CHAPTER **47**

GENERAL CONCEPTS AND BASIC PRINCIPLES OF MAGNETIC RESONANCE IMAGING

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Magnetic Resonance Imaging, MRI, is rapidly becoming the imaging modality of choice for many pathologies of the foot and ankle. Since podiatric physicians are utilizing MRI on a frequent basis, we must become proficient in reading MR images. Confidence in reading imaging studies takes time and experience, and can be very challenging. The key is to first understand basic principles and general concepts of MR imaging. This paper includes a brief review of MRI physics and a description of basic imaging equipment and technical staff responsibilities. A brief description of all of the pulse sequences is also included. One should be more concerned with the appearance of different anatomical structures on the various pulse sequences than the physics of how the images are created. Once a physician possesses general knowledge of MR imaging, the remainder of the learning curve is dependent on repetition. The more images one reviews, the more comfortable he or she will become with their interpretations.

PHYSICS

The physics of MR imaging can be very intimidating to a physician. One should be more concerned with the basic principles and general concepts than the technical, detailed physics. The goal is to gain a basic understanding that can be applied clinically. The basic circuit in the production of a MR image can be explained in simple terms. First, the patient is placed into a magnet. Next, a radio wave is induced and then turned off. Finally, the patient emits a signal that is interpreted by the computer and constructed into a visual image. With this general understanding, one can now analyze the individual steps involved with the image production.

MRI utilizes the hydrogen atom in the body to create images. The hydrogen atom is chosen for several reasons. First, it is the most abundant proton in our body. Second, it has the highest gyromagnetic ratio (GMR). The GMR is a fixed number, specific for each individual proton. It is determined by the Larmor equation:

$$\omega = \gamma \times \beta$$

ω = Precessional (Larmor) Frequency

γ = Gyromagnetic Ratio

β = Strength of External Magnet

From this equation, the precessional frequency, the speed at which the proton spins around its axis when placed in a magnetic field, can be determined. Since hydrogen has the largest GMR, it precesses at the highest frequency.

Atoms with an odd number of protons and neutrons in their nucleus are small, rotating magnets. Until an external magnetic field is applied, these atoms are randomly oriented. Once a magnetic field is applied, the atoms align themselves in the direction of the magnetic field. A radio frequency pulse can then be applied. This radio frequency pulse stimulates the protons and they assume a higher energy state. When the radio pulse is turned off, the protons then relax and return to the lower energy state. Upon doing this, they induce a signal intensity in the body which is read by a computer and constructed into the image that we see.

The signal produced depends on two main factors; the number of nuclei present in a particular tissue and the time it takes the nuclei to relax after excitation. Various tissues throughout our body have different amounts of hydrogen present. These hydrogen nuclei can either be tightly or loosely bound to the tissue. The atoms will resonate at different speeds depending on how tightly the hydrogen is bound to the tissue and how much hydrogen is in a particular tissue. This effect produces the different signal intensities of the various tissues.

EQUIPMENT

The MRI machine itself is like a wall with a hole in the center. A bed slides in and out of this hole so that the anatomic part to be imaged is directly within the magnetic field. The strength of the magnet varies with each MRI unit ranging from 0.5-4.0 Tesla, with the average strength being 1.5T. The 4.0T magnets are still in experimentation. Stronger magnets produce faster and superior quality images; however, there are drawbacks. Stronger magnets are much noisier and patients have complained of dizziness during the exam.

A major factor contributing to the quality of the images is the actual position of the patient. The anatomic region to be imaged should be near the center of the magnet. The closer the region of interest is to the center, the better the field of homogeneity and resultant image. In addition, the major axis of the region to be imaged should be parallel with one of the three main cardinal planes. The MRI will then create all three cardinal planes from this one position.

In MRI, radio frequency coils are utilized to transmit radio frequency pulses and receive the resulting signals. A variety of coils are available, and are used in various combinations depending on the particular body part to be imaged. The most common coil is a body coil, which is a type of volume coil. The body coil is a permanent part of the scanner and surrounds the patient. This is an important coil because it is the transmitter for all types of examinations. It can also act as a receiver when larger body parts are imaged.

Another coil to be familiar with is the surface coil. It is commonly used for imaging of the upper and lower extremities. A surface coil is placed on the extremity and acts as an antenna. It directly affects signal intensity, resolution, and magnification. The coil must be positioned as close to the region of interest as possible and must be complimentary in size and configuration to its anatomic features. Surface coils are receiver coils only. To summarize, for MR imaging of the foot and ankle, the body coil transmits the signal and the surface coil receives it.

TECHNICAL STAFF

The staff at the MRI center is crucial to the production of good quality images. Not only are they responsible for positioning of the patient and application of the surface coil, they are also responsible for employing the proper protocol and selecting the appropriate pulse sequences to best display the proposed pathology. Therefore, it is extremely important to send a patient with a prescription listing possible pathologies and specific anatomic areas of interest. If the technicians are unaware of exact regions to image, and do not have a working diagnosis, they will probably only obtain basic pulse sequences of the entire foot and or ankle. Also, without a differential diagnosis, the radiologist reading the MRI may not focus on the exact area of interest. The expertise of the radiologist, in foot and ankle anatomy and pathology, varies from center to center. This is why communication between the requesting physician and the testing center is critical. If given a clinical impression, the radiologist can read the signal in the anatomic area of interest and relay whether it is normal or pathologic, even though he or she may not have a vast amount of experience in foot and ankle pathology.

ADVANTAGES AND DISADVANTAGES OF MRI

MRI is an excellent imaging modality when used appropriately. The ability of MRI to evaluate bone, joint, and soft tissue pathology makes it a valuable diagnostic tool. No other imaging modality has this capability. Exquisite contrast and excellent spatial resolution characterize the images. This allows for superb visualization of anatomic structures and pathological processes.

A unique characteristic with MRI is that it not only identifies pathologic processes but it also differentiates them. MRI has the ability to differentiate tissue types by producing various signal intensities. Pathological processes alter tissue structure; therefore, the signal intensity of that tissue will also change. Since the production of an image is dependent on the components of a tissue, it is highly sensitive to any change. The remarkable aspect of MRI is that it is not only capable of detecting a change, it is also able to identify what the change is. So, not only is it sensitive, it is highly specific in diagnosing various pathologies of the foot and ankle. A final advantage of MRI is that it utilizes only magnetic fields. Since non-ionizing radiation is employed, MRI is one of the safest imaging modalities available.

Although MRI has become the imaging modality of choice for various pathologies of the foot and ankle, it does have some disadvantages. MRI can provide valuable information; however, it is only an adjunctive test and it should not be used to make a diagnosis. It should only be used if information provided could not be obtained by a simpler means or if it could alter the treatment regimen.

MRI is a very expensive test averaging between $1,000 to $1,500 per scan. It is imperative therefore, in these cost-conscious times, that a physician thoroughly ascertains whether the scan is a cost-effective adjunct to therapy.

As previously discussed, equipment and staff vary from center to center so the quality of the images also vary. Testing centers with stronger magnets and well-trained personnel will produce superior quality images, as opposed to testing centers with smaller strength magnets and an average technical staff.

PATIENT CONSIDERATIONS

The MR scanner itself can be a limiting factor. The average magnet is usually about 21-24 inches in diameter and has a limit of about 300 pounds. Obviously, larger people may not fit into the apparatus. The advantage of MR imaging of the foot and ankle is that only the distal extremity has to be placed into the magnet, not the entire body, so some centers may perform the scan regardless of size. Also, if size becomes an issue, some testing centers have open-air magnets, which do not completely encompass the patient, so there are no size or weight limits.

Another limiting factor with MR imaging is claustrophobia. Some patients may not be able to tolerate the scanner because of the confinement. Fortunately, with foot and ankle imaging, that is the only part that has to go into the magnet and patients can usually handle the anxiety. However, if the patient cannot, an anxiolytic agent can be given prior to the scan. This can also be helpful in older or demented patients who may not cooperate fully for the exam.

The scanner can be frightening to the patient. The scanning time is very long, averaging an hour per study. In addition, a constant loud knocking sound is heard throughout the study and may cause patients to move. Earplugs are often dispensed to avoid discomfort and distraction. It is imperative that the patient lies completely still while the images are obtained. When a patient moves, a "blurry" picture, called motion artifact, is obtained. The image is of very poor quality and anatomic structures are very difficult to identify.

The physician must also be aware of any type of metal throughout a patient's body. Because of the interactive nature of metal and magnets, MRI is contra-indicated for patients with cardiac pacemakers, intracranial aneurysm and vascular clamps, cochlear implants, ocular implants, and patients known to have metal foreign bodies in their eye. Heart valve prostheses are not contraindicated and most intravascular coils, filters, and stents are not hazardous as long as suitable time has elapsed since placement of the device, to allow for incorporation into the vessel wall.

Most of the various orthopedic devices are made from nonferromagnetic materials and do not pose a problem with MR imaging. Several types of screws, plates, wires, rods, staples, and bone anchors have been evaluated and all are acceptable and do not pose any harm to the patient when placed in the MR scanner. If there is any doubt as to whether a certain implant or device will react with the magnet, the test should be deferred and the center should be notified. The manufacturer of the device should know whether or not the component would react when placed in a magnetic field.

Although orthopedic implants and devices are not contraindicated in MR imaging, they can render the study useless if they interfere with the visualization of the images. Metal substances create a significant artifact and a void (black area) is visualized on the image surrounding the device. (Fig. 1) Since metal possesses limited amounts of hydrogen, it displays low signal intensity and appears black on all pulse sequences. One must be sure that the retained metal in the foot and or ankle does not obscure the area of interest. If it does, the scan should not be obtained because it will not provide useful information.

Figure 1. A T1-weighted image displaying a metal artifact. This patient had a closing base wedge osteotomy of the first metatarsal with screw fixation. The screw is creating the black void around the first metatarsal.

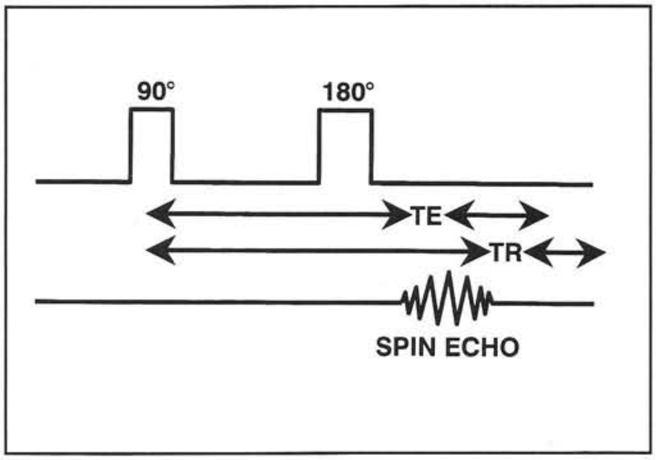

Figure 2. A spin echo is created by a 90° excitation pulse, followed by a 180° refocusing pulse. Notice TE, the time to echo, and TR, the time to recovery.

PULSE SEQUENCES

MRI's are conducted utilizing pulse sequences. The amount of tissue contrast obtained is highly dependent on the utilization of various pulse sequences. Although there are many pulse sequences, they all involve manipulation of two values; TE and TR, to produce a spin echo. TE, time to echo, is the time between a 90° excitation pulse and the production of a spin echo. TR, time to recovery, is the time between 90° excitation pulses.

One image is composed of the production of numerous spin echoes. The number varies according to the values of TE and TR and the type of pulse sequence desired. A spin echo is the basic building block utilized in every pulse sequence. It utilizes a 90° excitation pulse followed by a 180° refocusing pulse. (Fig. 2)

The three basic pulse sequences include: T1-weighted images, proton density images, and T2-weighted images. There are many more pulse sequences than these basic three; however, they are only modifications of these standard pulse sequences and have been created to improve evaluation of pathological processes. Depending on the pathology, certain pulse sequences are preferable over others. Once the general principles of these basic pulse sequences are understood, it is easier to comprehend the more detailed and sophisticated modifications.

The T1-weighted image combines a short TR (600msec or less), with a short TE (40msec or less). The proton (spin) density image combines a longer TR (1500msec or more) with a short TE (40msec or less). The T2-weighted image combines a long TR (1500msec or more) with a long TE (90msec or more). The shorter the TR and TE, the greater the T1 weighting; whereas, the longer the TR and TE, the greater the T2 weighting.

When evaluating MR images, it is important to utilize proper terminology. Images are described as having an increase or decrease in signal intensity. Tissues with an increase in signal intensity appear bright or white and tissues with a decrease in signal intensity appear dark or black. The terms density or lucency should never be used when describing MR images since they are associated with ionizing radiation.

T1-Weighted Images

T1- and T2-weighted images provide the greatest range of contrast, therefore, these images are the first pulse sequences employed on every scan. A T1-weighted image is very useful in displaying normal anatomy. Since subcutaneous fat and bone marrow have the brightest signal, this image is also called the "fat image." Muscle, nerve, and cartilage display intermediate signal intensity, which is gray in appearance. Tendon, ligament, cortical bone, and fluid have little or no signal intensity on T1-weighted images and appear black. Since fluid is commonly involved with pathological processes, T1-weighted images do not display pathology very well. Figure 3 lists different types of tissues and their signal intensities on T1-weighted images. A typical T1-weighted image is seen in Figure 4.

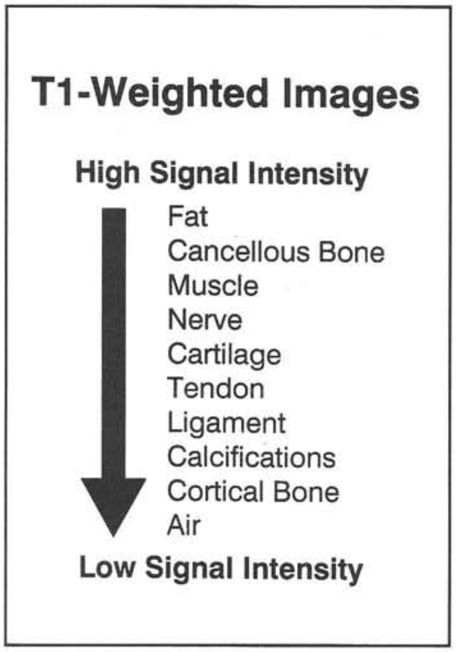

Figure 3. T1-weighted images display various signal intensities depending on the tissue.

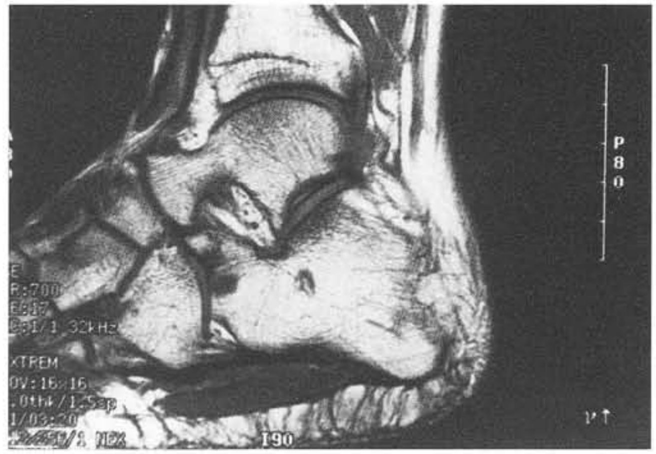

Figure 4. This is a basic T1-weighted image. Notice the excellent visualization of anatomic structures. Subcutaneous fat and bone marrow display a bright signal intensity.

Figure 5. This is a basic T2-weighted image. Notice the increased signal intensity in the metatarsophalangeal joint denoting septic arthritis. This T2-weighted image was acquired utilizing the FSE technique.

T2-Weighted Images

A T2-weighted image is very useful in displaying pathological processes. It is called the "water image" because any tissue containing fluid will have a bright signal. This includes all inflammatory responses: tendinitis, synovitis, cellulitis, abscess formation, osteomyelitis, septic arthritis, neoplasms, post-traumatic episodes, and neuropathic osteoarthropathy. After reviewing this list, it becomes evident why a T2-weighted image is also called the pathology image. As opposed to T1-weighted images, normal subcutaneous fat and bone marrow have a darker, gray appearance on T2-weighted images. Muscle, nerve, and cartilage still display an intermediate, gray signal intensity and tendon, ligament, and cortical bone continue to appear black on T2-weighted images if pathology is not present (Fig. 5).

Proton Density Images

The third type of basic pulse sequence is the proton density image. This is an intermediate-weighted image, meaning it is between a T1- and a T2-weighted image. It has a short TE like a T1-weighted image, however, it has a long TR similar to a T2-weighted image. Although, by looking at the TE and TR values, it would suggest that a proton density image have both T1 and T2-weighted qualities, it appears more similar to a T1-weighted image. Therefore, it is more useful for delineating basic anatomy, than evaluating pathologies. Visualization is sometimes better with the proton density image than a T1-weighted image because it has a high signal to noise ratio. This is the ratio between the strength of the signal coming back from the nuclei and the intensity of the noise from the patient and the machine. The higher the ratio, the less noise acquired, and the better the image quality.

One may ask then why a T1-weighted image is more commonly used than a proton density image if the latter gives better image quality. The answer is based on time versus quality. Since the proton density image has a longer TR value, the scan takes longer to perform. This means that the patient has to be in the scanner longer and may become restless and move, causing distortion. The final result is a poor quality image, regardless, of the pulse sequence utilized. Also, the testing centers are forced to perform fewer studies if each individual scan takes longer. Most testing centers have adequate magnet strength to produce good quality images, therefore, the extra time utilized in obtaining a proton density image really is not necessary. The difference in image quality is minimal and not worth the extra time.

Fast Spin Echo Images

The main advantage of a fast spin echo, (FSE), image is less imaging time. A FSE image is basically a T2-weighted image. In fact, most centers are utilizing FSE in place of "standard" T2-weighted images. A FSE image typically has a longer TR (4000-5000msec), but multi-echo trains make it faster than standard T2-weighted images. For each spin echo pulse sequence, multiple samples are used. Instead of one data line per phase pulse, there are several sample echoes in the train of each TR sequence. Of course, the compromise for speed is a sacrifice in resolution. An increase in speed results in a decrease in phase direction resolution, resulting in a decrease in tissue contrast. However, the sacrifice in resolution is minimal and goes largely undetected by the amateur eye when evaluating MR images. Figure 5 displays a T2-weighted image acquired by the FSE technique.

STIR Images

A STIR, (Short T1 Inversion Recovery), image is a type of fat suppression pulse sequence (Fig. 6). It utilizes a 180° excitation pulse prior to the standard spin echo. Tissues with a short T1 value, such as fat, will reach zero when the standard 90° excitation pulse of the spin echo is introduced, and the signal will be suppressed. It should be noted however, that all tissues with a short T1 value, not only fat, will be suppressed. This pulse sequence is not specific for fat. On the other hand, tissues with a long T1 value, such as water will produce a high signal intensity. So, on a STIR image, fat has decreased signal intensity and fluid has increased signal intensity. This is useful for evaluating edema in high lipid regions, such as bone marrow. This pulse sequence is commonly used to evaluate infectious processes, such as osteomyelitis and abscess formation. It is also useful for evaluating articular cartilage because the joint fluid is bright against the darker cartilage.

Fat Saturation Images

Fat saturation is similar to the STIR technique, however, it is specific for fat. This pulse sequence utilizes radio frequency pulses prior to the standard spin echo sequence. This radio frequency pulse will saturate the lipid protons and stimulate them to a higher energy state. Subsequent pulses place the lipid protons in a lower energy state and their resonance is inhibited. The unique characteristic with this pulse sequence is that all other protons, such as water protons and protons similar to fat, are unaffected because they have different resonant frequencies. Indications for the fat saturation image are similar to those for the STIR technique. The two pulse sequences look almost identical on displayed images. Fat is suppressed, therefore, fluid is enhanced and displays a bright signal. The only way to visually differentiate the two is by looking at the values on the side of an image block. Along with TE and TR values, a STIR image will also have a TI, T inversion value. It should be noted that a fat saturation image, although primarily a T2-weighted type of image, can also be T1-weighted. A T1-weighted fat saturation image is similar to a T2-weighted fat saturation image, however, instead of fat appearing black, it has a dark gray appearance. Fluid will still appear with a bright, increased signal intensity.

Figure 6. This is a STIR image. The increased signal intensity in the distal tibia is a typical presentation of a bone infarct. Notice the bone marrow possesses a black, decreased signal intensity.

Gadolinium

For MR imaging, gadolinium is employed as a contrast medium and is used in combination with other techniques to increase the sensitivity and specificity of diagnosing an infectious process. It is a paramagnetic ion and is usually chelated with DTPA to avoid side effects. Paramagnetic substances have small local magnetic fields, which cause a shortening of the relaxation times of the surrounding protons. Most paramagnetic substances are not harmful. In fact, some of these substances are present within our bodies. Examples are degradation products of hemoglobin, such as deoxyglobin and methemoglobin, found in hematomas.

Two methods of administration can be utilized for gadolinium: intravenous and intra-articular. After administration, the gadolinium is quickly distributed to well vascularized, inflammatory tissue revealing enhanced signal intensity. Non-vascularized areas, such as abscesses, display either no enhancement or enhancement only at the margin of the lesion. This rim of enhancement relates to a peripheral inflammatory zone and the central non-enhanced region indicates necrotic tissue.

The effect of the contrast medium is a change of the signal intensity by shortening T1 and T2 in its surroundings. The gadolinium enhanced fat saturation technique is an excellent image for delineation of an infection. Since the high signal intensity of fat is suppressed, there is great contrast among tissues. Caution should be utilized when gadolinium is combined with the STIR technique. It was previously discussed that the STIR pulse sequence suppresses all tissues with short T1 values similar to fat. When contrast agents that shorten T1, such as gadolinium, are also used, the desired contrast enhancement may be suppressed.

It is hard to identify whether gadolinium has been utilized when visually evaluating images. As was stated, it is commonly utilized with the fat saturation technique to evaluate infection. Usually the testing center will place a sticker on the jacket of the MR images displaying that a contrast agent was in fact utilized.

Gradient Echo Images

Gradient echo is a pulse sequence not commonly used for MR imaging of the foot and ankle, however, for completeness it will be reviewed. Instead of the standard 90° radio frequency pulse employed for a basic spin echo production, the gradient echo technique utilizes a radio frequency pulse less than 90°. This means that the protons are not completely rotated into a higher energy state and not completely excited. This leads to a shorter relaxation time, therefore, the TR value is shorter. Of course a shorter TR means a shorter imaging time. Once again, a quicker image has been produced.

This technique is commonly utilized in pelvic and abdominal MR imaging and for evaluating blood flow. It has a very "grainy" appearance with bone marrow possessing low signal intensity. In the foot and ankle it is sometimes used for joint imaging.

READING MR IMAGES

Typically, each MR image box will contain basic information. This includes the name of the testing center, the name, age, and chart number of the patient, and the date and time of the exam. In addition, useful technical information is also provided. This includes the strength of the magnet, the sequential image number, the cardinal plane examined, TE and TR values, and slice thickness. This information can be extremely helpful to the physician if he or she knows how to interpret these parameters.

One should develop a systematic technique when evaluating MR images to ensure thorough evaluation of the information provided. An evaluation should always begin with a scout film. For each type of pulse sequence, a scout film is provided for every cardinal plane evaluated. A scout film is a single image of an entire anatomic region scanned that is divided into "slices." The slices are spaced at a predetermined thickness. For foot and ankle imaging, slice thickness is usually between 5mm and 10mm. The slices are illustrated on the scout film by multiple lines, sequentially numbered. The number of images, per pulse sequence, per cardinal plane, varies depending on how many slices are needed to fully evaluate an area. The total number of slices is listed on the scout film and subsequent images are labeled according to the location of the slice. When viewing a scout film, matching the image number with the slice coordinate can easily identify an anatomic location.

A MRI exam usually contains multiple pulse sequences. Each pulse sequence is imaged in at least two cardinal planes, axial and sagittal, to provide a thorough evaluation of the foot and ankle. T1-weighted images should be the first pulse sequence evaluated. This lets the physician become familiar with the patient's basic anatomy. Once all T1-weighted images are reviewed in all planes, T2-weighted images should be evaluated and pathologies identified. Next, modification techniques such as STIR or fat saturation can be evaluated to ensure appropriate identification or lack of pathological processes.

CLINICAL INDICATIONS

MRI has become the imaging modality of choice for many pathologies of the foot and ankle. It is unique in its ability to completely evaluate bone, joint, and soft tissue structures. Not only does MR imaging display fine detail in basic anatomy; it also has the capability of differentiating various pathologic processes. By utilizing a combination of various pulse sequences, MR imaging allows the physician to thoroughly evaluate a disease process. The physician is able to delineate normal anatomy from pathology and define its boundaries. The MR image can also serve as a type of road map for preoperative planning. Unlike other imaging modalities, MRI can specify the exact anatomic location of a pathological entity.

MR imaging has a wide range of clinical indications ranging from trauma to infection to neoplasms. A thorough evaluation of each clinical entity is beyond the scope of this paper. Regardless of the indication for the exam, the basic principles of MRI evaluation remain the same. Anatomy is best visualized on T1-weighted images and pathologies are best evaluated with T2-weighted images. Anything producing an inflammatory response will produce increased signal intensity on a T2-weighted image. These pathological processes include bone contusions, stress fractures, and various infectious processes such as cellulitis, osteomyelitis, and septic arthritis. The STIR and fat saturation techniques are additional pulse sequences useful for evaluating infection.

One additional clinical indication for MR imaging deserves to be mentioned; evaluation of the vascular system. This recently developed technique is known as MRA, magnetic resonance angiography. MRA is noninvasive imaging of the vascular system using special MR pulse sequences to capture and display flowing blood (Fig. 7). MRA does not require iodinated contrast to visualize blood vessels, but instead creates an anatomic map based on physiologic flow, with blood velocity being a major factor in determining the strength of the MR signal. This is a superior technique for patients with allergies to intravenous contrast agents and renal insufficiency, who would have difficulty obtaining an invasive arteriogram. One drawback to MRA is that the vessels displayed are actually magnified; therefore, when evaluating them one must remember that the vessel of interest may actually be smaller than it appears.

FFigure 7. This is an MRA of both feet and ankles. One can compare the blood supply from one extremity to the other by identifying the major arteries and their collateral vessels.

CONCLUSION

MRI has many clinical indications and is being utilized on a routine basis. It is critical to interpret the results by viewing the images, not by reading a report. This is the same concept for radiographs and other imaging modalities. The requesting physician is ultimately the responsible party for the interpretation of the study. Patients are ultimately affected by exam results because physicians alter their treatment regimens accordingly.

With a basic knowledge of MRI technique, the physician can adequately review patient studies and have confidence in their interpretations. As a physician gains experience, MR imaging will become commonplace and can be utilized as an effective tool aiding in clinical diagnoses and treatment protocols.