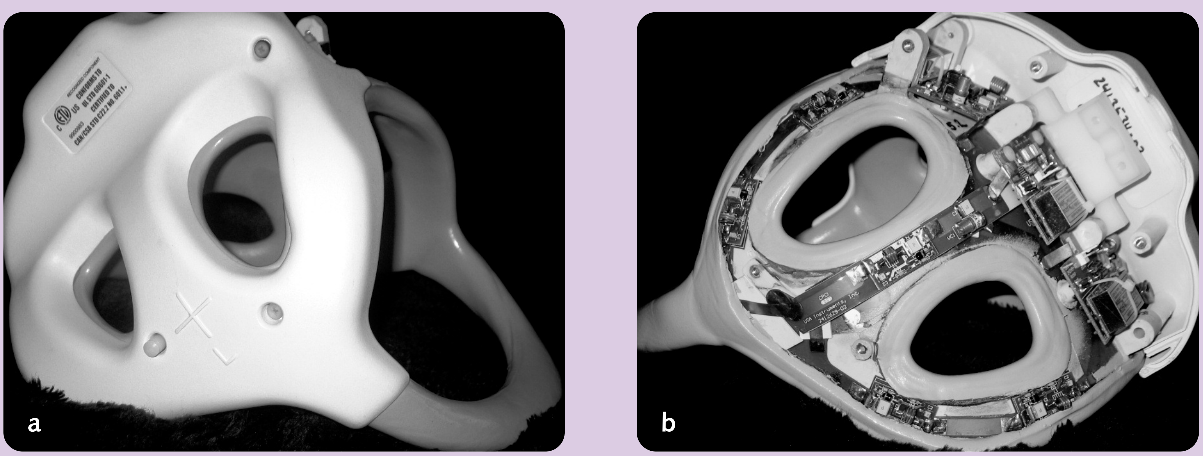

Figure 7. (a) Shoulder array coil covered. (b) Shoulder array coil uncovered.

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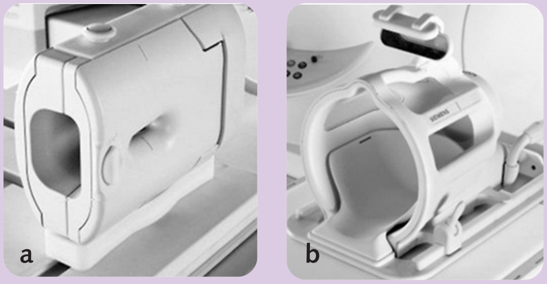

Figure 8. **(a) 8-channel wrist array coil. (b) 8-channel head array coil.** *Courtesy of Siemens.*

carries that signal back into the radiofrequency subsystem for analysis and conversion into *k*-space. Ultimately, this signal information generates a matrix of voxels that becomes the anatomical image. Surface coils generally refer to the family of coils that act as receive-only coils and are designed for a specific anatomical part. There are many different types of surface coils, including both single-coil and multi-coil designs. Surface coils are made in all shapes and sizes, depending on the area of interest (Figures 7-10). Surface coil development, while benefiting all MR applications, had the largest impact on body imaging. The most significant of these developments was the development of phased-array coils.

Phased-Array Coils: A Technological Revolution

All other factors remaining the same, the smaller the coil size, the better the SNR. However, the smaller size also means a smaller detection area. The earliest coil used in MR for body imaging was the inserted transmit/receive coil that makes up the bore of the magnet. While the coil coverage was excellent, the sheer size of the coil resulted in inadequate SNR (its length was as much as six feet). The development of localized abdominal surface coils greatly improved SNR as compared to the bore insert but still lacked the SNR boost that other applications were enjoying due to their much smaller size. Phased-array coil technology changed all of that.

In the mid-1990s, phased-array coil technology was a revolution in MR. The benefit was so evident that today there is no MR

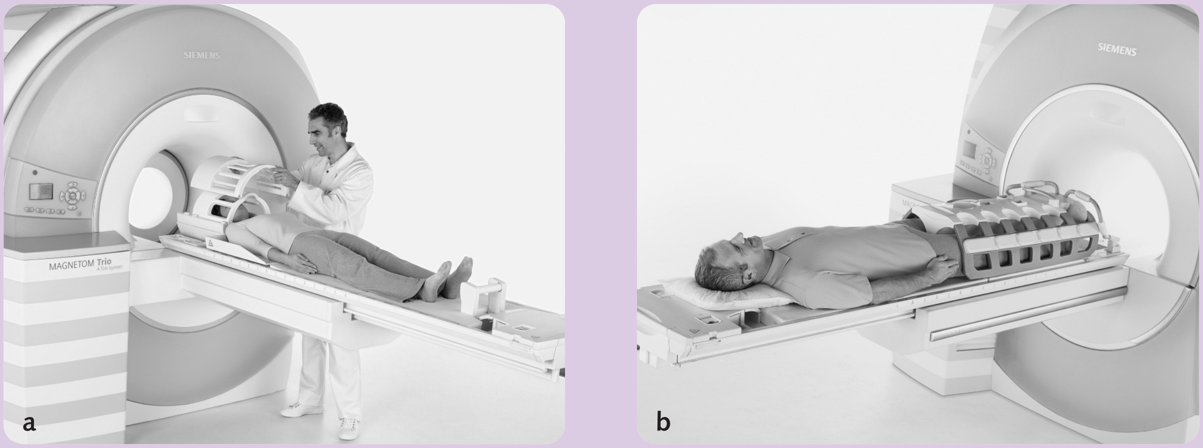

Figure 9. **(a) Example of placement of a head coil. (b) Example of placement of a run-off coil used for imaging blood vessels of the legs.** *Courtesy of Siemens.*

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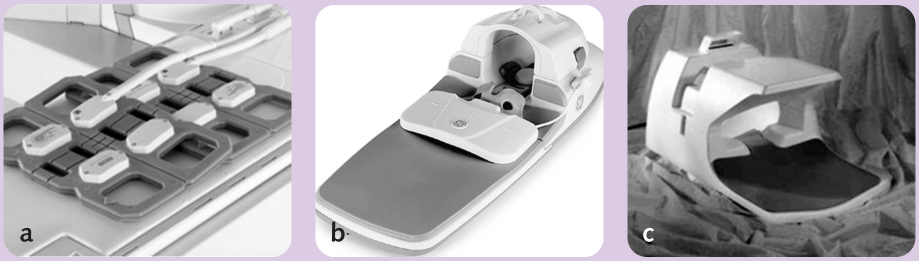

Figure 10. (a) **16-channel body array coil.** (b) **32-channel head-spine array coil.** (c) **Neurovascular array coil.** *Courtesy of GE Healthcare.*

system manufactured that does not provide a phased-array coil system as standard hardware.

Stated simply, phased-array coil technology uses the SNR boost of a small surface coil and "strings" together several smaller coils to obtain the coverage of a larger coil. The key is for each local coil, called a "coil element," to have a dedicated receiver channel that analyzes the signal from that coil only.

The early iterations of phased-array coil technology used four receivers and coils that contained six to eight elements or channels. With four receivers in the RF cabinet, these multi-channel coils could utilize up to four to six of the six to eight elements in the coil. For example, a phased-array coil designed for the spine might consist of six elements. The user could select the top two channels for cervical spine imaging, the middle four channels for thoracic spine imaging, and the bottom three channels for lumbar spine imaging. Note that the total number of coil elements used at one time is never greater than the number of receivers present in the RF cabinet. For body imaging, the first phased-array design called for two coil elements anteriorly and two coil elements posteriorly.

Today, phased-array coil technology has advanced to the point where MR systems routinely have 16-32 receivers, and phased-array coils can consist of even more elements.

Today, phased-array coil technology has advanced to the point where MR systems routinely have 16-32 receivers, and phased-array coils can consist of even more elements. Body arrays often are large enough to permit imaging of the abdomen and pelvis without the need to move the coil, resulting in a greater number of smaller elements providing high SNR over a large imaging area. However, all of this imaging power does not come without some trade-offs.

IMAGE RECONSTRUCTION

The image reconstruction process, referred to as **Fast Fourier Transform (FFT)**, is a highly mathematical computation. Converting *k*-space data into image data that are then projected as pixels onto a display screen requires vast processing power. The reconstruction of the image is done by the "array processor" engine. In phased-array architecture, each receiver produces its own image, with the final image a composite of all of the receivers' images. If there is only one array processor for four receivers, the time to reconstruct and display one composite image is four times longer than if only one receiver's data is used. If there are eight receivers, it will be eight times longer. If the time to reconstruct

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one receiver's worth of data is one second, then it requires eight seconds if eight receivers are used.

This may seem of little consequence until we review a real-world example: If the time to reconstruct 60 images is one minute with one receiver, using eight receivers results in an image construction time of eight minutes. This is a significant increase in reconstruction time. To address this issue, MR systems today often employ parallel-array processors. Like personal computers using dual processors, parallel-array processors are two or more processors that operate in tandem, resulting in far faster processing time for image reconstruction and display.

Likewise, continued development of faster processors also aids in keeping reconstruction times reasonable.

SUMMARY

Because of the unique challenges of body imaging, MR body applications lagged behind other MR applications. These challenges included overcoming respiratory motion artifacts, peristalsis, extremely long scan times, and tissue-air susceptibility artifacts. Body MR imaging has improved significantly with the continued advanced development of key components of the MR system. These developments include faster, more powerful gradient subsystems; better and more complex software such as parallel imaging; and the development of phased-array coil technology. MRI body imaging is currently a significant contributor in the diagnosis and staging of body-related pathologies and disease processes.

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POINTS FOR PRACTICE

1. **What are the pros and cons of MRI body applications as compared to CT and US?**

   An assessment using magnetic resonance imaging still generally requires more time than CT or US, but MRI's specificity and sensitivity make it an exemplary imaging modality. While patients are subjected to a smaller and somewhat noisier scanning environment during the MR exam, high-speed gradients and advanced pulse sequences have virtually eliminated motion artifact, allowing for more rapidly-acquired, high-quality diagnostic imaging.

2. **Name several strategies for reducing or eliminating respiratory motion artifact.**
   - Breath holding
   - Respiratory triggering
   - Respiratory ordered phase encoding
   - Increased signal averaging
   - Fat suppression
   - Gradient reorientation

3. **What two strategies can be used to suppress signal from subcutaneous fat?**

   The use of pre-saturation pulses and chemical saturation both help eliminate the bright signal of subcutaneous fat by suppressing high-intensity fat signal and pushing low-signal intensity ghosting below the noise floor. However, pre-saturation pulses can increase SAR and reduce slices/TR, ultimately increasing scan time. Chemical fat saturation can reduce the overall SNR and increase SAR, again increasing scan time.

4. **What are common causes of magnetic susceptibility? How can these best be managed?**

   Magnetic susceptibility refers to the ability of a material to become magnetized. Tissue-air interfaces, compact bone – tissue interface, and the presence of metal are primary sources. While methods for reducing magnetic susceptibility are limited, pulse sequence manipulation helps balance the reduction of susceptibility effects with the contrast, resolution, and SNR requirements of the exam. Strategies include:
   - Avoiding gradient echo-based pulse sequences
   - Using FSE/TSE sequences with higher echo train lengths to correct for T2′ (prime) effects
   - Increasing the receiver bandwidth to decrease the read-out window time
   - The use of local shimming volumes

5. **Why do the vast majority of body MRI applications use a combination of GRE and FSE/TSE sequences?**

   These types of sequences obtain abdominal imaging in the time of a single breath hold, providing the requisite SNR, contrast, and spatial resolution. GRE sequences can be obtained in very short scan times, eliminating respiratory artifacts and providing in- and out-of-phase image contrast. FSE/TSE pulse sequences provide excellent T2 contrast and can be used along with respiratory triggering to virtually eliminate respiratory artifacts. When used in conjunction with high-performance gradients and parallel imaging, FSE/TSE can also be accomplished within a few breath holds.

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POINTS FOR PRACTICE

6. **What are methods used to reduce the effects of echo spacing in FSE/TSE and EPI-based pulse sequences? What are the disadvantages of these methods?**

   Increasing receive bandwidth, reducing frequency-encoding steps and, to some extent, increasing field-of-view help reduce echo spacing. Disadvantages of employing these methods are decreased SNR when increasing the receiver bandwidth and decreased spatial resolution when decreasing frequency encoding and increasing field-of-view. A high-performance gradient subsystem also effectively reduces echo spacing but may be an expensive hardware purchase.

7. **What is the most important parameter for producing high-quality images?**

   Magnetic field homogeneity plays the most important role in producing high-quality images. The use of local field gradient shimming reduces susceptibility effects and maximizes SNR.

8. **Why have phased-array coils become a standard part of the MRI system?**

   Phased-array coils provide the SNR boost of a small surface coil, linking several smaller coils to individual receivers to obtain the coverage of a larger coil. This linkage results in a greater number of smaller elements providing high SNR over a large imaging area.

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Notes

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