Review on Magnetic Resonance Imaging Systems Available for Use in Equine Patients and the Implications of Field Strength on Clinical Imaging: Comparison of High- and Low-Field Systems

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This review addresses the differences between high- and low-field magnetic resonance imaging systems. Although many injuries can be well characterized with both high- and low-field systems, a high-field system is needed to identify certain lesions. Studies are needed to define the difference in conspicuity of lesions on high-field versus low-field systems. Authors’ address: Equine Orthopaedic Research Laboratory, College of Veterinary Medicine and Biomedical Sciences, 300 West Drake, Colorado State University, Fort Collins, CO 80523; e-mail: nmwerpy@colostate.edu. © 2007 AAEP.

1. Introduction
Magnetic resonance (MR) imaging provides excellent visualization of soft tissue and osseous injuries. Several MR systems, both high and low field, are available for imaging equine patients. High-field systems designed for use in human medicine have been modified to allow imaging of equine patients. Currently, there are low-field MR systems specifically designed for equine patients. This article addresses the fundamental differences between high- and low-field MR imaging systems. Equipment, examination time, image quality, and the implications on diagnostic accuracy are discussed.

2. Low- Versus High-Field MR Systems
High-Field Systems
High-field MR imaging systems are defined as having a field strength of 1.0 T or greater. One tesla is ~20,000 times the earth’s magnetic field. Creating a high-field strength MR system requires a superconducting magnet. Superconductivity is a characteristic of certain metals that have no resistance to electrical current when cooled to an extremely low temperature. A high-field MR system requires a cryogen, such as liquid helium, to maintain this extremely low temperature. The cryogen circulates throughout the MR system, eliminating electrical resistance in the circuit. Allowing current to flow through the circuit without electrical resistance creates an environment capable of producing field strengths of 1.0 T and higher. Many research centers use high-field, small-bore magnets ranging from 7.0 to 12 T for imaging tissue samples. These systems can characterize the articular cartilage layers and provide extremely detailed imaging of tissue samples. Clinical imaging systems with a field strength of 3.0 T have
been introduced into the human market relatively recently; however, 1.5 T is still the most commonly used system. The high-field MR systems currently in use in veterinary medicine are human systems that have been modified to allow imaging of equine patients. High-field, small-bore systems allow extremity imaging from the carpus and tarsus distally. High-field, large-bore magnets are available that allow imaging of the head and cranial cervical spine in addition to the extremities. High-field systems range in price from approximately $495,000 to millions of dollars and have expensive annual service contracts making them cost prohibitive for many practices.

Low-Field Systems

Low-field MR systems are defined as having a field strength of up to 0.3 T. Both of the currently available equine-specific MR imaging systems use low-field permanent magnets ranging in field strength from 0.20 to 0.29 T. Permanent magnets create a magnetic field using the ferromagnetic properties of certain metal alloys. The magnetic field is induced into the materials at the time of manufacturing. The cost of low-field systems have made MR imaging accessible to many practices in the United States and Europe and allowed imaging of horses that may not have otherwise had access to this modality.

3. Examination Time

Direct comparison of the time needed to complete a sequence or an examination using high- and low-field systems is difficult. The sequences used in MR imaging have ~20 different interrelated parameters that affect the image produced. Optimization of images requires that these parameters are set differently on a high-field system compared with a low-field system. Therefore, it is impossible to produce images created with identical sequence parameters from both systems. Similar sequences take 2–5 min longer to acquire on a low-field system than a high-field system. Low-field systems have a smaller field of view and a higher incidence of artifacts at the periphery of the field of view compared with high-field systems. Therefore, additional sequences are often needed to visualize the same area imaged with one acquisition by a high-field, large-bore system, further increasing examination time. An average protocol using six to eight sequences will take between 12 and 40 min longer on a low-field system compared with a high-field system. These comparisons assume that the patient is compliant or anesthetized. The biggest factor influencing the time needed to complete an MR study when imaging a standing horse is patient compliance. Image acquisition using a thorough protocol for a single site in one limb usually takes ~40–55 min in a standing, sedated horse. Should repositioning of the patient become necessary because of excessive movement, the exam time can be significantly extended.

4. Factors That Determine Image Quality

High-field MR systems produce more information from the patient, creating images of higher quality. Image quality is largely determined by three factors: the signal to noise ratio, the contrast to noise ratio, and artifacts. Of these, the signal to noise ratio has the largest effect on image quality. In this context, signal is defined as information generated from the tissues that is representative of the anatomy and is used to produce an image. Noise is false information produced from the tissues or the MR system that is also incorporated into the image. The signal to noise ratio shows the amount of true information in an image relative to the amount of noise.

The signal to noise ratio increases almost linearly with field strength. Field strength is the most important factor determining image quality. Higher field strength directly results in images with better resolution. As the field strength increases, the MR system is able to acquire more information from the imaged tissues. Therefore, high-field systems can produce images using thinner slices with more information, or signal, compared with a low-field system. The additional information is integrated into each pixel, producing a more detailed image, with a higher resolution of small structures. Within each type of MR system, steps can be taken to increase the signal to noise ratio, resulting in improved image resolution. Generally these modifications increase the image acquisition time. Increased acquisition time potentially increases the risk of motion artifact in both standing and anesthetized horses and may be unacceptable in anesthetized patients. In certain circumstances, increasing the signal to noise ratio significantly increases the acquisition time, without providing a proportional increase in image quality.

The ability to distinguish between various tissue types requires that the tissues have different signal intensities. The variance between signal intensities of different tissues is shown by the contrast to noise ratio. Similar to the signal to noise ratio, the contrast to noise ratio can be affected by many different sequence parameters. However, the contrast between different tissue types is dramatically influenced by the MR sequence selected to produce the image. When evaluating similar sequences, studies have shown that high-field systems produce a higher contrast to noise ratio compared with low-field systems. The increased contrast to noise ratio produced by the high-field images translates into easier identification of different tissues as separate structures, facilitating diagnosis of abnormalities.

High-field systems have better magnetic field homogeneity or stability, which results in a decreased incidence of artifacts compared with low-field systems. There are artifacts that are more prevalent with high-field systems; examples include chemical shift artifact and susceptibility artifact resulting
5. Relationship Between Image Quality and Diagnostic Accuracy

The next step is to examine the relationship between image quality and diagnostic accuracy. Does the improved image quality achieved with high-field systems translate into increased diagnostic accuracy or does it just produce nicer looking images? This has been a long and controversial debate in human medicine. Several papers concluded there is no statistically significant difference between the diagnostic accuracy of low-field and high-field MR systems. Barnett9 focused on derangements of the human knee, such as meniscal or cruciate liga- ment tears, and found no significant difference in specificity or sensitivity for lesion diagnosis between low- and high-field systems. In this paper, many of the cruciate injuries were full-thickness tears, and the meniscal lesions were substantial in size and severity. Kladny et al.8 compared high- and low-field images of human knee lesions, which included full-thickness articular cartilage defects. Of six defects detected with a high-field system, only one was detected with a low-field system. Currently, there is no publication that compares high- and low-field systems for identification of partial-thickness cartilage lesions in either people or horses. Taouli et al.9 compared detection of bone erosion in the hands and wrists of patients with a proven diagnosis of rheumatoid arthritis and suggested that there was no significant difference in the diagnostic accuracy between low- and high-field systems. However, patients with rheumatoid arthritis of <6-month duration were excluded from the study, and the images presented in the article had areas of severe bone erosion, with >50% of the affected bones destroyed as a result of the disease process. Critical analysis of the papers comparing high- and low-field MR images revealed that the lesion size and severity are neither specifically selected for nor discussed. In reality, these are the most important intrinsic factors determining the conspicuity of lesions.

A review of the literature and evaluation of images from patients examined with both systems showed that the diagnostic accuracy of high- and low-field systems is dependent on the lesion size and type. High-field systems allow detection of small and low-contrast lesions that cannot be identified with low-field systems. Certain lesions, such as articular cartilage defects, will have clinical significance in many cases and probably cannot be consistently and definitively identified with a low-field system. In other cases, the clinical significance of lesions identified only with a high-field system has not yet been determined. This process will be challenging because we are making the assumption that an identified MR lesion, providing it correlates with the history, clinical signs, and the postulated source of pain, is the source of the lameness. However, this may not always be the case. The same lesion may cause a different degree of lameness in different horses; there is clearly a large degree of individual variation. This makes categorization of lesions by MR appearance and degree of lameness, while necessary and helpful, not accurate if applied to every case. Further studies are needed to define the difference in the detectability of lesions on high-field versus low-field MR imaging systems and to determine the clinical significance of those lesions. Many injuries in the horse can be accurately diagnosed using both high-field and low-field MR systems (Fig. 1). However, a high-field system is needed to identify certain structures and lesions (Fig. 2).

Level of confidence in diagnosis of images from high- and low-field systems has been evaluated in human medicine. Rand et al.11 reported a significantly superior level of confidence from the investigators in their diagnoses from high-field images caused by the higher conspicuity of lesions. The increased resolution of high-field images yields greater confidence in the diagnosis of lesions.

Examples of structures that are more clearly delineated with a high-field system include articular cartilage, the flexor surface of the navicular bone, and the distal sesamoidean impar ligament. The increased resolution achieved with high-field systems results in improved visualization of these structures and diagnosis of subtle abnormalities. Relative to other tissues, articular cartilage is extremely thin. It lies between synovial fluid and subchondral bone, tissues with significantly different magnetic properties. Because of its size and surrounding tissue layers, articular cartilage is one of the most difficult tissues to accurately resolve. This difficulty is caused by partial volume averaging, an artifact that results in decreased resolution of thin structures and curved surfaces. The articular cartilage of the metacarpophalangeal joint is an area that most clearly shows the difference in image quality when comparing different MR systems, because it is highly susceptible to partial volume averaging (Fig. 3). The articular cartilage of the distal tarsal and carpal joints are less susceptible to partial volume averaging because of the cuboidal shape of the bones and the flat articular surfaces.
Fig. 1. A transverse STIR image at the level of the tarsus produced using a low-field system (A). A transverse STIR image at the level of the tarsus produced using a high-field system (B). These images are from different horses that have a similar degree of osteomyelitis of the calcaneus, synovitis of the tarsocru- ral joint, tenosynovitis of the tendon sheath, and generalized cellulitis. The increased signal intensity (light gray) in the calcaneus indicating the presence of extensive abnormal fluid as a result of the osteomyelitis is easily detected on both images as are the other major findings. Major differences in the images include visualization of the lateral collateral ligaments of the tarsus and the fibers of the talocalcaneal ligament.

Fig. 2. A sagittal proton density image produced using a low-field system (A). A sagittal proton density image produced using a high-field system (B). These images are from the same cadaver limb that was scanned on the same day in both systems. There is a large cystic lesion in the navicular bone that is apparent on both images (blue arrows). There are enthesophytes on the proximal margin of the navicular bone at the attachment of the collateral sesamoidean ligament and the attachment of joint capsule of the DIP joint, which are visible on both images but are more easily identified on the high-field image (yellow arrows). There are abnormalities in the deep digital flexor tendon and adhesions between the tendon and the impar ligament that can only be definitively identified on the high-field image (white arrows).
Therefore, the margins of the articular cartilage of the distal tarsal and carpal joints are more clearly delineated in comparison to the metacarpophalangeal joint. On the palmar aspect of the navicular bone, there is cortical bone and fibrocartilage. In addition, synovial fluid and the synovial membrane of the navicular bursa and the deep digital flexor tendon are all in close proximity and immediately adjacent to the navicular bone flexor surface. The navicular bone flexor surface is curved in multiple planes. The sagittal ridge, which is an area susceptible to pathology, is curved in both proximal to distal and medial to lateral directions. This creates many difficulties in accurately resolving small areas of bone and fibrocartilage abnormalities caused by the high incidence of partial volume averaging. The anatomy of the distal sesamoidean impar ligament makes it extremely difficult to accurately interpret on MR images. It is composed of individual fiber bundles, or fascicles, with interdigitations of the synovial membrane and fluid of the distal palmar recess of the distal interphalangeal joint. The ligament is small with multiple fluid–fiber interfaces and is a structure that is extremely susceptible to partial volume averaging. Signal intensity indicating the presence of fluid within the distal sesamoidean impar ligament is not necessarily synonymous with a lesion, unlike other ligaments.

Low-field images undergo additional post-processing such as filtering or smoothing in comparison to high field systems. The filtering or smoothing process blends information in pixels together preventing visualization of pixels. The end result of this process creates images that appear as an accurate representation of the anatomy; however, several important details are missing. This difference is apparent when comparing the trabecular bone pattern between high- and low-field systems (Fig. 4). The pattern overlying the trabecular bone in an image from a low-field system can represent the noise pattern in the image. A comparison of the pattern in the bone to the image noise present in the background outside the anatomy after adjustment of the window and level will reveal that they are similar. The trabecular bone cannot be accurately represented on most low-field images because of the resolution between the opposing cartilage surfaces on the distal aspect of the third metacarpus and the first phalanx. On the 1.0-T image (B), the distinction between the articular cartilage on the palmar condyle and the synovial fluid can be made in the small window between the first phalanx and the sesamoid bone, although it is slightly less apparent than on the 1.5-T image. No distinction can be made between opposing articular cartilage surfaces on the 1.0-T images. On the 0.27-T image (A), identification of the articular cartilage margin is only possible on the dorsal surface of the joint. The thin articular cartilage and curved surface of the metacarpophalangeal joint tests the resolving of the MR systems and provides the most accurate depiction of the differences in resolution between the systems.
olution limitations. Therefore, differentiating diffuse fluid within intact trabecular bone from cystic fluid accumulation with loss or destruction of the trabecular bone often cannot be achieved (Fig. 5). On a low-field image, the degree of injury to the trabecular bone can be presumed based on other abnormalities present. Assumptions about the trabecular bone can be made based on the severity of the signal intensity and the presence of a sclerotic rim surrounding the affected area; however, it cannot be confirmed. These two situations have different implications for the patient. In certain cases,
diffuse fluid can resolve; however, trabecular bone loss is a permanent change. Repair processes can take place, but the injured bone will never return to normal. Abnormalities accompanied by fluid infiltration are commonly encountered in frequently imaged regions such as the foot and fetlock. Accurately characterizing the lesion in these cases is important for treatment and prognosis. The difference in the trabecular bone pattern is just one example showing that, although on peripheral overview the images can appear similar, there are important differences.

6. Conclusions

MR imaging is an excellent diagnostic tool, but it is important to understand the uses, strengths, and limitations of this imaging modality. High- and low-field MR systems have provided diagnostically valuable information to thousands of horses and will continue to do so. However, like all modalities, proper use and understanding of the limitations are essential for accurate interpretation and diagnosis. Understanding the limitations of these different systems and accurately communicating it to in-house and referring veterinarians as well as clients reduces the chance of misconceptions and unmet expectations. High-field systems have faster acquisition times and superior resolution; however, the substantial investment needed for purchase and maintenance make them prohibitive for many practices. Many injuries can be accurately characterized and diagnosed using a low-field MR system. However, certain structures and lesions are better characterized with a high-field system, and certain lesions will require a high-field system for visualization. It is necessary to determine a critical lesion size for each system and validate a protocol that is most effective for showing lesions. In addition, studies are needed to determine the clinical significance of lesions based on size and type. As we continue to image horses and correlate findings with the results of clinical examination and other imaging modalities, we may be better able to determine which patients should be imaged with a high-field versus a low-field system.

References