Received: 27 February 2022 | Revised: 16 August 2022 | Accepted: 17 September 2022

DOI: 10.1111/vru.13182

ORIGINAL INVESTIGATION

WILEY

Computed tomographic evaluation of the distal limb in the standing sedated horse: Technique, imaging diagnoses, feasibility, and artifacts

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Abstract

In several veterinary institutions, adjustments of CT machines have been made that allow for imaging of the standing horse. The risk of general anesthesia is eliminated and the shorter scan completion time reduces cost to clients. The objective of this retrospective, analytical study was to evaluate the technique, imaging diagnoses, feasibility, and image artifacts of multi-slice helical CT of horses' distal limbs acquired under standing sedation. The CT images of 250 horses of various breeds, aged 3–23 years, that underwent standing distal limb CT were evaluated. Three observers assessed the CT images for artifacts and inter-observer agreement was calculated. Eighty-six percent (95% confidence interval (CI), 81–90) of the scans were carried out on the forelimbs, while 14% (95% CI, 10–19) were of the hindlimbs. A total of 65% (95% CI, 59–71) of horses that underwent standing sedated CT had single imaging diagnoses. Seventy-one percent (95% CI, 65–77) of the cases had unilateral lesions, 27% (95% CI, 22–33) had bilateral lesions and 2% (95% CI, 1–4) had no diagnosed lesions. The average CT acquisition time was 17.5 minutes (range = 15–20). The average number of acquisitions per horse was 1.7 (median = 1; range = 1–4). There was good to excellent agreement between all three observers for the presence of motion artifact in the metacarpo/metatarsophalangeal joints, identification of marked beam hardening artifact, mild solar/ skin dirt, and photon starvation artifact (kappa 0.61-0.80). No complications were encountered. Standing examination of the distal limb achieved diagnostic image quality that was obtained with minimal acquisition attempts and in a timely manner.

KEYWORDS
computed tomography, distal limb CT, horse, multi-slice helical CT scanner, standing CT

1 | INTRODUCTION

Computed tomographic (CT) imaging has become an accepted imaging modality in the veterinary world and has become routine practice at certain institutions, particularly universities and referral practices.[1] The distal limb of the horse is often injured and several conditions can be challenging to visualize with standard imaging techniques. Computed tomography is a valuable aid in diagnosing lameness associated with equine distal limb pathologies, such as fractures, tendinopathies, and cysts.[2–5] Computed tomography in equine practice is mostly used to identify and characterize musculoskeletal and cranial neck injuries and characterize skull, sinonasal- and dental disease and traumatic injuries.[6] There is increased awareness of CT imaging in equine orthopedic patients as CT offers superior information to radiography in many equine musculoskeletal conditions.[4] The short acquisition time to complete a standing CT scan, as well as the ability to perform it on the sedated horse, whenever possible, reduces the risks associated with general anesthesia (GA) and cost to clients.[7,8] Anesthetic complications in equines are well described with the incidence of mortality and serious morbidity being approximately 1.0% in healthy, elective cases.[9–13]

Computed tomography in horses was first described in 1984.[14–16] The first attempt at performing equine standing sedated CT of the distal limb was reported in 2002.[2] A small, peripheral quantitative CT scanner was used, which assessed bone mineral density. It was used successfully on 47 clinical foot cases, for diagnosis or to aid in surgical planning. The procedure was time consuming, taking 20 min to acquire ten slices.[2] Recently, two retrospective studies on distal limb standing CT were reported.[17,18] One study used a multi-slice helical CT machine, examining 33 cases,[17] while the other study used a cone-beam CT, examining 58 cases.[18] Both studies found that standing distal limb CT was feasible and that diagnostic information could be produced. To the best of the authors' knowledge, a retrospective study of a large series of standing distal limb CT examinations, relating to technique, imaging diagnoses, feasibility, and image artifacts has thus far not been published. The main objective of the study was to evaluate the technique, imaging diagnoses, feasibility, and image artifacts of multi-slice helical CT of 250 horses' distal limbs, over a three-year period, acquired under standing sedation. It was hypothesized that the proportion of motion artifacts would be more prevalent in the front limbs than in the hind limbs.

2 | MATERIALS AND METHODS

2.1 | Selection and description of subjects

The study was a retrospective, analytical design. All included horses were presented to one of Equicare Equine Hospital's (Johannesburg, South Africa) six member practices for investigation of lameness or poor performance. Lameness was an inclusion criterion for CT examination in most cases. There were a few exceptions, such as radiographic abnormalities noted at a pre-purchase examination or suspicion of a keratoma on solar examination during routine farriery. Resolution or improvement of lameness after peripheral nerve blocks of the distal limb was generally a prerequisite. On occasion, CT was performed without first performing nerve blocks when obvious pathology was present in the distal limb, like fractures or suspected fractures, penetrating wounds or obvious pathology on clinical examination. The digital imaging and communications in medicine (DICOM) images and electronic records and reports, written by ACVR (American College of Veterinary Radiology)-certified veterinary radiologists of Puchalski Equine Diagnostic Imaging (Petaluma, USA), of horses admitted to Equicare Equine Hospital for CT imaging of the distal limb (including the metacarpus (MC)/ metatarsus (MT) and distally), during the years 2016 to 2019, were included in this study. Individuals of several breeds and both sexes, aged two years and older were evaluated. No horses younger than two years of age were scanned at Equicare. Horses for which there were no longer sufficient records available were excluded from this study. Approval for this study was obtained from the Faculty Ethics Committee as well as the Animal Ethics Committee of the University of Pretoria, South Africa (Project 082-20).

TABLE 1 Technical settings used for acquiring standing CT images of the distal limb in a retrospective study between 2016 and 2019 in Johannesburg, South Africa

Technical setting	Number
Bore diameter	720 mm
Detector rows	64
Field of view	500 mm
kV	135
mA	350
Pitch	1
Rotation time	1.5 seconds
Rotations per second	0.35-1.5
Slice	0.5 mm x 64
Slice thickness	0.5 mm
Slices per rotation	128

As part of the inclusion criteria for the study, all cases were imaged with a helical 128-slice prototype hydrolically mounted CT scanner (Toshiba Aquilion, Canon Medical Systems, Japan). The gantry bore diameter is 720 mm, with 64 detector rows. Single rotations per second range from 0.35 to 1.5. The CT machine is mounted on a hydraulic lever system, which flips the gantry horizontally, and is installed in a pit in the ground (4370 mm width × 2540 mm length × 1300 mm depth), so that it is level with the floor. The gantry moves up and down in a vertical plane around the horse's legs. There is a small pedestal (650 mm diameter) in the middle of the gantry, upon which the horse's legs to be imaged are positioned. A rubber floor cover (2650 mm width × 3000 mm length) covers the CT machine to protect it (Figure 1). The machine was switched on two hours prior to the intended CT scan to complete its warm up sequence and standardized settings were employed (Table 1). All horses were sedated following a standard protocol using acepromazine (Neurotranq, dose: 0.03–0.1 mg/kg, Virbac, 38 Landmarks Avenue, Samrand Business Park, Centurion, South Africa) intramuscularly onehour before undergoing the standing CT scan, followed by romifidine (Sedivet, dose: 40–80 μg/kg, Boehringer Ingelheim, Randburg, South Africa) that was administered intravenously five minutes before the scan to effect; until horses were unresponsive to the CT noise and movement. The starting dose was 30 mg for a 500 kg horse and topped up, as necessary, to a maximum of 50 mg. In three cases, butorphanol tartrate (Torbugesic, 0.01–0.04 mg/kg, Zoetis, Sandton, South Africa) was administered

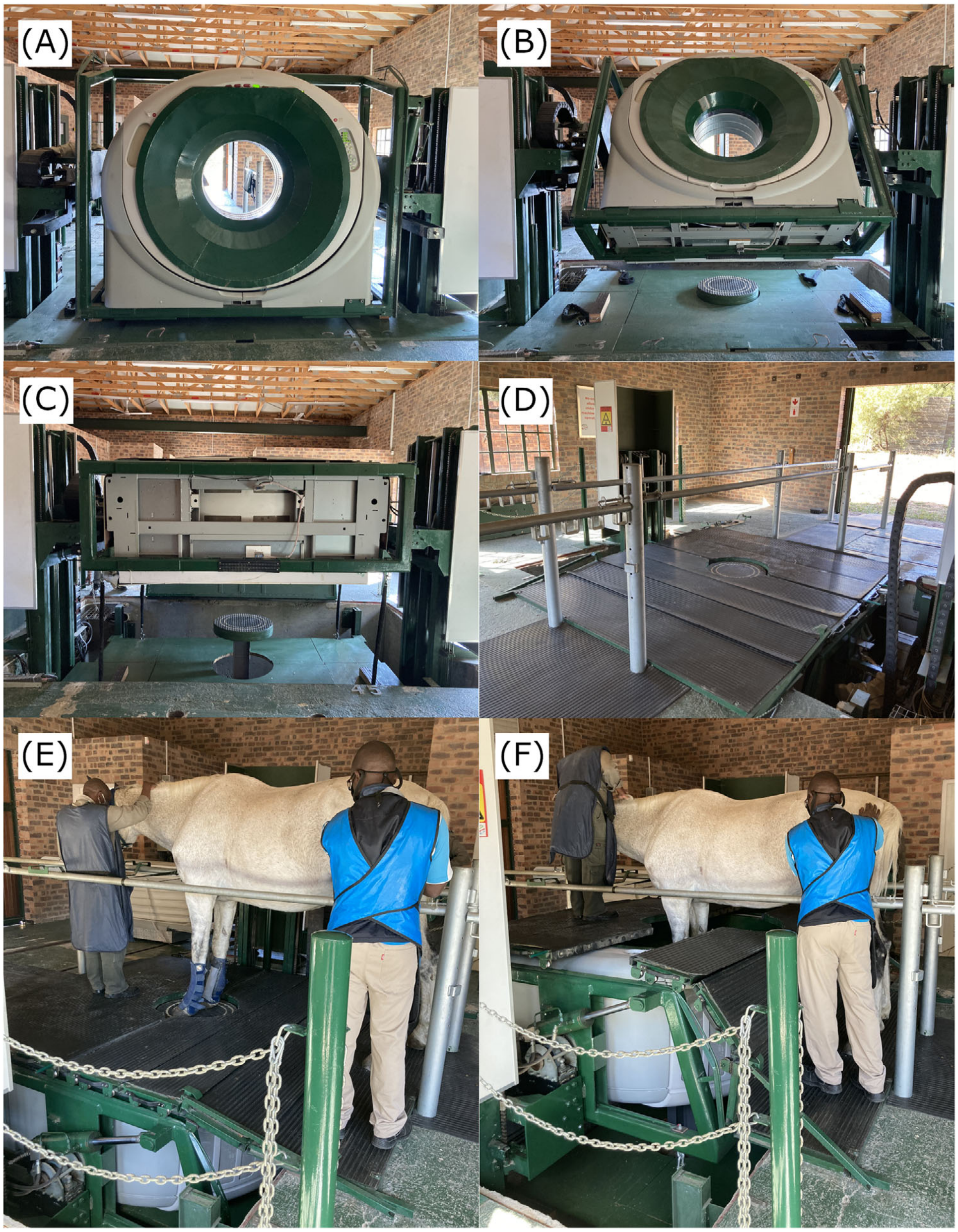

FIGURE 1 Helical 128-slice prototype CT scanner mounted on hydraulics used in this study. A, The 72 cm bore diameter gantry protected by a metallic shield in a vertical position. B, Gantry being tilted to a horizontal position. C, Gantry in a horizontal position being lowered until floor level into a pit. D, CT scanner ready for distal limb acquisition in the standing horse. A rubber floor cover protects the horizontally placed gantry. Stocks are in place. E, Pre-CT scan image showing the sedated horse positioned for examination of the front limbs. These are placed on a pedestal in the middle of the gantry. Notice the placement of the two handlers. F, Image obtained during CT acquisition of the front limbs. The gantry moves vertically along the horse's limbs [Color figure can be viewed at wileyonlinelibrary.com]

intravenously at 5–10 mg per 500 kg horse as the horses were considered fractious and it was anticipated that they would not stand safely. Horseshoes were removed from the legs to be imaged and hooves picked out and cleaned before the scan. Earmuffs and blinkers were used on all horses to minimize potential stimulation by noise and movement. Once sedated, the horse was walked into stocks and placed on the pedestal in the middle of the gantry. Both fore or both hind legs were systematically positioned together in the gantry so that bilateral images were consistently acquired. Additional sedation was given at this point if deemed necessary. No pilot scan was performed, as fast movement of the gantry might frighten the horses. The most time was spent positioning the horse appropriately and making sure both feet were in the field of view, that is, within the small pedestal in the middle of the gantry. Images of the same regions of the distal limbs in all horses were acquired (from the distal phalanx to the proximal MC/MT), regardless of clinical presentation. No contrast media was administered to any horse. Two handlers remained in the CT room for the duration of the scan; one at the horse's head, standing on the rubber floor covering, and one adjacent to the gantry holding the tail to keep the horse balanced (Figure 1). The handlers wore 0.5 mm lead gowns, lead thyroid shields and lead glasses, along with radiation dosimeters in compliance with the Code of Practice for Users of Medical X-ray Equipment compiled by the Department of Health Directorate: Radiation Control (2015), South Africa.[19] After the CT procedure, horses were allowed sufficient time in a stable to recover from the sedation after which they were discharged with the instructions of halving food volumes for the rest of the day to avoid possible colic due to the sedation. Images were stored in DICOM format and sent for reporting (see previous description). Toshiba's (Canon Medical Systems, Japan) Conexact (double slice) software was used for the image reconstruction. Two algorithms, namely "bone sharp" and "soft tissue sharp," were utilized, and the reconstruction slice thickness was 0.5 mm with 0.3 mm slice interval. For this study, both the reports and the DICOM images, using RadiAnt DICOM viewer (Medixant, Poland), were reviewed.

2.2 | Data recording and analysis

Variables recorded for each case included breed, use of horse, sex, age, reason for CT scan, duration of CT scan, number of attempted CT scans to obtain diagnostic quality images, evaluated limb(s), unilateral/ bilateral lesion, region of interest, imaging findings, radiologist that wrote the CT report, whether the case had a single imaging diagnosis, multiple imaging diagnoses likely contributing to the lameness or whether there were no important imaging findings, complications associated with the procedure and image artifacts. The imaging findings reported were based on a collation of previous radiographic reports by various ACVR-certified veterinary radiologists of Puchalski Equine Diagnostic Imaging (Petaluma, United States of America). The limbs evaluated were described as either front- or hindlimbs, as this technique of standing CT images both left and right limbs simultaneously. Image series were defined as diagnostic if the entire region of interest was included, with no to minimal motion artifact, and from which an imaging diagnosis could be made. Image series were defined as having a single imaging diagnosis if there was only one imaging diagnosis that could have contributed to the lameness. Image series were defined as having multiple imaging diagnoses likely contributing to the lameness if there was more than one imaging diagnosis that could have contributed to the lameness, necessitating further diagnostics, and a single imaging diagnosis for the perceived lameness could not be established. No important imaging findings were defined when no cause for the perceived lameness could be identified. Three different reviewers each evaluated the DICOM images for artifact detection and agreement was measured among the three observers using kappa-statistics.[20] The three evaluators included an ECVDI-certified veterinary radiologist (A), a recent veterinary graduate (B), and an experienced equine veterinarian (C), with a particular interest in diagnostic imaging. The evaluators examined ten cases together in which all of the types of artifacts (to be examined in the study) were identified and discussed so that a similar foundation of recognition of artifacts was established prior to the evaluations. The artifacts evaluated in this study included: motion blurring, beam hardening, high-density streaks, partial volume averaging, photon starvation, solar/skin dirt, and image cut-off (Figure 2).[21] In cases where consensus was not obtained amongst the evaluators, only the ECVDI- certified veterinary radiologist's results were used for the purpose of reporting a percentage value. Motion blurring artifact was evaluated as any movement throughout the image series, regardless of whether it was present in the region of interest or not, as the aim was to evaluate the presence or absence of motion. The number of images affected per case was calculated, but not used in the evaluation. Motion blurring artifacts were grouped into being present in the following anatomical areas to facilitate evaluation: (a) digit distal to the fetlock (zone A), (b) metacarpo- or metatarsophalangeal joint (zone B), and (c) MC/ MT proximal to the fetlock (zone C). It was hypothesized that the proportion of motion artifacts would be more prevalent in the front than in the hindlimbs.

2.3 | Statistics

The following descriptive analyses were performed by an observer with advanced diagnostic imaging expertise (AC), and the first author (NM): number of lesions identified on distal limb CT images, evaluated limbs, unilateral/ bilateral lesion(s), duration of the CT scan, complications, the number of cases per anatomical region with motion blurring artifact present and the number of cases with respective image artifacts present. An ACVPM (American College of Veterinary Preventative Medicine)-certified veterinary epidemiologist selected and completed statistical tests. Pearson's chi-square tests were used to compare the proportion of motion artifacts between the front- and hind limbs. The *P*-value that was accepted for significance was $P < 0.05$. A 95% CI was calculated for all the percentages reported, using mid-P exact confidence intervals from Open Epi.[22] Cohen's kappa-coefficient was used to measure interrater agreement on artifact detection of standing distal limb CT images.[20] Kappa was calculated for motion in the anatomical areas of, respectively, the digit distal to the fetlock, the metacarpo- or metatarsophalangeal joint, and the MC/MT proximal to the fetlock. Agreement was calculated for the entire anatomical area examined for beam hardening, partial volume averaging, photon starvation, and solar/skin dirt artifacts.

3 | RESULTS

Two-hundred and fifty examinations met the inclusion criteria. These included 81 mares, 16 stallions, 115 geldings, and 38 without sex information, with a mean age of 11 years (range 3–23 years). There were 146 Warmbloods, 36 Thoroughbreds, 17 Ponies, 4 Irish Sport Horses, 3 Arabians, 3 Friesians, 2 Hanoverians, 1 South African Boerperd, 1 Clydesdale Cross, 1 Connemara, 1 Percheron Cross, and 35 of which the breed was not recorded. The following was determined using the retrospective radiographic reports. Of the 250 CT examinations, 12 were follow-up scans (thus classified as a separate procedure) to monitor lesion or disease progression/healing. Sixty-five percent (163/250; 95% confidence interval (CI), 59–71) of the horses had a single imaging diagnosis (Tables 2–4), 27% (68/250; 95% CI, 22–33) had multiple

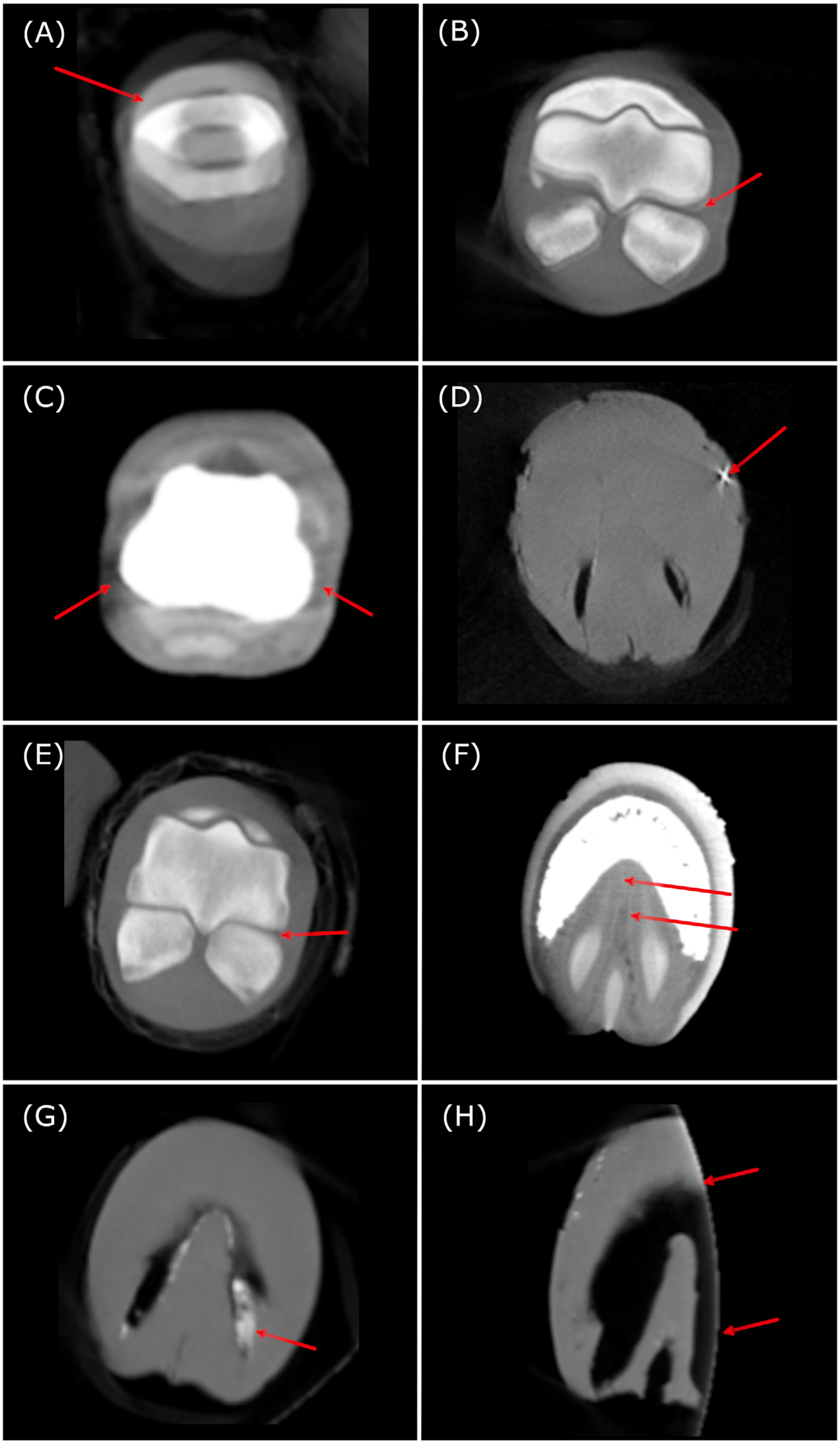

FIGURE 2 Different artifacts evaluated in this study. Dorsal is to the top. A, Marked motion blurring in the distal right metacarpal region (arrow). B, Moderate motion blurring in the left metacarpo-phalangeal region (arrow). C, Moderate beam hardening in the distal aspect of the proximal phalanx (arrow). D, High-density streaks in the left forefoot due to a hoof nail remnant (arrow). E, Mild partial volume averaging in the left metacarpo-phalangeal region (arrow). F, Mild photon starvation in the foot region. G, Solar dirt in the sulci of the feet (arrow). H, Image cut-off on the left foot (arrow) [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Number and percentage of each single imaging diagnosis (163/250) of horses that underwent standing computed tomographic imaging of their distal limbs in a retrospective study between 2016 and 2019 in Johannesburg, South Africa

Diagnosis	Number	Percentage (95% CI)
Tendinopathy	33	20.3 (15-27)
Fracture	18	11.1 (7-17)
Desmopathy	16	9.8 (6-15)
Osteoarthritis	15	9.2 (5-14)
Navicular degenerative changes	14	8.6 (5-14)
Keratoma	11	6.8 (4-11)
Subchondral bone trauma	11	6.8 (4-11)
Osseous cyst-like lesion	7	4.3 (2-8)
Palmar/plantar osteochondral disease of metacarpal/ metatarsal III	7	4.3 (2-8)
Stress induced bone remodeling	5	3.1 (1-7)
Pedal osteitis complex	4	2.5 (1-6)
Laminitis	3	1.8 (1-5)
Osteochondrosis	3	1.8 (1-5)
Digital flexor tendon sheath tenosynovitis	2	1.2 (0-4)
Enthesopathy	2	1.2 (0-4)
Follow up- abnormalities have resolved	2	1.2 (0-4)
Metatarsophalangeal (MTP) joint bone fragment	2	1.2 (0-4)
Distal phalanx collateral cartilage ossification	2	1.2 (0-4)
Distal interphalangeal flexural deformity	1	0.6 (0-3)
Hoof abscess	1	0.6 (0-3)
Localized infection of lateral heel region	1	0.6 (0-3)
Manica flexoria tear	1	0.6 (0-3)
Navicular bursitis	1	0.6 (0-3)
Osteomyelitis	1	0.6 (0-3)
Total	163	100

TABLE 3 Number and percentage of each desmopathy of horses that underwent standing computed tomographic imaging of their distal limbs in a retrospective study between 2016 and 2019 in Johannesburg, South Africa

Diagnosis	Number	Percentage (95% CI)
Distal interphalangeal medial collateral ligament desmopathy	6	37.5 (17-62)
Oblique sesamoidean desmopathy	4	25 (9-50)
Proximal digital annular desmopathy	3	18.8 (5-43)
Suspensory desmopathy	2	12.5 (2-36)
Straight sesamoidean desmopathy	1	6.2 (0.3-27)
Total	16	100

TABLE 4 Number and percentage of each tendinopathy of horses that underwent standing computed tomographic imaging of their distal limbs in a retrospective study between 2016 and 2019 in Johannesburg, South Africa

Diagnosis	Number	Percentage (95% CI)
Deep digital flexor tendinopathy	27	81.8 (66-92)
Superficial digital flexor tendinopathy	5	15.2 (6-30)
Deep digital flexor and superficial digital flexor tendonitis	1	3 (0.2-14)
Total	33	100

imaging diagnoses likely contributing to the lameness and the imaging diagnosis contributing to the lameness could not be confirmed for 8% (19/250; 95% CI, 5–11) of the cases. After establishing which horses had a single imaging diagnosis (163/250), several evaluations were made only using these cases. The most common imaging diagnosis for horses that underwent standing CT was a tendinopathy in 20.3% (33/163; 95% CI, 15–27) of cases, the second most common was a fracture in 11.1% (18/163; 95% CI, 15–27) of cases and the third most common was a desmopathy in 9.8% (16/163; 95% CI, 6–15) of cases. Of the cases that had a single imaging diagnosis, 87% (141/163; 95% CI, 81–91) were in front limbs and 13% (22/163; 95% CI, 9–19) were in the hindlimbs. In total, 86% (214/250; 95% CI, 81–90) of the scans were carried out on the front limbs, while 14% (36/250; 95% CI, 10–19) were of the hindlimbs. Seventy-one percent (178/250; 95% CI, 65–77) of the cases had unilateral lesions, 27% (67/250; 95% CI, 22–33) had bilateral lesions and 2% (5/250; 95% CI, 1–4) of the cases had no important lesions detected. The mean number of acquired scans per horse was 1.7 (median = 1, range = 1–4). Fifty-one percent (127/250; 95% CI, 45–57) required a single scan attempt, 33% (84/250; 95% CI, 28–40) required two scans, 15% (37/250; 95% CI, 11–20) required three scans and 0.8% (2/250; 95% CI, 0.1-3) required four scan attempts. The total duration of the CT scan was between fifteen and twenty minutes, with an average of 17.5 minutes. No complications before, during, or after the CT procedure were recorded.

As determined by the three evaluators, a total of 82% (205/250; 95% CI, 77–86) of cases had motion-blurring artifact present. Forty-eight percent (99/205; 95% CI, 42–55) had motion blurring present in zone A, 41% (83/205; 95% CI, 34–47) had motion blurring present in zone B and 11% (23/205; 95% CI, 7–16) in zone C. Fifteen percent (38/250; 95% CI, 11–20) of the cases had motion blurring present in two anatomical areas and 2% (5/250; 95% CI, 1–4) in three anatomical areas. The proportion of motion was not significantly different between the fore- and hind limbs, ($P = 0.437$ (Pearson's chi-square)). Only 2.4% (6/250; 95% CI, 1–5) of cases had photon starvation artifact present. All image series had some degree (mild/ marked) of beam hardening present. High-density streaks were observed in 13% (33/250; 95% CI, 9–18) of the cases, mostly caused by one or more metallic hoof nail remnants. The lateral aspect of one limb's images was cut off in 4% (9/250; 95% CI, 2–7) of the cases as it was outside the field of view. Mild to moderate solar dirt was identified in 93.6% (234/250; 95% CI, 90–96) of cases. Partial volume averaging was present in 98% (246/250; 95% CI, 96–99) of cases (as identified by the ECVDI-certified veterinary radiologist). Motion blurring artifacts in zone B, beam hardening, photon starvation, and solar skin/dirt had a substantial inter-rater agreement, meaning that raters agreed between 61% and 80% of the time (Table 5). Identification of motion in zone A had a fair inter-rater agreement (0.317). Motion in zone C had a moderate inter-rater agreement (0.524). Partial volume averaging had inter-rater agreement consistent with random chance alone.

4 | DISCUSSION

This retrospective study describes the use of a multi-slice helical CT machine for scanning the distal limb of standing, sedated horses. Sixty-five percent (95% CI, 59–71) of the horses that underwent standing CT had a single imaging diagnosis identified. Twenty-seven percent (95% CI, 22–33) of horses undergoing standing CT had multiple imaging diagnoses identified. This could have been anticipated prior to the CT scan, particularly if the horse had a multi-limb lameness. The significance of multiple lesions in the same leg is difficult to interpret as it might not be clear which lesion(s) is the cause of lameness. The relative contribution of each lesion would have to be established, by using peripheral nerve blocks, intra-articular anesthesia, or functional evaluation using gamma scintigraphy. In most cases, peripheral nerve blocks and other clinical evaluations would have preceded the CT and the location of the lameness thereby would be correlated to the CT changes observed in the vicinity. A limitation of this study is that no correlation could be made to the cause of lameness and therefore the findings described are imaging findings only. Extrapolation of the imaging findings/ diagnoses to the clinical diagnosis was not possible. It was decided only to report and collate the cases with a single imaging diagnosis as this was likely the cause of the perceived lameness in these cases. Due to our inability to definitively correlate the imaging findings to the clinical diagnoses, we were unable to identify the likely causes of lameness in cases with multiple imaging diagnoses. Depending on the specific lesions, multiple lesions can potentially worsen the prognosis compared to a single lesion, although this evaluation was not within the scope of this study. No imaging diagnosis could be made in 8% (19/250; 95% CI, 5–11) of the cases. The causative lesion might have been more proximal in the limb or caused by lesions not detected by CT, such as bone edema.

In this study, the standing sedated CT procedure was sometimes used as a screening tool of the distal limb as all horses did not necessarily undergo peripheral nerve blocks, radiography, or ultrasonography prior to the procedure; however, this is not advisable as it leads to unnecessary radiation of personnel involved. Ten handlers were routinely rotated to hold the horses and dosimeters worn by the handlers never had readings above acceptable levels. However, we would still suggest trying to limit personnel involved to only one person and placing lead protection under the feet of the handler holding the horse's head. Mapping the room for scattered radiation with this specific horizontal gantry set-up should also be considered.

One could not be sure that the imaging diagnoses identified were the cause of the lameness and not simply incidental findings. In a lame horse, the decision whether to send it for advanced imaging immediately and potentially finding the reason for the lameness early on, versus first resting the horse for a few weeks and then re-evaluating, could potentially be easier when one has standing distal limb CT at one's disposal. Further studies evaluating the sensitivity and specificity of standing CT compared with other modalities, like magnetic resonance imaging (MRI) and radiographs, are needed.

TABLE 5 Inter-rater agreement (Kappa) for seven CT artifacts of horses that underwent standing computed tomographic imaging of their distal limbs in a retrospective study between 2016 and 2019 in Johannesburg, South Africa

	Kappa (95% CI)			
Artifact	**All 3 Raters**	**Raters A&B**	**Raters A&C**	**Raters B&C**
Motion P1-3	0.317 (0.258, 0.377)	0.543 (0.439, 0.646)	0.048 (−0.055, 0.151)	0.273 (0.170, 0.376)
Motion fetlock	0.643 (0.584, 0.703)	0.804 (0.700, 0.907)	0.546 (0.442, 0.649)	0.569 (0.466, 0.672)
Motion MC/ MT	0.524 (0.464, 0.583)	0.732 (0.629, 0.835)	0.369 (0.266, 0.473)	0.402 (0.299, 0.505)
Marked beam hardening	0.746 (0.686, 0.805)	0.750 (0.647, 0.853)	0.778 (0.674, 0.881)	0.708 (0.605, 0.811)
Partial volume averaging	−0.098 (−0.158, −0.039)	−0.040 (−0.143, 0.063)	−0.282 (−0.385, −0.179)	−0.088 (−0.191, 0.016)
Photon starvation	0.647 (0.588, 0.707)	0.707 (0.604, 0.810)	0.640 (0.537, 0.744)	0.600 (0.497, 0.704)
Mild solar/ skin dirt	0.709 (0.649, 0.768)	0.688 (0.585, 0.791)	0.769 (0.666, 0.872)	0.671 (0.568, 0.774)

Rater A: ECVDI-certified veterinary radiologist, rater B: newly graduated veterinarian, rater C: experienced equine veterinarian.

Having both legs scanned in nearly the same transverse location facilitates comparative evaluation of anatomical areas, as potential lesions could be identified in the contralateral limb that would otherwise have gone unnoticed. This is an advantage in comparison with standing mMRI, as MRI acquisition of the contralateral limb needs to be performed separately. It is also imperative to know which region is required for the comparison as MR imaging is more time consuming than CT and fewer areas are therefore scanned. Standing CT machines can quickly image the full distal limb, regardless of the suspected lesion location. This has advantages and disadvantages. Advantages include that the entire distal limb is imaged, thus facilitating the investigation of the extent of the lesion. Also, potential lesions might be identified that otherwise might have been missed under other circumstances. The disadvantage can be that the clinical significance of the lesion(s) cannot be known. Although it might be tempting to image as many areas as possible, one may be left with an array of findings not linked to an isolated region of pain, which could make determining the appropriate therapy difficult. However, it might help with the early detection of, for example, degenerative disease or other concurrent conditions. Throughout the standing CT procedure, the horse is weight bearing on the legs being scanned, compared to CT under GA where the horse is non-weight bearing. Further studies are needed to determine the differences, and possible significance, between weight bearing and non-weight bearing CT imaging.

Eighty-six percent (95% CI, 81–90) of the cases scanned were front limbs and 14% (95% CI, 10–19) were hind limbs. This suggests that more distal limb injuries are diagnosed in the front limbs compared to the hind limbs. Front limb lamenesses are more common than hindlimb lamenesses,[23] partially because of the center of gravity being positioned closer to the forelimbs. The weight distribution between the fore- and hindlimbs is approximately 58% and 42% respectively.[24] It could also be that owners are more likely to detect a forelimb lameness and subsequently seek veterinary advice.

Desmopathies were a common imaging diagnosis in horses undergoing standing distal limb CT, which suggests that even though CT has been described as being inferior to MRI in diagnosing soft tissue lesions of the equine foot,[2,5,25] CT could be a valid imaging modality for soft tissue structures, similar to findings of other studies,[17,18] if MRI is not available. Computed tomography can assist in identifying the exact location and extent of the lesion. It can also be used as a monitoring tool to assess healing or disease progression, which is similar to the findings of another study.[26] In this study, no contrast was administered to any horse. Regional limb perfusion (intravenous or intra-arterial) with contrast would have been challenging with the positioning of the CT machine bore around the limbs and could be dangerous as tourniquets are painful and could create potential risk for the horse and the CT machine. However, had it been administered, it might have enabled us to detect more tendon or ligament lesions.[6] Although uncommon, systemic intravenous contrast injection can cause adverse reactions, like intravascular air injection or extravasation.[26] Intravenous contrast administration would likely also increase the CT acquisition time. Multi-slice CT displays a greater ability to produce clear, anatomically correct images and is better at soft tissue differentiation, than cone-beam CT.[26] We were able to identify lesions affecting soft tissues, in the absence of contrast, although it is possible some lesions were missed. In the future, contrast administration should be considered as it enables improved tissue evaluation and monitoring of tissue healing and disease progression in horses.[26]

The entire acquisition time for standing sedated CT, from walking the sedated horse into the CT room, placing the earmuffs and blinkers, ensuring optimum positioning, and acquiring the CT scan, until the horse walked out after the scan took an average of 17.5 minutes (range = 15–20). This is similar to a recent report on the duration of standing CT of the distal limb (median of 14 minutes).[18] The actual scan itself took approximately 60–90 s. Once the limbs were scanned the images were briefly examined to ensure they were of diagnostic quality, with no motion blurring artifact over particularly, the region of interest. If the horse noticeably had moved, the scan was repeated. Once the examiner was satisfied that the images were diagnostic, the horse was walked out of the CT room.

Motion blurring artifact was present in a total of 205 of the standing sedated CT image series, spread over three anatomical regions (zones A–C); however, some cases had motion blurring artifact present at more than one anatomical region. It was expected to see some motion as the horse was only sedated. Despite this artifact, diagnostic image quality was achieved in all horses; if the first scan series had motion present at the region of interest (ROI), the scan was repeated until diagnostic quality images of at least the ROI were obtained. The mean number of CT acquisitions per horse was 1.7 scans (range = 1–4 scans). This was less than two other studies that reported the mean number of acquired scans per horse as 3.[17,18] One study reported only using handlers when a hind limb was scanned and not for a forelimb,[17] which might have contributed to their increased number of scans per horse. The temperament of the horses, the sedation protocol, and the setting in which the CT scan was conducted might also have contributed to this study's fewer scans per horse.

The main cause of motion was the horse shifting its weight, possibly due to being slightly over or under-sedated, due to discomfort/ pain related to the lesion, or the need to urinate. It was interesting to note that the percentage of motion blurring artifacts was the same in the front- and hindlimbs, as horses' front limbs have a higher weight distribution compared to the hindlimbs (58%:42%).[24] In standing MR imaging motion artifact tends to be more pronounced in the hindlimb, than in the forelimb.[27] Although the motion artifact did not cause too many rescans in this study, motion correction software exists that could reduce or eliminate the motion artifact by 90% in the multi-slice helical system.[28] The machine used in this study does not currently have any motion correction software. Future studies, assessing whether motion correction software would enable standing CT scans to a single scan per horse, regardless of how severe the motion blurring artifact was, could be beneficial.

Horses of various breeds, sizes, and ages had beam-hardening artifact present. It was particularly apparent in the middle and distal phalangeal regions and although it was present in the bone and soft tissue windows, it was more apparent in the soft tissue window. Increasing the kilovoltage (kV) could cause less beam hardening artifacts; however, this creates less tissue contrast.[29]

High-density streaks were mostly caused by one or more metallic hoof nail remnants, and in a few cases by orthopedic screws. These artifacts were more visible in the bone window, but did not affect the diagnostic quality of the images. Filters can be used to decrease artifacts caused by metallic implants.[30]

Inter-rater agreement (kappa) was substantial between all three evaluators for identifying motion in zone B, marked beam hardening, photon starvation, and mild solar/ skin dirt. Motion in zone A only had a moderate agreement between two evaluators (A and B). Possible reasons for this difference in agreement might be that one or more of the evaluators were too strict or less experienced and it might be more challenging to identify motion present distally to the fetlock than had been originally anticipated. Inter-rater agreement for motion in zone C was substantial between two evaluators (A and B; kappa = 0.732), whereas agreement was noticeably less (kappa = 52%) among all three evaluators. A possible explanation for this difference might be that one observer could not differentiate motion blurring as well as the others. Additionally, it might not have been clear where on the limb the evaluators were to identify the motion-blurring artifact as part of the MC/ MT and not the fetlock. Perhaps the anatomical areas could have been more clearly defined prior to starting the evaluation, to avoid confusion. There was no inter-rater agreement greater than random chance for the partial volume averaging artifact. This artifact might have been confused with motion blurring, and vice versa, as both artifacts cause margin blurring.[21] One observer might have been more aware of or more experienced in identifying very mild partial volume averaging.

There were no complications associated with the standing sedated CT procedure, as has been reported in other studies.[2,17] Potential complications could include a horse reacting adversely to the procedure and subsequently injuring the handler and/ or itself, and damage to the CT machine.

Limitations of the study include the lack of signalment information for some of the patients and some of the CT reports identifying several abnormal imaging findings per limb, which occasionally made it difficult to identify the main imaging diagnosis. This retrospective study was based on retrospective CT reports; thus, CT findings were not correlated to clinical examinations and other diagnostic tests performed prior or subsequent to the CT scan. It was not within the scope of this study to re-evaluate the entire image series, and history, of each case to correlate imaging diagnoses to clinical diagnoses.

In conclusion, standing examination of the distal limb, using a multislice helical scanner mounted on a hydraulic lever system, achieved diagnostic image quality with minimal acquisition attempts and within a reasonable time frame. Once the system is installed, this technique is easy to perform and provides a safe, convenient alternative to CT examination under GA. Despite motion blurring artifacts, this method proved feasible in obtaining clinically relevant imaging diagnoses in a range of cases including bone, ligament, tendon, and synovium injuries.

ACKNOWLEDGMENTS

The authors would like to acknowledge Blue Hills Veterinary Hospital, Chartwell Equine Clinic, Crowthorne Vet, Fourways Equine Clinic, Glen Austin Equine Clinic, Witbos Veterinary Clinic, and Puchalski Equine Diagnostic Imaging for their contributions to this project.

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Category 2

(a) Drafting the Article: Mathee, Carstens, Robert
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Category 3

(a) Final Approval of the Completed Article: Mathee, Robert, Higgerty, Fosgate, Rogers, d'Ablon, Carstens

Category 4

(a) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: Mathee, Robert, Higgerty, Fosgate, Rogers, d'Ablon, Carstens

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

PREVIOUS PRESENTATION OR PUBLICATION DISCLOSURE

This article is based on an MSc dissertation titled "Computed tomographic evaluation of the distal limb in the standing sedated horse" by Nicoli Mathee, supervised by Ann Carstens and co-supervised by Mickaël Robert.

REPORTING CHECKLIST DISCLOSURE

The STROBE-VET reporting checklist was used.

DATA AVAILABILITY STATEMENT

Data available at https://doi.org/10.25403/UPresearchdata.18550880.v1.

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How to cite this article: Mathee N, Robert M, Higgerty SM, et al. Computed tomographic evaluation of the distal limb in the standing sedated horse: Technique, imaging diagnoses, feasibility, and artifacts. *Vet Radiol Ultrasound*. 2022;1-10. https://doi.org/10.1111/vru.13182