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Equine Imaging Modalities

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1. Introduction

Introduction of computed and digital radiology, technical advancements in ultrasound and nuclear scintigraphy, and increased availability of magnetic resonance imaging (MRI) and computed tomography (CT) are resulting in imaging that parallels what is present in human medicine, increasing the standard of care for our equine patients. Advanced imaging, such as MRI and CT, is becoming more commonly accessible for use in diagnosing musculoskeletal disease and causes of lameness. As this occurs, selecting from all the available imaging modalities and determining what will provide the most accurate and complete diagnosis can be challenging. These decisions are determined by many factors, some of which involve the specifics of the case such as the localization of the lameness. They also include the severity of lameness and therefore likely the severity of the lesion being investigated. Proximity to facilities that have advanced imaging and owners’ financial considerations, as well as any concerns about general anesthesia, also play a role in this process. Every available imaging modality has advantages and disadvantages, as well as strengths and weaknesses. This knowledge is necessary to navigate the imaging modality selection process and help owners make choices that will provide you with the diagnostic information necessary to accurately treat your patients and provide the best possible outcome.

Many lesions appear obvious using advanced imaging, such as CT or MRI. These same lesions can appear obscure on other modalities. This often results in the impression that these lesions were not able to be diagnosed with other modalities. However, this may not be the case or may only be the case initially. Advanced imaging provides a great educational tool that will cause us to re-examine the results of other imaging modalities with great scrutiny. This re-examination will set in motion a process that will make us better at reading radiographs and at obtaining and interpreting ultrasound images. It will not change the fact that certain lesions will require advanced imaging for diagnosis, based on location and/or severity. In contrast, other cases will initially require advanced imaging for a diagnosis. However, the information from these cases will provide the knowledge and development of the skills facilitating the diagnosis to be made without advanced imaging in the future.

As previously stated, all modalities have advantages and disadvantages. Despite the vast information obtained with advanced imaging, using different modalities in conjunction is often a requirement for obtaining all the necessary diagnostic information about a lesion. Owner education about this fact is important because it prevents the com-
mon scenario that MRI answers “all questions,” which we recognize is not always the case. Owner preparation is always easier done before completion of the study, as opposed to justifying additional imaging after an MR study that required a considerable financial investment. Understanding the strengths and weakness of the modalities in combination with suspicions about the sources of the lameness based on clinical examination findings can facilitate this conversation with owners. Their understanding for the potential need of additional diagnostics after an MR study will allow you an opportunity to obtain all the necessary information before making a final diagnosis. The goals of this paper are to outline the strengths and weakness of the different modalities in conjunction with examples that will provide a guide for navigating the process of deciding what modalities will provide the best diagnostic information for your case.

2. Radiography

Certainly, computed radiography (CR) and direct radiography (DR) have added convenience that cannot compare to plain film-screen systems. However, it is just as possible to take a poor radiograph with a DR or CR system as it was with the film-screen systems. Although CR and DR systems allow adjustability in poor exposure, only so much compensation is possible. Therefore, it is important to recognize the boundaries of the latitude in these systems and not mistakenly accept substandard images.

Radiography has traditionally been among the first steps in imaging musculoskeletal disease. It is readily available and can be performed in the field. It has major limitations for diagnosing certain types of abnormalities. A large change in the bone mass is needed to create radiographically detectable lesions. Therefore, depending on the location and type of lesion, a significant amount of abnormality must occur before we can identify it. Radiographs have extensive superimposition of structures because we are taking three-dimensional objects and making them into two-dimensional images. This modality does not allow detailed soft tissue imaging. Although the advancements in CR and DR systems allow adjustments that make soft tissue and fat margins identifiable, and gross aberrations in the position and size of these margins can be detected, this modality does not provide information beyond that.

Although summation of structures is often a disadvantage, it actually allows some abnormalities to be more clearly visualized on radiographs compared with multi-slice modalities. Summation of bone proliferation actually can make it more apparent on radiographs compared with multi-slice acquisition modalities such as CT and MR (Fig. 1). On CT and MR images, the bone proliferation is divided up between slices and can still be identified but is often not as apparent as it appears on radiographs. This is dependent on the location of the bone proliferation. The use of three-dimensional reconstruction can make bone proliferation more apparent than evaluation of the same abnormality while scrolling through individual images obtained from a multi-slice modality. On MR images, fibrosis of the joint capsule and/or synovial proliferation can appear similar to bone proliferation. In contrast, these changes would appear markedly different from each other on radiographs. Abnormalities in trabecular bone patterns are often visible in hindsight on radiographs when evaluated in combination with advanced imaging. Continuing to use advanced imaging as an education process will improve radiograph interpretation skills and allow more information to be gained from this modality. Advanced imaging can also contribute to new techniques and views as we attempt to visualize lesions on radiographs that were diagnosed with advanced imaging.

3. Diagnostic Ultrasound

Ultrasound remains accessible and safe. In addition, high-quality machines have become smaller and more portable. Therefore, examinations can be easily performed in the field. This modality is extremely operator dependent, and the ability to obtain a diagnosis is dependent on the training, skill, and experience of the operator. The acoustic properties of tissue, both normal and abnormal, determine their echogenicity and therefore will determine the difference in appearance of injured tissue compared with normal tissue. Certain types of injuries, such as fiber disruption and fluid accumulation in tendons and ligaments, are very apparent with ultrasound (Fig. 2). However, with other types of injury, tendon and ligament fibers can remain echogenic despite clinically significant abnormalities. This occurs with certain stages of degenerative injury and results in an ultrasound appearance that is not markedly different from normal, making this type of injury challenging to diagnose with ultrasound. This type of injury causes more marked changes in the chemical properties of the tissues, making the change quite apparent on MR images.

The results of MR studies often prompt re-examination of structures with ultrasound to determine whether the abnormalities can be detected. This practice will continue to improve our ultrasound skills and will aid in the development of new techniques that will allow more precise and novel diagnoses with ultrasound. The echogenicity of tendons and ligaments is dependent on the angle of the ultrasound beam relative to the orientation of the structure’s fibers, a principle defined as anisotropism. Using this principle and applying it to different structures and different tissue types and stages of injury allows more information to be obtained from ultrasound exams (Fig. 3). This technique can be used to better and more fully examine the proximal aspect of the suspensory ligament in the forelimbs. It can also be used to correctly iden-
Fig. 1. Sagittal proton density MR images (A, B) from 2 different front feet with corresponding radiographs (C, D). Images from Case 1 (A, C) demonstrate bone proliferation on the dorsal aspect of the middle phalanx. Images from Case 2 (B, D) demonstrate synovial proliferation and thickening of the distal interphalangeal joint capsule. The radiographs appear markedly different while the MR images appear similar when comparing the dorsal recess of the distal interphalangeal joint and the dorsal margin of the middle phalanx. The bone proliferation on the dorsal margin of the middle phalanx identified in Case 1 is readily apparent when imaged with ultrasound (E). The similarities in the appearance of the MR images occur because mineralization and fibrous tissue can appear similar on MR images but share no similar radiographic characteristics. In addition, the summation of the bone proliferation across the dorsal surface of the middle phalanx makes it more apparent on the radiographs that when it is divided in the multiple 3 mm MR images.
tify areas of scarring and/or malaligned fibers in tendons and ligaments.

Ultrasound continues to be very valuable for assessing bone surfaces and will often be more sensitive to superficial changes in bone margins than radiographs. Of course, ultrasound is limited to abnormalities that are involving or extend to the bone surface. In cases where the bone surface is accessible, ultrasound can be easily used to examine questionable areas identified on radiographs.

Ultrasound requires diligence and commitment, as well as consistency.

4. Nuclear Scintigraphy

Nuclear scintigraphy is sensitive but not specific in its ability to localize areas that potentially have clinical significance. It can provide information about vascular integrity, soft tissues, and bone (Fig. 4), as well as insight into the entire patient. Nuclear scintigraphy provides vital information in cases where the cause of lameness is difficult to localize or there are anatomical regions of the horse that are clinically suspicious but difficult to fully image with other modalities. This modality can provide supporting evidence and allow targeted imaging with other modalities. Nuclear scintigraphy provides information about the presence or absence of ongoing bone turnover on abnormalities identified on radiographs. The clinical significance of these findings is not always clear, and correlation with clinical findings is important in every case.

Regional anesthesia of the site of increased radiopharmaceutical uptake can be performed to confirm the source of lameness. The use of other imaging modalities is usually necessary to further evaluate the site. In horses, conventional radiography and/or ultrasonography usually follow a scintigraphic diagnosis. More sophisticated CT or MRI studies may be needed to arrive at a definitive diagnosis, especially within the hoof capsule. In horses with multiple limb involvement or where regional anesthesia has been inconclusive or ambiguous, it is often cost effective to scan the horse first and then perform the regional anesthesia and additional imaging techniques.

Because bone is dynamic and responds to stress, specific patterns of increased uptake will be present in horses performing certain athletic functions. Radiographic examinations of these areas of increased isotope uptake after scintigraphic examination are often unrewarding unless the pattern is significantly asymmetrical between the limbs. These patterns are usually learned very quickly and become less confusing as users become more familiar with the technology.

5. CT

CT provides the most superior bone detail of any currently available imaging modalities (Fig. 5). However, it cannot identify fluid in bone (Fig. 5). It can be used to identify soft tissue abnormalities but has limitations for use in identifying soft tissue abnormalities compared with MRI. These limitations are significantly lessened but still present by the use of contrast. A great advantage of CT is the speed at which the exam can be performed. In cases where the desired information can be obtained from CT, the reduction in anesthesia compared with MR makes it the superior modality to pair the sur-
gery or other interventional techniques in the same anesthesia. MR studies can be tailored under similar circumstances to reduce anesthesia time, but CT will remain the faster modality. This is especially true in cases using three-dimensional reconstruction for fracture repair planning, which will often not necessitate the use of contrast. Patients with ferrous implants can be safely imaged with CT. Although the implants will result in artifacts, there are not the same restrictions that are present with MR.

Intravascular and intrasynovial contrast administration is possible with CT examination.\textsuperscript{4,5} Contrast enhancement of lesions after intravascular administration of contrast requires vascular ingrowth or communication with the tissues. This will aid in assessment of the tissues and their vascularity.\textsuperscript{6} However, lesions and injury can be present without associated vasculature, which may not contrast even in delayed phase images, and these lesions shouldn't necessarily be excluded as a clinically significant lesion.

CT arthrography has allowed diagnosis of lesions in the stifle joint that is not possible with other modalities. Positioning of this joint for MR examination is unreliable, and shorter horses or horses with large gluteal musculature typically cannot fit in the magnet, making CT the best currently available advanced imaging modality. Many horses will fit into the CT gantry for imaging of the stifle. However, not all patients can be imaged because of size constraints. CT arthrography creates an outline of the cruciate ligaments and other areas of the joint not completely assessable with ultrasound. Regions that are limited with radiography because of superimposition of structures are easily evaluated.

Fig. 3. MR (A), US (B, C) and gross (D) images at the proximal aspect of the third metacarpal bone. All images are oriented with dorsal at the bottom and medial on the left of the image, the suspensory ligament is indicated with a white arrow. On the proton density MR image (A) the suspensory ligament fibers are black. The lobes of the suspensory ligament can be identified and contain muscle and adipose tissue that appear gray. The initial US image (B) was obtained with the carpus flexed and the ultrasound beam perpendicular to the longitudinal axis of the suspensory ligament. The palmar margin of the suspensory ligament can be well defined; however, the ligament lobes as well as regions of fat and muscle cannot be identified. The second US image (C) was obtained with the carpus flexed; however, the US beam was not oriented perpendicular to the ligament fibers. Utilizing the principles of anisotrophism allows identification of both the suspensory ligament lobes as well as the regions of muscle and adipose tissue. This technique allows the use of ultrasound to produce an image that much more closely represents the anatomy of the ligament as demonstrated by the MR (A) and gross (D) images. MR images will improve the knowledge gained with ultrasound by furthering our understanding about the changes in different tissues at different stages of injury as well as facilitating the development of new ultrasound techniques.
Fig. 4. CL multimodality case. Soft tissue (A) and bone phase (B, C) images with increased radiopharmaceutical uptake on the medial aspect of the foot. Subsequent imaging revealed extensive soft tissue and osseous injury associated with the medial collateral ligament of the distal interphalangeal joint. Enthesophyte formation (*) at the origin of the collateral ligament on the middle phalanx is well visualized on radiographs (D) and ultrasound (E). Bone loss (solid arrowhead) at the insertion of this ligament is well demonstrated on radiographs (F, G) and MR images. Diffuse injury and enlargement of this ligament (arrow) at the level of the middle phalanx is well demonstrated on ultrasound (H) and MR (I) images. At this level the axial aspect of the ligament is most affected with an area of fiber disruption and diffuse fluid accumulation. However, the ligament is most severely affected beginning at the level of the joint and continuing to the insertion where there is a complete tear in the ligament (open arrowhead). Due to the location of the tear, this area can only be visualized on the MR images (J, K). All the modalities contributed valuable information to the diagnosis in this case. Due to the location of the most severe injury in the ligament, MRI was required to obtain all the vital information in this case.
Fig. 4. Continued. A—Dorsal soft tissue phase scintigraphic image; B—Dorsal bone phase scintigraphic; C—Solar (palmar) bone phase scintigraphic image; D—Dorsolateral-palmaromedial oblique radiograph; E—Longitudinal US image at the origin of the collateral ligament of the DIP joint, proximal at the top of the image; F—Dorsopalmar radiograph; G—Dorsoproximal-palmarodistal oblique radiograph; H—Transverse US image at the origin of the collateral ligament of the DIP joint, dorsal is at the top of the image; I—Proton density transverse MR image at the level of the middle phalanx and navicular bone; J—T2-weighted FSE frontal oblique image oriented parallel to the longitudinal axis of the collateral ligaments of the distal interphalangeal joint; K—Proton density transverse MR at the level of the distal interphalangeal joint.
with CT. However, when evaluating soft tissue structures and articular surfaces, CT arthrography is limited to identifying lesions that communicate with both the joint and a superficial surface of a structure (Fig. 6). The lesions are identified because of abnormal contrast patterns or the presence or absence of contrast. Therefore, if a lesion does not create an abnormal contrast pattern because of lack of contact with the contrast, it will not be identified.

6. MRI
MRI provides excellent visualization of soft tissue and osseous injuries (Figs. 2, 4, and 6). It has some important limitations; it does not have the same osseous detail as CT. Small fractures and certain osseous lesions will be more apparent on CT images compared with MR (Fig. 5). Tissues that have no mobile protons, such as mineralization and mature scar tissue, both appear black (Fig. 1). Mineralization and mature fibrous tissue can be completely obscured when located in structures that are normally black, such as tendons and certain regions of ligaments. Abnormalities in the size and shape of these structures in the absence of changes in signal pattern can provide some indication of abnormalities. These areas of mineralization are readily apparent on radiographs and ultrasound images. The degree of mineralization of structures affects the shade of gray that the area will appear on the MR images. Diffuse, incompletely mineralized enthesophyte formation can appear gray and blend in with the joint capsule on MRIs and will again be readily apparent on ultrasound, radiographs, and CT (Fig. 1).

Fig. 5. CT MR fracture image. There is a fracture (arrow) in the distal aspect of the third metacarpal bone that can be identified on proton density (A) and STIR (B) MR images as a focal interruption in the subchondral bone margin. This fracture is more evident on the CT image (C), which has superior bone detail and it cannot be identified on the radiograph (D). There is extensive fluid in the distal aspect of the third metacarpal bone and proximal aspect of the proximal phalanx which cannot be identified on the CT image. The fluid appears as a light gray area demarcated by the white arrowheads on the STIR image (B). Normal trabecular bone on the STIR images should appear dark gray, similar to the region denoted by the asterisk.
In a similar manner, synovial proliferation that has mature fibrous tissue adjacent to structures with a similar signal intensity can appear adhered.\(^8\)

MRI has unparalleled soft tissue detail when comparing currently available imaging modalities. It can detect subtle lesions that will not be identified using any other modality. It has a longer acquisition time, which translates into a longer anesthesia time compared with CT. The higher the field strength, the more quickly images can be acquired, which is an advantage to high field strength MR systems in addition to superior image quality. Because of the image acquisition time, precise localization of the lameness is required when performing an MR study. This can be challenging, and it is best whenever possible to include as much anatomy as possible proximal and distal to the region of interest. This prevents missing a lesion that may improve with nerve blocks outside the anatomy that we would normally expect to be responsive. The total number of regions that can be imaged is limited by anesthesia time.

Similar to CT, there is no current method for performing dynamic studies. The limb can be positioned in a specific manner, such as flexion or extension, to gain additional information. If multiple studies are needed, for example, to compare flexion versus neutral, this would still be better achieved with CT because of the image acquisition time. This method doesn’t provide the same information gained by performing a dynamic ultrasound examination to assess tendon movement or evaluate structures for the presence of adhesions. Similar to CT, currently there is not a method for performed dynamic MR studies looking at tendon movement or verifying adhesions. However, CT studies are short enough in length that multiple positional studies, changing the position of the limb from flexion to

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**Fig. 6. CT MR image.** Frontal T2-weighted image (A) of a stifle with a horizontal tear in the medial meniscus that extends into medial cranial tibial meniscal ligament (arrowhead). In addition, there is horizontal tear in the lateral cranial tibial meniscal ligament (arrow). The tear in the lateral cranial tibial meniscal ligament extends through the distal margin of the ligament. The corresponding reformatted frontal CT contrast arthrography image (B) shows contrast entering the lesion in the lateral cranial tibial meniscal ligament (arrow). No contrast is present in the lesion in the medial meniscus and medial cranial tibial meniscal ligament. A sagittal proton density fat saturated MR image (C) demonstrates that the tear in the medial meniscus (arrowheads) extends from the cranial horn to the caudal horn. However, it does not extend through any of the superficial surfaces of the meniscus which would allow communication with the contrast in the joint. Therefore, the lesion in the medial meniscus and medial cranial tibial meniscal ligament is not visible using CT contrast arthrography.
extension, can be done without excessive anesthesia time.

Understanding the science and physics behind MRI is a daunting but necessary task for anyone interpreting MRIs. Although MRIs provide us unparalleled information about soft tissue and osseous abnormalities, there is always a trade-off. That trade-off is that the images are produced by a complicated modality with numerous artifacts. Artifacts that directly affect image interpretation occur commonly in this modality because of the method in which the images are acquired. They are present in every study, regardless of the system, high or low field, used to acquire them. Multiple sequences are used in a MR study to provide the most precise characterization of an injury. Although the increased characterization of an injury obtained with MRI is a remarkable advantage, the process of making that assessment requires understanding and comparison of the different sequences. A thorough understanding of MRI physics is necessary for artifact detection and accurate image interpretation. Image interpretation requires a comprehensive knowledge of MRI, anatomy, and the clinical presentation of the horse.

MRI is an excellent diagnostic tool, but it is important to understand the uses, strengths, and limitations of this imaging modality. A thorough knowledge of the science behind MR imaging will ensure accurate interpretation and diagnosis. Although many injuries can be accurately diagnosed using both high- and low-field MR systems, certain structures and lesions are better characterized with a high-field system. Furthermore, 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.

7. Summary
The importance of the clinical examination of lame horses cannot be stressed enough. The use of diagnostic techniques must be predicated by a thorough examination. If the problem causing the lameness can be localized, additional imaging techniques will be more effective in arriving at a definitive cause. Imaging of some type is used on virtually every significant injury or lameness in horses. Although conventional radiography still provides the basis for bone imaging, its limitation regarding soft tissue diagnosis and subtle osseous lesions allows the alternate modalities to play an important role in diagnosis and prognosis. Scintigraphy has augmented radiographic diagnosis to the level that a negative radiograph does not rule out bone involvement. MRI has already had a profound effect on lameness diagnosis. Lameness diagnosis, as it was known in horses, is currently being rewritten primarily because of the new technologies and advancements in diagnostic imaging.

References