

Use of a novel helical fan beam imaging system for computed tomography of the distal limb in sedated standing horses: 167 cases (2019–2020)

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OBJECTIVE

To evaluate the diagnostic capabilities of a novel helical fan beam CT system used for imaging of horses with a range of clinical distal limb problems.

ANIMALS

167 horses.

PROCEDURES

Medical records were reviewed of horses presented for CT of the distal limb at 2 university-based veterinary hospitals. The following data were recorded: age, sex, breed, presenting complaint, sedation used for imaging, scanning time, procedure time, other diagnostic imaging methods performed, imaging diagnosis, clinical diagnosis, and complications during imaging.

RESULTS

Most horses were Thoroughbreds and Quarter Horses. Procedure times ranged from 15 to 40 minutes, with scanning completed in 15 to 45 seconds for each region of interest. The foot or pastern region was commonly scanned (88/167 [53%] horses), with navicular bone disease diagnosed in 42 of 88 (48%) horses. The fetlock region was also commonly scanned (42/167 [40%] horses), with palmar or plantar osteochondral disease diagnosed in 17 of 42 (40%) horses. Horses were compliant during scanning, and no complications with sedation or damage to the scanner occurred. A specific imaging diagnosis for the lameness was achieved more frequently with CT imaging (166/167 [99%]) than with planar digital radiography (26/58 [45%]).

CLINICAL RELEVANCE

The helical fan beam CT system could be used safely to scan sedated standing horses from the carpal or tarsal region distally. Subjectively, the machine was easy to operate, allowing CT to be incorporated into lameness investigations. CT imaging was very likely to result in a clinical diagnosis in horses with distal limb lameness.

Use of nuclear scintigraphy and low-field MRI in sedated standing horses has revolutionized clinical practice over recent decades, but use of CT in such situations remains limited. In human medicine, CT is considered the best modality for investigation of many orthopedic injuries, such as evaluation of complex fractures. However, use of CT in horses with orthopedic problems has been limited owing to the need for general anesthesia, which adds expense and time and requires additional personnel. General anesthesia also has associated morbidity and mortality risks that must be considered.^{1–4}

CT imaging of the head of sedated standing horses has been evaluated in several studies,^{2,5–11} but studies involving CT imaging of the distal limbs have been

more limited.^{3,12–14} A modified quantitative CT scanner has been used to image the equine foot, but clinical applicability was limited.² Cone-beam volumetric imaging has also been used for distal limb scanning.^{3,4,14,15} However, the entire imaging study is affected if the patient moves during image acquisition, and cone-beam imaging is more likely to result in streaking artifacts, scatter and noise artifacts, and image distortion, compared with helical fan beam CT.^{3,4,15,16}

Helical CT systems developed for imaging of human patients can be used in standing horses. For instance, a helical fan beam system installed over a platform has been used to scan the distal limbs of horses.¹³ However, only 1 limb could be scanned at a time, and the limb was in a partial non-weight-

bearing position.¹³ Recently, a novel multislice helical fan beam CT scanner (Equina system; Asto CT Inc) was developed with a sliding gantry that can be tilted from 0° to 90° for horizontal or vertical scanning. The CT system was specifically designed to be used for scanning the head and neck and distal limbs of horses. For limb scanning, imaging from the foot to the distal portion of the radius or tibia, including the carpal or tarsal region, can be performed on both limbs simultaneously. Clinical use of this CT system for imaging of the head and neck in horses is described elsewhere.¹⁷ However, an assessment of its use for imaging of the distal limbs has not been published previously.

The objective of the retrospective study reported here was to evaluate the diagnostic capabilities of the Equina system when used for imaging of horses with a range of clinical distal limb problems.

Materials and Methods

Animals

Equine patients with a complaint related to the distal limb that were presented for CT imaging with the Equina system at the University of Wisconsin-Madison Morrie Waud Large Animal Hospital between January 2019 and December 2020 or at the University of Melbourne Equine Centre between January 2019 and June 2020 were included in the study. The following data were recorded for each horse: age, sex, breed, presenting complaint, sedation used for imaging, other diagnostic procedures, imaging diagnosis, clinical diagnosis, and imaging complications. Initially, lameness localization was performed by a referring equine veterinarian, specialist in equine surgery, or specialist in equine sports medicine through a lameness examination and regional anesthesia, as appropriate. Lameness locations were classified as foot and pastern region, fetlock region, metacarpal or metatarsal region, or carpal or tarsal region. For horses with clinical evidence of multilimb lameness, multiple sites were scanned. In addition, for some horses with lameness affecting a single limb, multiple limbs were scanned.

CT scanning procedure

The Equina scanner was a fixed, 24-slice, helical fan beam CT machine with a 240 V, single-phase, 30 A, uninterruptible power supply. Scanning was performed with an exposure of 160 kVp and 8 mA at 1 second for each 360° revolution; there were 24 detector rows with a variable helical pitch, typically 0.55. Slice acquisition rate was 36 slices/s with an image acquisition matrix of 1,024 X 1,024 and a resolution at isocenter of 0.75 mm. Maximum vertical scanning distance was 75 cm at 2 cm/s. No scout images were required, and the gantry bore diameter was 75 cm with a field of view of 75 cm. Bone and soft tissue reconstruction algorithms were available. On the basis of principles that were as low as reasonably achievable, personnel with protective radiation shielding and dosimeters were allowed to stay in the

room during scanning to optimize horse handling, as determined by the regional radiation safety office. Window width and level were adjusted by reviewers as needed to optimize image evaluation.

Horses were sedated with acepromazine (0.03 mg/kg, IM) about 30 minutes before scanning. Horses were then given a bolus of detomidine (0.01 to 0.02mg/kg, IV) immediately before they were led into the CT room. Butorphanol (0.01 mg/kg, IV) was also given if deemed necessary. Additional IV boluses of detomidine were administered to maintain sedation as needed. Cotton earplugs and a blinker hood were placed, and room lighting was dimmed during scanning if necessary.

For limb scanning, the CT system was used to scan both thoracic or both pelvic limbs in a weight-bearing position (**Figure 1**). Sedated horses were



Figure 1—Photograph of the setup used for imaging of the distal pelvic limbs in a horse with a novel helical fan beam CT system. A sedated horse is positioned on the bore pedestal of the system during scanning. The gantry is then raised from the floor to the desired level, and scanning is performed from proximal to distal. Photograph courtesy of Dr. Chris Whitton.

walked across the scanner gantry, which was recessed into the floor, and positioned on the bore pedestal. The gantry was then mechanically raised with the robotic system to the appropriate level to scan the lameness location from proximal to distal. The number of scans needed was recorded. Scans were evaluated by a board-certified radiologist or equine surgeon for diagnostic quality, and scanning was repeated if needed. Once scanning was completed, the gantry was fully recessed into the floor, and the horse was returned to the hospital stall for recovery.

For studies involving IV regional perfusion of contrast medium, a precontrast CT scan was performed. A regional nerve block was then performed proximal to the region to be examined. An Esmarch tourniquet was placed proximal to the catheter site, and a site over the palmar or plantar digital vein or saphenous or cephalic vein was aseptically prepared, depending on whether lower or upper IV regional limb perfusion was needed. A 21- to 23-gauge butterfly needle was placed in the vein and secured with tape to the skin, and an extension set was attached. Undiluted iohexol (240 mg of iodine/mL;

Omnipaque) was then slowly infused manually. A volume between 24 and 40 mL was injected depending on the anatomic site of interest over a 3- to 5-minute period. CT images were obtained immediately after contrast injection with the Esmarch tourniquet in place and again after tourniquet removal. The catheter was removed after the procedure, and a compression bandage was applied.

For studies involving intrasynovial administration of contrast medium, a precontrast CT scan was performed. A regional nerve block was then performed, with the location of the block depending on the joint to be injected. The injection site was aseptically prepped, and a 20-gauge needle was inserted into the joint. An extension set was attached, and undiluted iohexol was slowly infused manually. The injected volume varied depending on joint size, but injection was continued until distension and slight back pressure was felt. After contrast injection was completed, passive manipulation of the joint was performed to disperse the contrast medium, and CT images were acquired immediately. After imaging, a compression bandage was applied.

For each horse, the total number of scans and lameness location were recorded. Once a diagnostic-quality scan was obtained, a board-certified veterinary radiologist evaluated multiplanar reconstructions with image viewing software (Intellispace; Koninklijke Philips NV) and assigned an imaging diagnosis.

Radiography and ultrasonography

Digital radiographs of the lameness location were obtained in a subset of horses, as deemed clinically appropriate on the basis of the presenting complaint. A standard approach for radiographic examination (Varex Imaging with Canon film or Toshiba Model DS-PB with Fuji film) was used, with multiple views obtained (dorsopalmar or dorsoplantar, craniocaudal, lateromedial, dorsoproximal-palmarodistal oblique at 65° to the standing surface, palmaroproximal-palmarodistal oblique at 45° to the standing surface, dorsomedial-palmarolateral or dorsomedial-plantarolateral oblique at 45° to the standing surface, and dorsolateral-palmaromedial or dorsolateral-plantaromedial oblique at 45° to the standing surface), depending on the region of the limb imaged. For each region, a minimum of 4 standard views were obtained.

An ultrasonographic examination (Logiq E Vet machine; GE Healthcare; MyLab 70XVision; Esaote SpA) was performed after CT imaging for some horses with soft tissue injuries. The examination was performed by a board-certified veterinary radiologist or equine sports medicine specialist. A standard approach was used, and both longitudinal and transverse images were obtained.

All images were evaluated by a board-certified veterinary radiologist, who assigned a radiographic or ultrasonographic diagnosis. Horses were sedated with a combination of detomidine (0.01 to 0.02 mg/kg, IV) and butorphanol (0.01 mg/kg, IV) for these examinations.

Data analysis

Descriptive statistics (median, mean, range, and percentages) were generated with a commercially available spreadsheet program (Excel; Microsoft Corp). A clinical diagnosis was assigned on the basis of all findings, including results of clinical and lameness examinations

and diagnostic imaging. For each imaging method, the percentage of cases for which an imaging diagnosis was determined was calculated. Agreement between radiographic and CT imaging diagnoses was also determined.

Results

Animals

During the study period, 167 horses underwent standing CT scanning of the distal limbs and met the study criteria. Breeds represented included Thoroughbred (n = 50), Quarter Horse (47), Warmblood (29), Paint Horse (14), Arabian (4), stock horse (3), Standardbred (3), Morgan (3), Friesian (2), Appaloosa (2), grade horse (2), Clydesdale (2), Percheron (1), Pony (1), Peruvian Horse (1), Saddlebred (1), Andalusian (1), and Missouri Fox Trotter (1). There were 94 geldings, 58 mares, and 15 stallions; mean age was 9.1 years (range, 1 to 27 years). Standing CT scanning was performed for the following reasons: lameness (n = 141), fracture or suspected fracture (9), foot abscess (7), trauma or a wound (3), poor performance (3), keratoma (2), quitter (1), and suspected tendon injury (1).

CT imaging procedure

One hundred thirty-six of the 167 (81%) horses were sedated with a combination of acepromazine IM and detomidine IV for CT imaging. Seven (4%) horses were sedated with a combination of acepromazine IM, butorphanol IV, and detomidine IV. The remaining horses were sedated with a combination of butorphanol IV and detomidine IV (11/167 [7%]) or were not sedated (13/167 [8%]).

A total of 175 CT scans were acquired; 159 of the 167 (95%) horses had only a single lameness location scanned, and 8 had multiple locations scanned. For the horses in which multiple locations were scanned, the most common scenario was CT imaging of all 4 fetlock regions (5 Thoroughbreds). Three of these 5 horses were scanned because of multilimb lameness and poor performance; the other 2 were presented because of single-limb lameness, and screen of all 4 fetlock regions was performed. For the remaining horses in which multiple locations were scanned, scanning locations consisted of the thoracic limb fetlock and tarsal regions (2 horses) and the carpal region and pelvic limb fetlock region (1). These 3 horses were presented with multilimb lameness and underwent diagnostic imaging of multiple locations on the basis of results of a clinical evaluation.

The time required for scanning was dependent on the location scanned. Procedure times when contrast medium was not used ranged from 15 to 40 minutes, with scanning completed in 15 to 45 seconds for each location. For horses in which contrast studies were performed, procedure times ranged from 40 to 60 minutes. Diagnostic-quality scans were obtained in all instances. Median number of scans was 1 scan/case (mean, 1.8 scans/case; range, 1 to 5 scans/case). Repeated scanning was needed for imaging of proximal locations (metacarpal, metatarsal, carpal, or tarsal region) in 26 horses and for imaging of distal locations (foot, pastern region, or fetlock region) in 13 horses. Multiple scans were needed for 15 carpal and 11 tarsal locations. Reasons for repeated scans were movement of the horse during scanning that created artifacts or incorrect

positioning of the limbs. Procedure and scanning times for repeated scans were similar to those for initial scans.

Patients were imaged without any complications and tolerated the scanning procedure well. Two horses kicked the CT scanner, but no damage to the scanner occurred. No complications with horse sedation or contrast administration were identified.

Clinical diagnosis

Lameness was localized to the foot or pastern region in 88 of the 167 (53%) horses (79 horses with thoracic limb lameness and 9 horses with pelvic limb lameness). Most (42/88 [48%]) of these horses had navicular bone disease (**Figure 2**). Other diag-

noses were foot abscess (8/88 [9%]), a tendon or ligament lesion (6/88 [7%]), fracture of the distal phalanx (5/88 [6%]), keratoma (5/88 [6%]), osteoarthritis (5/88 [6%]), pedal osteitis (4/88 [5%]), quittor (2/88 [2%]), middle phalanx fracture (2/88 [2%]), navicular bone fracture (2/88 [2%]), subchondral bone cyst (2/88 [2%]), effusion of a digital tendon sheath due to sepsis (2/88 [2%]), distal phalanx sequestrum (1/88 [1%]), and osteochondritis dissecans of the palmar aspect of the middle phalanx (1/88 [1%]); in 1 horse, the diagnosis remained open (**Table 1**). Tendon and ligament lesions consisted of deep digital tendinopathy (n = 3) desmopathy of the collateral ligaments of the distal

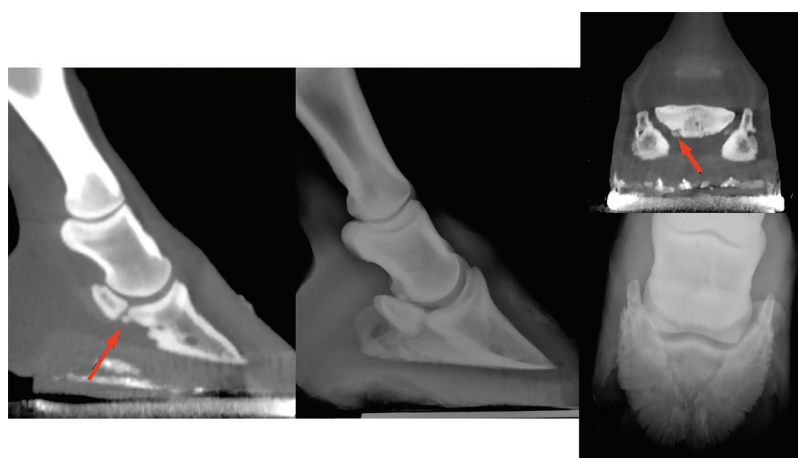


Figure 2—Lateral and dorsoproximal-palmarodistal oblique radiographic views (left) and associated sagittal and transverse multiplanar reconstructed CT images (right) of the right forefoot of a 20-year-old Quarter Horse with changes to the navicular bone. The CT images show fragmentation of the distal border of navicular bone (arrows), which is not visible on the radiographic views.

Table 1—Results of diagnostic imaging for 88 horses with lameness localized to the foot or pastern region.

Clinical diagnosis	No. of cases	Radiographic imaging	Ultrasonographic imaging	CT imaging
Navicular bone disease	42	13/25	0/0	42/42 ^a
Foot abscess	8	4/6	0/0	8/8 ^a
Tendon or ligament lesion	6	0/3	0/2	6/6
Distal phalanx fracture	5	1/5	0/0	5/5
Keratoma	5	1/2	0/0	5/5
Osteoarthritis	5	3/3	0/0	5/5
Pedal osteitis	4	1/3	0/4	4/4
Quittor	2	1/2	0/0	2/2
Fracture of palmar or plantar eminence of middle phalanx	2	2/2	0/0	2/2
Navicular bone fracture	2	0/1	0/0	2/2
Subchondral bone cyst	2	0/2	0/0	2/2
Effusion (septic) of digital tendon sheath	2	0/2	2/2	2/2
Distal phalanx sequestrum	1	0/1	0/0	1/1
Osteochondritic lesions of palmar aspect of middle phalanx	1	0/0	0/0	1/1
Open diagnosis	1	1/1	0/0	1/1
Total	88	26/58	2/8	87/88

For all horses, a clinical diagnosis was assigned on the basis of all diagnostic findings, including results of clinical and lameness examinations and diagnostic imaging. For each imaging method, data represent number of horses in which the diagnosis was made/number of horses that underwent imaging. Radiography and ultrasonographic imaging were not performed in all horses.

^aContrast medium was used in 3 horses.

interphalangeal joint (2), and enthesopathy of the straight sesamoidean ligament (1).

Lameness was localized to the fetlock region in 42 of the 167 (25%) horses (29 horses with thoracic limb lameness and 13 horses with pelvic limb lameness). Palmar or plantar osteochondral disease (POD) was diagnosed in 17 of the 42 (40%) horses, including the 3 Thoroughbred racehorses that underwent fetlock screening because of poor performance (**Supplementary Figure S1**). Other findings in the fetlock region were subchondral bone cyst (10/42 [24%]), condylar fracture (5/42 [12%]), fracture of the proximal phalanx (5/42 [12%]), tendon or ligament lesion (3/42 [7%]), and osteoarthritis (2/42 [5%]; **Table 2**). The ten-

don and ligament lesions were deep digital flexor tendinopathy (n = 1), desmitis of the distal oblique sesamoidean ligaments (1), and superficial digital flexor tendinopathy with manica flexoria involvement (1).

Lameness was localized to the metacarpal (n = 6) or metatarsal (2) region in 8 of the 167 (5%) horses. Proximal suspensory desmitis (3/8) was the main finding. Splint bone fracture (2/8; **Figure 3**), other tendon or ligament injury (2/8), or an exostosis impinging on the proximal suspensory ligament (1/8) were the other findings (Table 2). The 2 tendon and ligament injuries were deep digital flexor tendinopathy and desmitis of the lateral branch of the suspensory ligament.

Table 2—Results of diagnostic imaging for 79 horses with lameness localized to the fetlock region, metacarpal or metatarsal, or carpal or tarsal region.

Clinical diagnosis	No. of cases	Radiographic imaging	Ultrasonographic imaging	CT imaging
Fetlock region				
Palmar or plantar osteochondral disease	17	0/3	0/0	17/17
Subchondral bone cyst	10	0/6	0/0	10/10
Condylar fracture	5	0/1	0/0	5/5
Proximal phalanx fracture	5	0/2	0/0	5/5
Tendon or ligament lesion	3	0/1	3/3	3/3
Osteoarthritis	2	1/1	0/0	2/2
Total	42	1/14	3/3	42/42
Metacarpal or metatarsal region				
Proximal suspensory desmitis	3	0/1	1/3	3/3 ^a ; Two with contrast
Splint bone fracture	2	0/1	0/0	2/2
Tendon or ligament injury	2	0/1	2/2	2/2 ^b ; One with contrast
Exostosis impinging on tendon or ligament	1	0/1	0/0	1/1
Total	8	0/4	3/5	8/8
Carpal or tarsal region				
Fracture of carpal or tarsal bone	8	0/5	0/0	8/8
Subchondral bone cyst	7	0/3	0/0	7/7
Osteoarthritis	6	2/2	0/0	6/6
Subchondral bone disease	5	0/0	0/0	5/5
Sequestrum	2	0/1	0/0	2/2
Joint capsule tear and hemarthrosis	1	0/1	0/0	1/1 ^b with contrast
Total	29	2/12	0/0	29/29

^aContrast medium was used in 2 horses. ^bContrast medium was used in 1 horse.

See Table 1 for remainder of key.



Figure 3—Dorsomedial-palmarolateral oblique radiographic view (left) and associated oblique and transverse multiplanar reconstructed CT images (right) of the fourth metacarpal bone in a 2-year-old Quarter Horse with a fracture fragment remaining after resection of an infected distal splint bone. CT images show the fracture fragment (arrows), which is not visible on radiographs.

Lameness was localized to the carpal or tarsal region in 29 of the 167 (17%) horses. Fracture of the cuboidal carpal and tarsal bones was diagnosed in 8 of these 29 (28%) horses. Other findings were subchondral bone cyst involving the carpal or tarsal bones (7/29 [24%]), osteoarthritis (6/29 [20%]), subchondral bone disease (5/29 [17%]), sequestrum (2/29 [7%]), and hemarthrosis with tearing of the palmar joint capsule (1/29 [4%]; Table 2).

Contrast medium was used in 10 CT studies. Contrast medium was used to identify a draining tract in the foot in 3 of these horses (**Supplementary Figure S2**). IV regional limb perfusion was used to identify a tendon or ligament injury in 5 of the 10 horses, and contrast medium was injected into a joint or tendon sheath in 2 (Tables 1 and 2).

Agreement among imaging methods

Clinical and CT imaging diagnoses were made in 166 of the 167 (99%) horses. A radiographic diagnosis was made in 26 of 58 (45%) horses with a clinical diagnosis of foot or pastern region lameness, 1 of 14 (7%) horses with a clinical diagnosis of fetlock lameness, 0 of 4 (0%) horses with a clinical diagnosis of metacarpal or metatarsal region lameness, and 2 of 12 (17%) horses with a clinical diagnosis of carpal or tarsal region lameness.

There was agreement between the radiographic and CT diagnoses for 29 of the 88 cases for which both radiography and CT imaging were performed. There were no cases in which the radiographic diagnosis disagreed with the CT diagnosis. In the remaining 59 cases, a radiographic diagnosis could not be made after radiography was performed. Differences in identification of structural changes between radiographic and CT images were particularly apparent for tendon and ligament lesions and subchondral cysts in the foot or pastern region (Table 1), subchondral bone cysts and POD in the fetlock region (Table 2), splint bone fracture in the metacarpal or tarsal region (Table 2), and fractures of cuboidal bones in the carpal or tarsal region (Table 2).

An ultrasonographic diagnosis was made in 2 of 8 (25%) horses with a clinical diagnosis of a foot or pastern region lameness, 3 of 3 (100%) horses with a clinical diagnosis of a fetlock region lameness, and 3 of 5 (60%) horses with a clinical diagnosis of a metacarpal or metatarsal region lameness. Ultrasonography was not performed on horses with lameness of the carpal or tarsal region.

Discussion

The present report described use of a helical fan beam CT system in a large population of sedated standing horses, ranging from draft horses to ponies, with diverse clinical problems involving the distal limbs. We were able to scan all 167 horses safely without complications. Compliance of the horses was excellent, and positioning and restraint were comparable to those required for other standing diagnostic imaging procedures.

For the present report, sedation was generally achieved with a combination of acepromazine and detomidine without the use of opioids such as butorphanol. Initially, we found that sedation with opioids increased motion and swaying of the horses, which adversely affected patient positioning and scan quality. This opioid effect has been recognized in other diagnostic imaging studies.^{7,8,11} Because the CT system allows horses to stand in a comfortable, natural position, we were able to scan 13 horses with no sedation at all. Noise generated by the system was minimal during scanning. If earplugs were not tolerated by a horse, background music and dimming of the room lights were used to help calm the horse.

For both patients and personnel, CT imaging produces more radiation than conventional radiography, and cone-beam volumetric imaging systems typically produce more radiation than conventional helical fan beam CT systems.^{16,18,19} Cone-beam volumetric imaging systems use large sensor panels to detect a cone of x-rays generated by an x-ray tube that rotates around the patient. These cone-beam volumetric imaging systems require higher dosages to image thick body parts and still maintain good image quality.^{15,16} With the Equina scanner used in the present report, we found that it took 2 or 3 people to optimize CT scanning, with 1 or 2 people to handle the horse and 1 person to operate the scanner. Personnel wore lead shielding and dosimeters and followed radiation protection principles that were as low as reasonably achievable and approved by the regional office of radiation safety to remain in the CT room during scanning. We believe that the presence of horse handlers minimizes the risk of adverse events and need for repeated scans. As standing CT becomes more widely adopted in equine clinical practice, having a clear understanding of occupational exposure associated with operating a standing equine CT system is critically important. More research is needed to comprehensively evaluate occupational exposure from standing equine CT systems, including the Equina system.

Motion artifact or incorrect positioning were the most common reasons for repeated scanning in the present report. With cone-beam CT systems, motion artifact can be a major challenge.^{1,3,11} In our study, a median of only 1 scan was necessary to complete image acquisition. The need for repeated scans was higher for proximal (26/37 [70%] horses) as opposed to distal (13/130 [10%] horses) limb locations. Including a larger scan region means there is increased opportunity for the horse to move during image acquisition. In general, motion artifacts were minimal because of rapid image acquisition and the comfortable natural stance of the horse. Also, we found that not all reconstructed images were lost if motion occurred during scanning, in contrast to the case with cone-beam systems. A second scan was only needed if motion artifact was present in scan slices of the region of interest.

In our study, the most common indication for CT imaging was lameness localized to the foot or pastern region or to the fetlock region. This was not surprising, in that the distal limb is a common source of lameness in horses.²⁰ CT imaging resulted in a new diagnosis or confirmed an existing diagnosis and refined clinical management in almost all cases (166/167 [99%]). Navicular bone disease was the most common diagnosis for the foot and pastern region, and POD was the most common diagnosis for the fetlock region in this case series. It is well documented that CT imaging is advantageous for investigation of the podotrochlear apparatus, POD, and fractures of the foot and pastern regions, compared with radiography.^{14,21–28} MRI, like CT, has also been used as an imaging method for conditions of the podotrochlear apparatus and POD, especially if other imaging modalities were inconclusive.^{29–35} Standing low-field MRI and high-field MRI give comparable results. High-field MRI results in higher resolution images that improve the accuracy of diagnosis, but access to such machines is limited.^{29,30,32} Low-field standing MRI does have some limitations in detection of articular cartilage lesions in the absence of subchondral abnormalities and in imaging of anatomic structures in the pastern region.^{21,22,29,32,36} If standing low-field MRI is used to image the podotrochlear apparatus, it should be accompanied by an additional imaging modality for a complete evaluation of anatomic structures.^{21,22} CT imaging and contrast-enhanced CT imaging have been shown to image the pastern region better than standing low-field MRI.^{21,22} Standing CT imaging and standing PET-CT imaging are imaging methods that also give additional valuable information in horses with lameness, compared with radiography, and might become more readily available in the future.

We found radiography was most likely to yield an imaging diagnosis in horses with lameness localized to the foot or pastern region (26/58 [45%] horses). There was excellent agreement between radiography and CT imaging in cases for which a radiographic diagnosis could be obtained. However, it was common for there to be no diagnosis after radiography. CT imaging was more likely to yield an imaging diagnosis, compared with radiography, for all limb regions. Currently at 1 of the 2 hospitals included in the present report, CT scanning is used as an initial imaging method for horses suspected to have lameness of the foot or pastern region.

Ultrasonographic imaging was used in a relatively small proportion of cases in the present report, which limited inferences related to the utility of ultrasonographic imaging. For soft tissue conditions of the foot, we found that CT imaging was complementary with ultrasonographic imaging. Contact of the probe, angulation of the probe, sonographer skill, and condition of the hoof itself can make ultrasonographic examination of the foot challenging. Non-contrast-enhanced CT scanning provides detailed

multiplanar images of the distal phalangeal region to identify lesions.^{21,22,25,37} Furthermore, contrast studies may provide additional information about tendons and ligaments in the pastern region, especially compared with standing low-field MRI.^{21,22,38,39} Soft tissue injuries proximal to the foot were identified equally well by both CT imaging and ultrasonography. However, MRI, particular high-field MRI, is still considered the best method for soft tissue imaging.^{1,22,25} Duration of standing MRI is longer than that of standing CT, and imaging time is substantially influenced by the number of sequences and imaging planes that are selected and whether bilateral imaging is needed.⁴⁰

There was no radiographic diagnosis for 27 of 30 (90%) horses in the present report that underwent radiography of the fetlock, metacarpal or metatarsal, or carpal or tarsal region. However, CT imaging did provide a diagnosis. CT scanning was superior to planar radiography for imaging of the fetlock and carpal or tarsal region, particularly for horses with bone lesions such as POD, subchondral bone cysts, subchondral bone disease, and fractures.^{26–28} CT imaging has potential for screening Thoroughbred racehorses to assess fitness for racing because of its high resolution, rapid image acquisition, and high case throughput.⁴¹

Local injection of contrast medium was used as part of the CT scanning procedure in 10 patients in the present report and was most often used for imaging of soft tissue structures such as tendons and ligaments or synovium. Diagnostic findings obtained by means of ultrasonography were confirmed with CT scanning in 3 of 5 horses. Contrast medium can be administered through IV, IA, intra-synovial, or intrathecal routes, and its use has been described in normal and abnormal soft tissues of the distal limb.^{21,37–39,42–44} However, CT contrast studies of the limb have typically been performed under general anesthesia with the limb in a non-weight-bearing position. Reduction of mechanical compression in joints and tendon sheaths can enhance distribution of contrast medium to intra-synovial and intrathecal soft tissue structures or enhance cartilage surface imaging.^{21,38} CT arthrography has also been shown to have better sensitivity for detection of articular cartilage defects than MRI arthrography.³⁶ In the present report, contrast medium was administered by means of IV regional limb perfusion to identify suspensory ligament desmitis or by intrasynovial or intrathecal injection to identify abnormalities of the joint or tendon sheath in a full weight-bearing position. If needed, mechanical compression can be reduced by means of positioning the limb in a partially weight-bearing position, enabling comparison of scans with the limb in different weight-bearing positions.

Interpretation of CT images in this case series was facilitated by means of imaging limb pairs. This can be of tremendous interest in high-level athletic horses such as Thoroughbred racehorses, in which asymmetric bilateral lesions are common. In the present study, 3 Thoroughbred racehorses

were presented with POD, multilimb lameness, and poor performance and underwent screening of all 4 fetlock regions. With regional contrast injection, comparison of one limb with contrast medium and the contralateral limb without contrast medium under the same weight-bearing conditions was also possible. Further research is needed to understand differences in weight-bearing versus non-weight-bearing limb positions for optimal CT imaging with or without contrast medium.

In the present study, CT image quality was good with reasonable soft tissue resolution with and without contrast medium (**Supplementary Figure S3**). With cone-beam volumetric imaging, scattered radiation can reduce soft tissue contrast.^{3,4,15} Viewing multiplanar reconstructions was particularly useful when scans were reviewed. Both CT and MRI produce multiplanar images, but the images they provide are different. CT images exhibit excellent definition of bone and soft tissue structures.^{45–47} CT can also detect foreign materials more accurately than MRI or digital radiography.⁴⁵ Image acquisition is more rapid with CT than with MRI, an important consideration when there is risk of movement of standing horses.⁴⁰ However, CT is not as good as MRI for distinguishing normal from abnormal soft tissue structures because CT is based on x-ray attenuation instead of detection of fluid.^{1,40,45–47} Osseous inflammation or bone marrow lesions are, therefore, also harder to detect with CT.

The novel helical fan beam CT system used in the present report requires fixed installation, in contrast to some other CT systems used in veterinary medicine,^{3,4,11,13} and it cannot be moved to other rooms such as a surgical suite. Anecdotally, however, we have performed distal limb surgery in the scanning room with CT imaging guidance. The surfaces of the gantry are made of materials that are waterproof and easy to clean. Another drawback of this machine is that proximal limb imaging is constrained by horse conformation, with imaging above the carpal and tarsal regions limited in horses with short limbs and a deep trunk. However, under general anesthesia, images of the stifle and elbow joints can be acquired with the horse placed on a commercial equine surgery table.

There were several limitations to the present retrospective study. Each location was selected for scanning on the basis of the result of a rigorous lameness examination with regional anesthesia, if appropriate, performed by a referring equine veterinarian, specialist in equine surgery, or specialist in equine sports medicine. However, no pathologic or histologic examinations were performed to confirm imaging findings. It can be difficult to robustly confirm structural changes in the navicular bone identified by diagnostic imaging as the cause of lameness, because structural changes in this bone are common. In addition, structural changes without activity can be noted in bone, as has been demonstrated by PET-CT.^{48,49} Furthermore, imaging diagnoses and structural changes identified with standing CT should be confirmed with another method for con-

troversial diagnoses, particularly soft tissue lesions such as structural changes to ligaments, synovium, or cartilage. One can also argue that case selection in the present report was biased toward cases for which other imaging modalities could not provide a diagnosis. Additionally, in this retrospective study, images were evaluated by a board-certified veterinary radiologist in a routine clinical fashion without blinding to the history and result of previous imaging, potentially influencing image interpretation. However, for several conditions clearly associated with lameness, such as subchondral bone cysts, POD, and cuboidal bone fractures, lesion detection with CT was markedly different from that obtained with radiography, suggesting that CT imaging can aid in individual patient management. CT screening in athletic performance horses, such as Thoroughbred racehorses, could prove valuable for investigation of poor performance and risk assessment for serious injuries on the basis of results for the limited number of racehorses in the present study. In future studies, prospective comparison of CT imaging with other diagnostic methods would enable determination of diagnostic sensitivity and specificity for common conditions such as navicular bone disease, POD, and subchondral bone cysts.

In conclusion, we described routine use of a helical fan beam CT system for vertical scanning of distal limb pairs from the carpal or tarsal region distally in sedated standing horses. Simultaneous scanning of a limb pair as well as the natural stance of the horse during imaging were considered advantageous for image interpretation and establishing a clinical diagnosis. The system was subjectively easy to operate, and personnel with protective shielding were allowed to remain in the room during scanning to care for the horse, as determined by the regional radiation safety office. Widespread access to standing CT imaging of the distal limbs may enable a clinical diagnosis to be made in most cases. In the future, longitudinal clinical research studies using CT scanning are needed to compare imaging diagnoses with pathologic or surgical findings and to document the impact on clinical management of specific conditions in horses.

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Supplementary Materials

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