Abstract

MRI of the distal limb is a feasible technique in the standing horse. The procedure has proven useful in the evaluation of undiagnosed foot lameness. Motion correction software allows imaging of the fetlock, carpus, and tarsus.

1. Introduction

Magnetic resonance imaging (MRI) uses the body's natural magnetic properties to produce detailed images of the tissues. The part of the limb being imaged is placed within a strong magnetic field and subjected to radiofrequency pulses. A unique radiofrequency signal, based on each tissue's magnetic characteristics, is emitted in response to the pulses; these radiofrequency pulses are collected to form the image [1,2]. Magnetic resonance signal intensity varies widely in different musculoskeletal tissues because of differences in the proton density and the status of the chemically free versus chemically bound molecular water [1]. Most diseases manifest themselves by an increase in water content, and therefore, MRI is a sensitive test for the detection of disease. The high soft-tissue contrast afforded by MRI makes it ideal for assessment of articular cartilage, ligaments, tendons, joint capsules, synovium, and bone marrow [3,4]. MRI has proved to be extremely valuable in the evaluation of the musculoskeletal system in man and is also being increasingly used in small animals. Preliminary observations suggest that it will be just as useful in the horse [4-15]. While many of the early reports of MRI in horses are based on cadaver studies, clinical use of the technique is currently being undertaken at several centers [2,16-20]. However, the use of MRI in equine orthopaedics is currently very limited because of the expense, availability, and logistical problems associated with performing the procedure on large animals. Open and cylindrical MRI scanners designed for human use require that the horse be placed under general anesthesia to image the limb. This adds additional risk (with the use of general anesthesia) and expense to the procedure.

Recently, an open MRI scanner [a], designed specifically for imaging the distal limbs of the standing horse has been developed. The first scanner of this type was installed at the Bell Equine Veterinary Clinic and has been in clinical use since June 2002 [21]. Since that time, over 60 horses have been scanned. Although the scanner is designed to image up to the level of the carpus and tarsus, most of these initial scans have concentrated on the feet. The purpose of this paper is to describe the system and scanning procedure and to review the details of 40 horses with foot lameness that have been examined using this system.

2. Materials and Methods

The Equine MRI Limb Scanner

The MRI scanner [a] consists of a "U"-shaped 0.21-tesla permanent magnet, mounted on a frame that is moved using electric motors (Fig. 1).

There are 20 cm of space available between the poles of the magnet, and the imaging volume is approximately a sphere of 12
cm diameter located at the center. Movable elements in the floor allow the magnet to be positioned around the foot, and the height is adjustable up to the level of the carpus/tarsus. The system uses Windows NT-based software (also used in human MRI systems) to control the scans and display the images. The system is installed in a purpose-built building, incorporating the necessary radiofrequency (RF) shielding and temperature control.

Scanning Procedure - The Foot
In most horses, the foot can be kept still for long enough to permit image acquisition in the standing patient without the need for motion correction software. The patient is positioned in specially designed stocks and sedated before bringing the magnet into position. Sedation is currently achieved by a combination of romifidine [b] (0.04 mg/kg, IV), butorphanol [c] (0.02 mg/kg, IV), and acepromazine [d] (0.02 mg/kg, IV). "Top-up" sedation is administered as required during the scanning procedure. After sedation, the receiver RF coil is fitted around the foot, and the magnet is moved in and around the leg so that the foot is central. Pilot sequences (taking around 15 s) are used to check positioning, to correct for any lateral axis deviation, and to set the position and angle of subsequent scans.

The current protocol for routine scanning of the foot uses three-dimensional (3-D) T1 (repetition time [TR] 40, echo delay time [TE] 7, flip angle 60°), multislice T1 (TR 120, TE 7, flip angle 90°), and T2* (TR 200, TE 18, flip angle 40°) weighted images in three planes. Short T1 inversion recovery (STIR) (fat suppressed) images are included in certain situations, especially if bony pathology is suspected.

3-D T1-weighted images imaging 32 x 4-mm slices are taken in sagittal and transverse planes to survey the foot. Multislice T1 and T2* images (slice thickness, 5 mm) are then taken of the area of interest in at least three planes (sagittal, transverse, and frontal planes relative to the hoof-pastern axis). Three millimeter slices can also be acquired if deemed appropriate. Each image sequence takes between 2.5 (T1 multislice) and 4.5 min (T2* and 3-D images). Generally, the entire scan protocol takes between 60 and 120 min to scan both front feet or both hind feet. Images are viewed during the procedure, and repeat scans taken to confirm the presence of any suspected lesion.

Scanning Procedure - The Distal Limb Proximal to the Foot (Motion Compensation)
In most cases, scanning the limb proximal to the foot requires the manipulation of the acquired data to compensate for motion of the limb. Before the scan, a very rapid, low-resolution navigator image is collected in the transverse plane (parallel to the floor), and a small, high contrast region of this image is identified manually. The main data acquisition consists of a series (8 or 16) of rapid T1 or T2*-weighted multislice gradient echo images taken at an arbitrary oblique angle, each preceded by a repeat of the transverse navigator scan. Software within the scanner uses the selected high contrast region of the navigator scan to detect and measure movement in the transverse plane; it then calculates the through slice component according to the main image orientation and adjusts the slice position accordingly. Thus, provided that the horse does not move in the second or so between the low-resolution navigator and the high-resolution data collection, the part of the limb imaged in each slice will be the same. The resulting scans will be suitable for averaging.

The post-processing step to correct in-plane motion operates in a similar way to the navigator position detection. First, the high resolution, low signal:noise ratio images with negligible motion are selected manually (an automatic algorithm is under development). One is arbitrarily selected as a reference image. Then, for each of the other (target) images, a small sub-image is compared with the reference image and moved in plane to minimize the sum of squares difference. At the position of best fit, one or more pixels from the target are transferred to the destination image. This process is repeated for sufficient sub-images to cover the entire image plane and for each of the selected images, successively adding pixels to the destination image (Fig. 2).

As currently implemented, the data collection for each sub-image is only sensitive to motion for a period of 20 - 30 s. It has proved feasible to keep the fetlock, carpus, and hock still for a sufficient number of these 20- to 30-s periods within a 4- to 5-min imaging time to produce high quality motion corrected final images.

Clinical Cases
Forty horses with unilateral or bilateral forefoot lameness were examined using MRI as described above. The horses were of mixed age, breed, and use. They included 35 horses (group 1) where pain was localized to the foot by regional analgesic techniques but where no specific diagnosis had been reached using conventional diagnostic procedures. Five horses (group 2) had a history of unresolved lameness after a penetrating foot wound.

All horses in group 1 were examined by a routine clinical examination with assessment of the gait in straight lines and in
circles on the lunge on a hard surface. Lameness was graded on a scale of 0 - 10 (0 = sound; 1 - 3 = mild; 4 - 6 = moderate; 7 - 9 = severe; 10 = non-weight-bearing). Local analgesic techniques included perineural analgesia at either palmar digital and/or abaxial sesamoid levels in all horses. Intra-articular analgesia of the distal interphalangeal joint and intra-thecal analgesia of the navicular bursa was performed in selected cases using standard techniques. Standard radiographic examination (minimum of lateromedial, dorsoproximal-palmarodistal oblique views of the navicular bone and distal phalanx, and palmaroproximal-palmarodistal oblique views) of the feet was performed in all cases. Diagnostic ultrasonography of the deep digital flexor tendon (DDFT) was performed in 10 horses using the palmar aspect of the pastern, the bulbs of the heel, and the frog [22,23]. Nuclear scintigraphy (bone phase) [24] was performed and assessed subjectively in five cases. The five horses in group 2 had a history of persistent lameness of at least 7 days duration after a penetrating injury to the frog or frog sulcus. In each case, standard investigative procedures, including synoviocentesis and contrast radiographic studies (arthrography, bursoscopy, and/or fistulography), showed no evidence of synovial cavity involvement.

3. Results
The 35 horses in group 1 included 12 Thoroughbred or Thoroughbred-crosses, 8 Warmbloods, 7 ponies, 4 Irish Drafts, 3 Cobs, and 1 Quarter Horse. The mean age was 10.3 yr (range = 5 - 16 yr), and their uses included general use (16), eventing (7), show jumping (5), racing (4), polo (1), pony club activities (1), and Western riding (1). The duration of lameness varied from 1 to 11 mo, and the severity of lameness varied from 1 of 10 to 8 of 10. The lameness was unilateral in 15 horses and bilateral in 20 horses.

Lesions identified by MRI in the group 1 horses are summarized in Table 1. Lesions considered to be of significance were detected in 30 of 35 horses (85.7%). In many horses, more than one lesion was identified in each foot.

<table>
<thead>
<tr>
<th>MRI Lesion</th>
<th>Number</th>
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<tbody>
<tr>
<td>Deep digital flexor tendon damage</td>
<td></td>
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<tr>
<td>Insertional damage</td>
<td>5</td>
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<tr>
<td>Dorsal border damage</td>
<td>4</td>
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<tr>
<td>Core lesion</td>
<td>3</td>
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<tr>
<td>Sagittal tear</td>
<td>2</td>
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<tr>
<td>Thinning of tendon</td>
<td>3</td>
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<tr>
<td>Navicular bone/bursa changes</td>
<td>5</td>
</tr>
<tr>
<td>Navicular collateral ligament damage</td>
<td>3</td>
</tr>
<tr>
<td>Distal sesamoid impar ligament changes</td>
<td>2</td>
</tr>
<tr>
<td>Distal interphalangeal joint collateral ligament enlargement</td>
<td>8</td>
</tr>
<tr>
<td>Distal interphalangeal joint distension</td>
<td>2</td>
</tr>
<tr>
<td>Sesamoidean ligament damage</td>
<td>2</td>
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<tr>
<td>No abnormalities detected</td>
<td>5</td>
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</table>

Fourteen horses in group 1 (40.0%) had lesions or abnormalities of the DDFT. These horses included six Thoroughbred or Thoroughbred-crosses, four Warmbloods, one pony, one Quarter Horse, one Cob, and one Irish Draft. The mean age of these horses was 9.9 yr (range = 5 - 15 yr), and their uses included eventing (5), show jumping (3), general use (4), pony club activities (1), and Western riding (1). The duration of lameness ranged from 1 to 5 mo, and the severity of lameness varied from 1 of 10 to 6 of 10. Eleven horses had unilateral lameness (right front in 5 horses, left front in 6 horses), whereas 3 horses were bilaterally foreleg lame. The results of regional analgesic techniques were inconsistent, although not all of the techniques were applied to all cases. The lameness showed a significant (>75%) improvement after palmar digital nerve block in 6 of 12 horses, and the lameness was abolished by abaxial sesamoid nerve block in the remaining eight of eight horses. Analgesia of the distal interphalangeal joint resulted in a significant improvement in the degree of lameness in seven of seven horses, and analgesia of the navicular bursa resulted in a significant improvement in one of three horses. Standard radiographic views of the feet were obtained in all horses. No significant radiological abnormalities were detected in 9 of 14 horses. Radiological changes, considered of “equivocal” significance, were found in 5 of 14 horses. Ultrasonographic changes involving the DDFT were identified in only one of seven horses. Nuclear scintigraphy was performed in four horses; abnormalities in the lame foot were identified in two of these cases (increased radiopharmaceutical uptake in the navicular bone in one horse and the distal phalanx in one horse). Lesions within the DDFT were identified by MRI in both T1-weighted and T2*-weighted sequences. Four different types of DDFT lesions were identified: core lesions (Fig. 3), sagittal splits (Fig. 4), dorsal border lesions (Fig. 5), and insertional lesions (Fig. 6).
Combinations of these different forms of lesions were common. Three horses had abnormal thinning of one or both lobes of the DDFT. One of these horses was re-examined because of a marked deterioration in the degree of lameness 4 mo after the initial scan. Rupture of the DDFT with subluxation of the distal interphalangeal joint was identified at this time (Fig. 7).

Eleven horses in group 1 had changes affecting the navicular bone (including abnormal signal within the bone, roughening of the flexor border, modeling and irregular proximal and distal borders, and enlarged synovial invaginations along the distal border). Such changes were found either alone or in association with soft tissue changes in the foot. Enlargement and synovial proliferation of the navicular bursa were also identified in some of these horses. Changes affecting other soft tissue structures within the foot included enlargement and abnormal signal in the distal sesamoid impar ligament (3), collateral ligament of the navicular bone (3) (Fig. 8), and collateral ligament of the distal interphalangeal joint (2).
The horses in group 2 included three Thoroughbred or Thoroughbred-crosses, one Cob, and one pony. Their ages ranged from 5 to 12 yr, and their uses included general purpose riding (3), show jumping (1), and racing (1). All five horses had had penetrating injuries to the frog or frog sulcus. The left fore was affected in four horses, and the right fore was affected in one horse. In all cases, standard investigative procedures showed no evidence of sepsis of the navicular bursa, distal interphalangeal joint, or digital tendon sheath. The duration of lameness ranged from 7 days to 5 mo. The degree of lameness ranged from 1 of 10 to 6 of 10. On MRI, all five horses had abnormal morphology and signal involving the DDFT and surrounding tissues from the level of its insertion onto the distal phalanx to the distal region of the navicular bone. The DDFT lesions consisted most commonly of thickening of one or both lobes and areas of hyperintensity (Fig. 9). Roughening of the dorsal border was commonly observed. The tract of the penetrating wound was identified within the frog and cluneal part of the digital cushion in four horses (Fig. 9). Thickening and abnormal signal of the distal sesamoid impar ligament was identified in three cases. In one horse, a low signal (black) area was present in both T1-weighted and T2-weighted images involving the DDFT and tissues palmar to it (Fig. 10).

4. Discussion
Optimization of the equine limb MRI scanner is still in progress, but to date, it has proved capable of producing diagnostic images of the foot and fetlock of standing horses. Its use in other regions of the distal limbs is currently being evaluated. The motion correction mechanism has been shown to be effective, but further modification of the system is currently being undertaken. We believe that this technique could revolutionize the assessment of certain musculoskeletal lesions of the distal limb. The ability to perform MRI in the standing equine patient using the open "U"-shaped magnet is a considerable advantage over conventional closed magnets that require general anesthesia. However, the open magnet is, by necessity, of lower field strength than many human closed magnets. Lower field strength results in a lower signal-to-noise ratio, and this, in turn, results in lower resolution or longer imaging times for the same resolution as a higher strength magnet [2,25]. Imaging time needs to be kept as short as possible because of the risks of movement in the standing horse; however, it must be long enough to acquire images of adequate resolution. The system described here seems to achieve this goal. Image contrast-to-noise ratio (the ratio of image intensity difference between two tissues and background noise) tends to be higher at lower field strengths [26]. Although it is generally accepted that image quality is determined by the signal-to-noise ratio, the contrast-to-noise ratio may be more relevant clinically for distinguishing one tissue type from another (i.e., general lesion detectability) [26]. In addition to permitting use in standing horses, low-field open magnets also have considerable advantages to the veterinary profession in terms of lower initial cost, lower operating costs, and lack of necessity to employ cryogens [15,25]. We believe that this system will allow the application of MRI technology in general equine practice, which would be unlikely with higher field closed magnets because of their inherently higher cost.

MRI has many advantages over other conventional imaging techniques, including radiography, ultrasonography, nuclear scintigraphy, and computed tomography (CT). MRI does not use ionizing radiation and provides multiplanar, 3-D imaging capabilities. Both bone and soft tissues can be imaged simultaneously. In addition, MRI allows assessment of physiological differences between normal and abnormal tissues by use of various imaging sequences. Although CT can be used to evaluate...
bone and soft tissues, soft tissue contrast in CT is inferior to MRI [27,28]. Interpretation of MRI images requires knowledge of magnetic resonance physics, normal anatomy, and characteristic findings in abnormal tissues [29]. For example, each examination of the front or hind feet in a horse can generate over 100 images, and a comprehensive understanding of foot anatomy is required to mentally visualize normal and abnormal structures within the 3-D space.

The signal intensities seen in images obtained with this system resemble those reported previously for low-field MRI of the equine tarsus [15]. Our standard imaging protocol includes 3-D T1-weighted sagittal images, 3-D T1-weighted transverse images, and multislice T1-weighted and T2*-weighted transverse images. Multislice T1- and T2*-weighted frontal plane images and STIR sequences are used if deemed necessary. Frontal view slices are particularly helpful in the foot to image the distal border of the navicular bone and the distal sesamoid impar ligament. The T1-weighted imaging provides the best anatomical detail and is considered to be the standard accepted sequence for baseline information of the musculoskeletal system [13]. T2*-weighted images are particularly useful for evaluating synovial structures. Synovial fluid has a high signal intensity, which appears bright white on the image. The TE of T2*-weighted images is longer than T1-weighted images, and therefore, there is a lower signal-to-noise ratio, which results in a more grainy image. They are, therefore, less useful for studying fine anatomical features. However, T2*-weighted images can be more helpful in identifying disease processes than T1-weighted images. The STIR sequence is a fat suppression technique that reduces the interference from the fat signal, thereby allowing the identification of medullary fluid.

Magnetic resonance imaging is particularly sensitive to movement during the data acquisition. Because data relating to the entire image is collected throughout the scan, significant movement at any time during the scan can render the entire image set non-diagnostic (Fig. 2). Scan time can be shortened to a few seconds but only at the expense of the image signal:noise ratio, again rendering individual images non-diagnostic. Successive rapid images can be averaged together to improve the signal:noise ratio, but if there is movement between scans, the final image still lacks resolution (Fig. 2). MRI images relate to scans through thin (1 - 5 mm) slices of tissue. If there is movement in the slice direction, successive scans cannot be averaged, because they correspond to different parts of the limb under examination.

A free-standing, heavily sedated horse moves to such an extent that standing MRI requires some form of motion compensation to collect diagnostic images above the foot. The horse tends to exhibit four distinct movement patterns over a period of time. First, an unrestrained horse tends to sway in both the cranial/caudal and lateral directions within a period of about 6 s, pivoting about the distal joints. At the level of the carpus/tarsus, such sway is ± 20 mm, with considerable variation between individuals. This sway can largely be eliminated if the horse is gently supported by appropriately designed stocks. Second, with the sedation protocol currently being used, there are periods of trembling that usually occur within the first few minutes of sedation and then decline. Third, there are short, sudden movements when the horse readjusts its weight balance, after which the horse does not necessarily return to the original position and on occasion may move completely out of the magnet. Finally, with manual support of the leg in the scanner and sensitive handling of the horse's head, there are considerable periods when the leg barely moves.

We have developed techniques that take advantage of the periods of negligible movement to collect a series of rapid MRI, correcting in real-time for through slice motion between acquisitions. We have also developed a method for averaging the resulting low signal:noise ratio images, which corrects for arbitrary in-plane movement including rotations and small degrees of articulation within a joint that would cause standard image registration techniques to fail.

The location and appearance of the DDFT lesions identified in the present study were similar to those reported previously using conventional MRI scanners [17-20]. Focal lesions were usually confined to either the medial or lateral lobes, and they rarely affected both lobes as is reported by others [18-20]. Core lesions, sagittal full-thickness splits, dorsal border erosions, and insertional lesions were all identified as described previously [18-20]. Lesions most commonly extended along the proximodistal length of the navicular bursa but were sometimes restricted to the distal insertion of the DDFT or extended up into the pastern region [17-20].

Other soft tissue lesions, including damage to the distal sesamoid impar ligament, the collateral ligament of the navicular bone, and the collateral ligaments of the distal interphalangeal joint were also identified using this system. In addition, changes to the navicular bone and navicular bursa can be identified, although the significance of some of these findings remains uncertain at present. These findings indicate that the standing system is capable of producing diagnostically acceptable images, although direct comparisons with high-field conventional MRI scanners have yet been undertaken. The technique proved particularly helpful in assessing horses with persistent lameness after a penetrating injury to the frog or frog sulcus (group 2 horses). Penetrating foot wounds can be classified according to their depth and location [30]. Type II wounds penetrate the corium deep to the frog and may result in septic deep digital flexor tendonitis, septic navicular bursitis, distal interphalangeal joint septic arthritis, septic tenosynovitis of the digital sheath, abscess of the digital cushion, septic osteitis of the distal phalanx or navicular bone, or fractures of the distal phalanx. Plain radiography, radiography with a sterile metal probe placed in the tract, and contrast radiography are commonly used techniques to assess the direction and depth of the penetration and to investigate the involvement of vital structures (primarily the synovial structures) [31]. However, these techniques are relatively ineffective in identifying DDFT damage distal to the level of the digital sheath. Septic tendinitis of
the DDFT is one of the potential reasons why horses with such penetrating wounds may fail to return to soundness, even after appropriate treatment of synovial sepsis [30-32]. The accurate identification of DDFT lesions in such cases should greatly help in dictating the most appropriate treatment and in determining the prognosis. DDFT lesions within the foot have not been reliably diagnosed in the live horse before the advent of MRI scanning. The DDFT within the foot can be imaged using diagnostic ultrasonography and performed through the axial midline of the frog; [22,23] however, this technique often fails to identify subtle tendon lesions, because it is not possible to position the transducer perpendicular to the tendon fibers. DDFT lesions located just proximal to the navicular bone are in an area that is inaccessible for ultrasonographic evaluation through the frog. Lesions occurring at the level of the navicular bone will only be seen by ultrasonography if they lie in the midline; lesions that are confined to either the medial or lateral lobe of the DDFT (which includes the majority of such tendon lesions) will not be imaged. Ultrasonographic imaging of the DDFT through the distal pastern is possible, but the direction of the fibers in this region makes it difficult to identify pathological change. Consequently, it is impossible to give an informed prognosis on the likelihood or time scale of healing if the lesion cannot be imaged. Treatment protocols generally include box rest and remedial farriery, but a guarded prognosis must be given for return to soundness. In cases associated with a penetrating injury, the possibility of septic tendinitis should be considered, and surgical debridement of the infected tissue may be indicated [30,33]. At the present time, there is insufficient information available to know whether or not MRI could be used to distinguish septic from aseptic tendinitis in horses. In the cases described here, treatment included superficial debridement of the wound and systemic antimicrobial therapy; no surgical debridement of the tendon lesions was attempted, and it is uncertain whether these were septic or not. At the time of writing, all five horses have shown a satisfactory short-term recovery, but the long-term outcome is still uncertain.

We have shown that MRI of the distal limbs of standing horses is possible using this system. Imaging the feet is technically easy, and both front feet can be imaged in approximately 1 - 2 h. Movement correction features have been shown to be effective and are currently being evaluated; these will allow more proximal structures to be assessed. The system has already been used to image the fetlocks, carpus, and hocks in a number of horses. MRI is not considered to be a screening tool. For optimal results, the imaging should be focused on specific structures or regions as determined by previous clinical examinations, including the use of regional analgesia and other imaging modalities where appropriate. Optimal imaging sequences and parameters still need to be determined for the different orthopedic applications, but it is likely that this system will find an increasing number of applications over the next few years.

Footnotes
[a] Equine Limb MRI Scanner, Hallmarq Veterinary Imaging, Guildford, UK.
[b] Sedivet, Boehringer Ingelheim, Bracknell, UK.
[c] Torbugesic, Fort Dodge, Southampton, UK.
[d] ACP, C-Vet Veterinary Products, Leyland, UK.

References


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