J S Afr Vet Assoc. 2024;95:143-150
https://doi.org/10.36303/JSAVA.546

J S Afr Vet Assoc
ISSN 2224-9435 EISSN 1019-9128

ORIGINAL RESEARCH

Effects of lead shielding on gamma radiation scatter energy spectrum during equine bone scintigraphy

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The main aim of this pilot study was to determine how the energy spectrum of scatter radiation emitted from horses after injection of the radiopharmaceutical ^{99m}Technetium-methyl diphosphonate (^{99m}Tc-MDP), changed behind lead shielding of varying thicknesses (0.25 mm, 0.35 mm, and 0.5 mm Pb thickness), and if beam hardening occurred. The effect lead shielding has on the emitted gamma radiation energy spectrum has not been documented. In particular, the presence of beam hardening effects behind lead shielding was investigated, to determine whether or not it could discourage the use of lead shields during bone scintigraphy in horses. Horses were injected intravenously with ^{99m}Tc-MDP, and energy spectra emitted from horses without lead shielding were recorded initially to determine the emitted scatter spectrum. Thereafter, different combinations of lead shields of the various thicknesses listed above, draped over the horse and on simulated personnel, were recorded. The energy spectra were obtained at different anatomical locations of five horses on five consecutive days with a pulse height (multichannel) analyser two and a half hours post-injection. Energy spectra recorded from horses without lead shielding showed polychromatic energy spectra that encompassed a large portion of predominantly lower scatter energies (averaging around the 88–94 keV peaks). Higher ^{99m}Tc-MDP peaks averaging at 139–143 keV (useful for gamma camera acquisition) were consistently seen in all recordings but made up a very small part of the emitted spectra. With the application of lead shielding, peaks of 83–86 keV, which coincided with K-edges of lead, occurred. No significant beam hardening effects behind lead shields of varying thicknesses were observed. Thus, the wearing of lead shields during bone scintigraphy of horses is encouraged.

Keywords: scintigraphy, technetium, equine, radiation, safety, shielding, beam hardening

Introduction

Bone scintigraphy in the horse is a useful diagnostic imaging modality to identify sites of active bone metabolism. These are seen as increased radiopharmaceutical uptake (IRU) in the affected area (Kanishi 1993; Dyson 2003a). ^{99m}Technetium-MDP is injected intravenously and the bone phase scintigraphic examination initiated approximately 2.5 to 3 hours later (Dyson 2003a; Steyn & Uhrig 2005). The procedure may involve multiple anatomical regions of the horse and thus personnel may be subjected up to two hours of scanning time (Whitelock 1997; Neuwirth 2000).

The metastable radioisotope ^{99m}Tc decays by means of gamma ray emission. Most of this radiation is emitted at an energy peak of 140.5 keV (Diderlaurent 2005). After injection, there is interaction of ionising radiation within a patient's tissues, known as internal radiation exposure. Depending on the density of the exposed tissue, interactions occur by means of photoelectric and mainly Compton effects, resulting in emitted radiation from the patient, termed scatter radiation. Therefore, the injected monochromatic spectrum changes into a post-injection polychromatic beam that emanates from a horse in a vast spectrum of energies (Diderlaurent 2005). These cause external radiation exposure of bystanding personnel. (Steyn & Uhrig 2005; Whitelock 1997; Neuwirth 2000; Dyson 2003b). A study on external radiation exposures of personnel working with ^{99m}Technetium in humans (Schürnbrand et al. 1982; Willegaignon et al. 2023) showed that using the standard dose of 50 mCi of ^{99m}Technetium for human studies resulted in exposures to personnel that were lower than the limits established by the International Commission on Radiological Protection (ICRP) and the Atomic Energy Agency (AEA), however, higher, potentially hazardous, radiation exposures were recorded at the fingertips during injection when syringe shielding was not used. A study evaluating extremity doses when handling syringes (Prussin et al. 1998) suggested that K x-rays from the photoelectric effect in a lead-glass shield could be a significant contributor to the high extremity dose when handling syringes. Other studies (Sarihan & Abamor 2022; Marshall et al. 2023) have shown that during bone scintigraphy specifically, emitted scatter radiation from patients was highest in the chest and posterior regions and suggested keeping a 1 m distance from injected patients. Since the injected dose for horses is four times that of humans, and bystanding personnel cannot always maintain a 1 m distance from the patients, emitted radiation exposure from injected patients is expected to be far higher. To reduce potentially biologically hazardous effects of radiation (Bolus 2001), it is thus important to determine whether protective lead shielding, as used in radiography (Tyson et al. 2011; Mayer et al. 2018), would be suitable for use during scintigraphic examinations. Characteristic x-rays are produced when an element is bombarded with high-energy particles, which can be photons, electrons, or ions (such as protons). When the incident particle strikes a bound electron, the target electron, in an atom, the target electron is ejected from the inner shell of the atom. Due to characteristic x-ray production of emitted radiation energies within the lead apron itself (Bovenkamp et al. 2009) resultant radiation produced by this interaction could theoretically be biologically more harmful than the polychromatic spectrum emitted from the horse (Steyn &Uhrig 2005). Another potentially hazardous phenomenon of lead is called beam hardening. Beam hardening is the phenomenon that occurs when an x-ray beam comprised of polychromatic energies passes through an object, resulting in selective attenuation of lower energy photons. The effect is conceptually similar to a high-pass filter, in that only higher energy photons are left to contribute to the beam and thus the mean beam energy is increased ("hardened"). Lead could act as a filter and remove lower energy radiation resulting in a higher energy spectrum reaching bystanding personnel (McCaffrey et al. 2007).

To the authors' knowledge, there is no documentation in the currently available literature on whether, and to what extent, lead shielding (worn by personnel or patient) produces beam hardening effects that may preclude its use during the procedure. The main aim of the study was to determine how the quality of the energy spectrum of ^{99m}Tc gamma (γ) radiation changes behind lead aprons placed on the horse and/or those worn by personnel at varying thicknesses of lead. This information would serve to determine whether beam hardening effects take place, and if they do, at what level of shielding (and/or which thickness of lead combination) this phenomenon is most prominent. Variables expected in this study include the different sizes (mass) and bone density of the patients. Although these factors are expected to influence the attenuation of γ-rays and thus the emitted polychromatic beam, large, significant fluctuations are not expected. Our research hypothesis is that detrimental beam hardening effects would not occur despite variable lead thicknesses, and the wearing of lead aprons would be encouraged.

Materials and methods

The study was approved by and conducted in accordance with the Onderstepoort Animal Ethics Committee. To homogenise horse size and weight, four Thoroughbred horses and one Boerperd with a mean body weight of 486 kg, ranging from 450 kg to 520 kg, were included in the study. The activity of ^{99m}Tc-MDP, time of injection and the commencement time of data collection were recorded and tabulated in Table I.

The patients were housed as scintigraphy patients in dedicated isolation stables for at least 24 hours after which they returned to a public environment. At that point, the skin surface radiation was required to measure < 10 mSv/hr.

The primary investigator and all personnel involved wore currently required protective clothing which consists of white coats, disposable latex gloves and gumboots. The wearing of lead aprons, thyroid shields and lead glasses was optional. Personnel were advised to wear a 0.35 mm lead apron after the first day's data acquisition.

Every day of the study, the scintillation gamma camera (Equine Scanner, H.R. Medical Imaging Electronics, Seth, Germany) was calibrated for the use of ^{99m}Tc. A portable digital multichannel analyser (Transgalactic Instruments NetMCA-3, Bulgaria) attached to a sensitive 2.54 cm NaI:TI (sodium iodide crystal activated with thallium) detector connected to a dedicated portable computer was used to analyse radiation spectra. A pulse height analyser is an instrument that analyses the frequency distribution of the spectrum of photon energies that are captured by a gamma camera. Energy windows are selected to only allow certain photon energies that fall within the preset range to contribute to the output pulse. At the start of each set of measurements, a gamma energy spectrum of the syringe containing ^{99m}Tc was obtained and its typical pulse height spectrum recorded (Figure 1). As mentioned above, ^{99m}Tc decays mainly by gamma emission, about 98.6% of these gamma emissions result in 140.5 keV gamma rays and the remaining 1.4% are gamma rays of a slightly higher energy at 142.6 keV.

The following properties apply to all the recorded spectra: the height (Y-axis) of the spectrum correlates with the number of recorded counts in a specific energy range, and the width (X-axis) corresponds to increasing energies of the recorded radiation from left to right. The X-axis values are fixed energy levels of a preset range; however, the Y-axis values auto scale according to the number of counts recorded for a specific energy. The second, so-called centroid peak (X-axis) is fixed – calibrated at 140.5 keV. The Y-axis values in the figures below represent the quantity, that is, the number of ionising events recorded by the spectrometer for a specific energy level, plotted on a graph for ease of interpretation (the exact values are known but were beyond the scope of this report). The figures depict the ratio of high energy (140.5 keV) photons vs. scattered lower energy photons for each of the different measurement scenarios and locations. The ratio of the two peaks, the ratio of the counts in each peak divided by the spread at full width half maximum (FWHM), is a qualitative measure of radiation being emitted, or incident on the detector. The FWHM characterises the width of a peak on a graph and is used to determine the energy resolution of gamma camera systems or spectrometers.

Approximately 5.5 GBq (149 mCi total or 11 MBq/kg) of ^{99m}Tc-MDP in a 2 ml syringe was injected intravenously via a preplaced jugular catheter at the same time each day, refer to Table I, and flushed with 20 ml of sterile saline. Radioactivity within the body was confirmed over the cranial thorax (heart area) and mid abdominal region with a digital Geiger-Müller counter (RadEye™ G/G-10 Personal Dose Rate Meter, Thermo Fisher

Table I: Radioactivity at the time of injection and time of data acquisition

	Boerperd	TB	TB	TB	TBx
^{99m}Tc-MDP Activity (GBq)	5.3	5.5	5.6	5.2	5.4
Time of Injection	10:32 am	10:35 am	10:35 am	10:35 am	10:40 am
Data Acquisition Time	13:00 pm	12:50 pm	12:50 pm	12:50 pm	12:50 pm

TB = English Thoroughbred; TBx = English Thoroughbred cross

Scientific Inc, United Kingdom), after which the horse was placed into an isolation stall. Approximately two and a half hours post-injection, horses were sedated with 0.1 mg/kg detomidine (Domosedan® Novartis SA, Isando, South Africa) intravenously. A single standard 60-second lateral abdominal view of the bladder region was made with the gamma camera to assess bladder filling and to confirm uptake and excretion of the injected ^{99m}Tc-MDP. Spectrometer recordings were obtained in the following way:

1. Directly in front of the head (within 10–30 cm of the patient) (HF)
2. To the side of the head (lateral to the widest part near the angle of the jaw – cheek) (HC)
3. Shoulder region (S)
4. Caudal abdomen (region of the bladder) (B)
5. Proximal aspect of the pelvic limb (region of the coxofemoral joint) (P)

Gamma energy spectra were recorded initially at locations 1–5 without any shielding at all, followed by various combinations of no shielding on the horse and shielding on simulated bystanding personnel only. Simulation of bystanding personnel consisted of drip-stands on which lead aprons of varying thicknesses (0.25 mm, 0.35 mm and 0.5 mm lead equivalent) were hung and energy spectra were obtained from behind the aprons using the spectrometer. These so-called phantoms were rolled to the various parts of the horse's body to obtain energy spectra at different regions of the patient. A final set of measurements was obtained by using various lead shield combinations on the horse and the phantoms. For the recordings where shields (0.35 mm and 0.5 mm lead equivalent) were also placed on the horses, only locations 3–5 were used, as the equine head region could not be effectively draped.

Counts recorded from behind lead aprons and from the horse were collected during a 30-second acquisition period for each individual measurement. For the first subset of data acquisition, no lead shielding was applied. Gamma energy spectra were recorded to determine if and how the quality of the spectrum of gamma radiation, emitted directly from the horse, changed at the selected anatomical locations. These measurements were documented as WOH (= without [shielding] on horse). The second subset of data was obtained using standard lead aprons of 0.25 mm, 0.35 mm and 0.5 mm lead equivalent hung on drip stands approximately 30 cm from the patient. The resultant spectra are documented as WOH plus ("+") the shields of varying lead thicknesses described above (for example, WOH+0.25 mm). All four data subsets are tabulated in Table II.

Graphs of all the recorded spectra were acquired electronically and saved. The FWHM was calculated by the detector programme and reported as soon as acquisition of data stopped. It defines the energy resolution of the detector system. The FWHM was determined for the main spectrum peaks and used as a qualitative measure of the spectrum being emitted by the different horse/Pb combinations by comparing the FWHM values for the different measurement locations obtained with the same detector system. Larger FWHM values for corresponding peaks would be indicative of increased scatter or beam quality changes. The cross (X) on each recorded spectrum corresponds to an activation marker inside the selected region of interest (ROI) such that the system reports the data for that specific ROI. The cross does not coincide with the centroid of the peak, which is located at 140.5 keV.

Ethical considerations

Experimental animals were used, and ethical clearance was obtained for the study. All procedures performed in studies involving animals followed all international, national, and/or institutional guidelines for the care and use of animals.

As per regulations, all persons handling the radioisotope and radioactive animals always wore dedicated protective clothing. The wearing of lead aprons was voluntary but advised.

The radiopharmaceutical was delivered within a specified, shielded container marked "radioactive" and was not handled by unauthorised persons. The syringe was placed within a lead cover for injection. After injection the syringe was removed from the lead cover and placed back within its container for collection the following morning.

As per radiation safety precautionary measures and regulations, contaminated stable bedding was removed and discarded as normal waste after 24 hours (4 physical half-lives of ^{99m}Tc). Any urine or faecal voiding during the procedure was cleaned

Table II: Acquisition on data subsets using lead aprons (shields) of varying thickness, in mm lead equivalent, on the horse and phantoms

	HEAD	CHEEK	SHOULDER	BLADDER	PELVIS
WOH	**No shields**	**No shields**	**No shields**	**No shields**	**No shields**
Shields on phantoms only					
WOH + phantom	0.25 mm 0.35 mm 0.5 mm	0.25 mm 0.35 mm 0.5 mm	0.25 mm 0.35 mm 0.5 mm	0.25 mm 0.35 mm 0.5 mm	0.25 mm 0.35 mm 0.5 mm
Shields on horse only					
WSH			0.35 mm 0.5 mm	0.35 mm 0.5 mm	0.35 mm 0.5 mm
Shields on horse and phantom					
WSH + phantom			0.35 mm 0.5 mm + 0.25mm 0.35mm 0.5mm	0.35 mm 0.5 mm + 0.25mm 0.35mm 0.5mm	0.35 mm 0.5 mm + 0.25mm 0.35mm 0.5mm

(faecal material placed into stable) and rinsed with tap water immediately into designated drains.

The study was approved by the Animal Use and Care Committee of the University of Pretoria (V004/06).

Biosecurity measures

All handling of radioactive material and animals was treated according to the radiation safety regulations as stipulated by the University of Pretoria and the ALARA principle adhered to, to keep radiation exposure to a minimum. The primary investigator, a certified radiation officer in Austria, European Union, ensured that precautionary protective measures were always adhered to.

Results

Scanning time for each horse varied between 90 to 120 minutes. As more horses were measured, scanning time decreased due to routine setting in, the first horse took the longest to measure at roughly two hours. Measurement distances varied up to 75 cm from the horse depending on the intensity of the emitted spectrum, as the spectrometer dead time increased to a paralysed state if the number of counts measured became too high. This effect became less problematic during the data collection period, as the intensity of ^{99m}Tc-MDP decreased due to its natural decay, and measurements could be taken closer to the horse. Since energy spectra were of interest and not their intensity, the decreased intensity due to natural decay did not compromise the study in any way.

The high resolution of energy channels of the spectrometer used, provided accurate information about changes in radiation quality from the radiopharmaceutical at the different specified anatomical sites. The resultant energy spectra obtained from the horses injected with ^{99m}Tc-MDP were evaluated with two areas of interest in mind, around which all the results and points for discussion are based. The first, and most important area of interest within the spectrum for the purpose of this study, was the quality of scatter radiation emitted from the horses. The Y-axis showed a broadened base indicating a larger distribution (low and high) of scatter energies, seen on especially those graphs where no shielding was used. The second area of interest was the quality of the emitted ^{99m}Tc peak, as it forms that part of the spectrum which is useful in nuclear imaging. All graphs depicted below show the relative number of counts on the Y-axis and the individual energy levels on the X-axis.

Figure 1: Pulse height spectrum of ^{99m}Tc as measured with a digital multichannel analyser showing the characteristic monochromatic peak at approximately 144.47 keV (white cross).

The characteristic narrow 140.5 keV peak of ^{99m}Tc (Figure 1) recorded before injection into the patient was no longer apparent 2.5 hours after injection, as shown and documented in a previous study (Didierlaurent et al. 2005). A broad polychromatic spectrum, seen as a wider range of scatter energies (from 60–140 keV) with its peak usually recorded around 88–94 keV, was emitted from the unshielded horses due to the interaction of the radioisotope within the equine body. A small, higher energy peak was seen at 140.5 keV; this was considered to represent the ^{99m}Tc peak.

The cross (X) corresponds to an activation marker inside the selected ROI such that the system reports the data for that specific ROI. The cross does not coincide with the centroid of the peak, which is located at 140.5 keV. The Y-axis shows the number of counts (events) for a specific energy level, the X-axis the different energy levels. Pertaining to the information in the grey area to the right of the spectrum:

Number in the top right-hand corner = computational number of no relevance

In = number of ionising events incident on the detector (not all may be recorded due to dead time artefacts)

Tru = number of recorded ionising events (counts)

Dead+ = the dead time of the device, the device can no longer record ionising events. The lower the percentage, the better

Channel = channel number used for this recording

Energy keV = energy recorded in a specific channel

Counts = first value: total counts in the particular channel, second value: total counts in the region of interest (ROI) which comprises several channels

Time = acquisition time (in seconds)

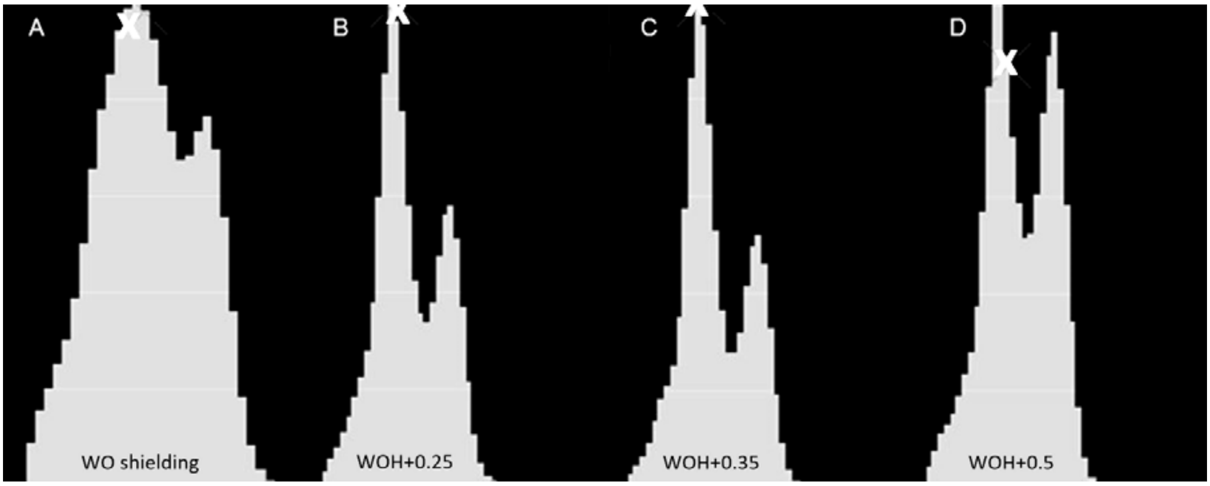
The unshielded radiation spectrum quality varied minimally between the various locations (Figures 2A–6A). With the application of lead shields representing personnel, the spectrum changed dramatically: a distinct narrowing of the spectrum with concurrent marked reduction (especially behind the 0.25 mm and 0.35 mm lead shields) of the 140.5 keV ^{99m}Tc peak was observed (Figures 5B, 6B and 6C). A deep trough is seen in the spectrum between the scatter and ^{99m}Tc peaks. This trough is deeper using 0.35 mm shields than using the 0.25 mm lead equivalent shields on graphs B and C. The 0.5 mm lead equivalent apron resulted in an unexpectedly high ^{99m}Tc peak and a filling in of the spectrum trough between the scatter and the ^{99m}Tc peak (Figures 2D, 3D and 6C). This phenomenon was consistently seen behind all 0.5 mm lead equivalent shields.

Energy spectra recorded in the front (HF) and at the side of the head (HC) were very similar in appearance. The only obvious difference was the height of the ^{99m}Tc peak. This was higher at the unshielded HC location and behind the 0.5 mm lead equivalent apron on personnel at the same location (Figures 3A and 3D). The most representative graphs of the spectra were recorded at HF and HC (Figures 2A–D and 3A–D). Spectra recorded behind 0.5 mm of lead equivalent shielding (on personnel) consistently showed a moderate increase in the region of the 140.5 keV peak at both head locations (Figures 2D and 3D). The scatter and ^{99m}Tc peaks were of nearly equal height and of similarly narrow shape. At both locations these peaks were higher than those on the pre-shielding recorded spectra.

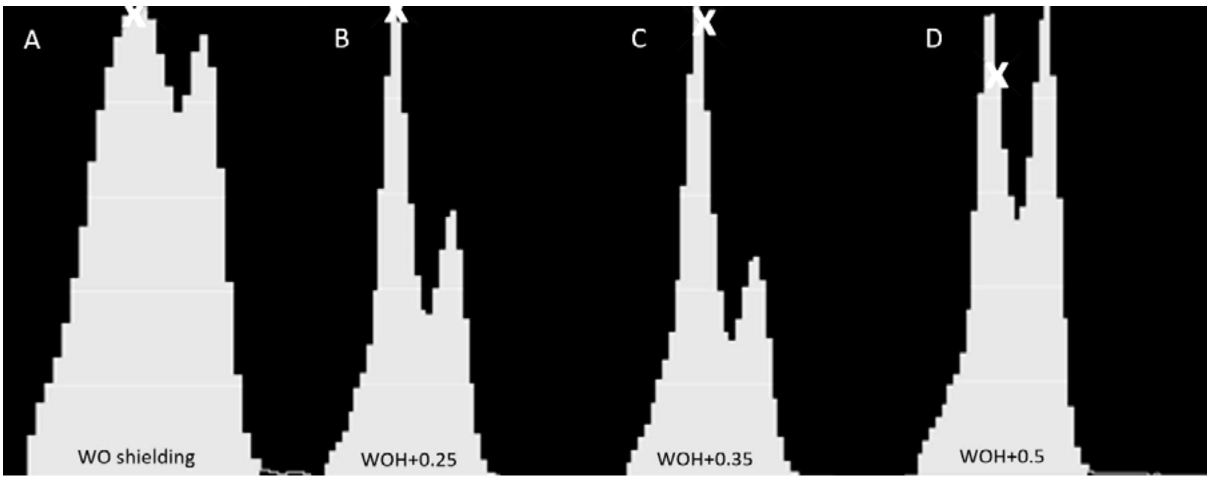
For the shoulder, bladder and pelvis regions, when lead shielding was placed on horses only, the emitted gamma spectra were consistently broader with higher troughs between the two peaks compared to the spectra that were obtained behind aprons representing personnel (Figures 4B, 4C, 5C, 6D and 6E). When lead shields representing personnel were applied, the spectrum became considerably narrower in appearance with the re-emergence of the two distinct peaks: one at 83–86 keV and a second smaller peak at around 140.5 keV (Figures 4D, 4E, 5D and 5E). Again, as seen at the head locations, the spectra behind 0.5 mm lead equivalent shields revealed an unexpected rise in the ^{99m}Tc peak, most noticeable behind the 0.5 mm on the horse and 0.5 mm on personnel combination (Figure 4E). The combination of the other two lead shield thicknesses on horses with the 0.5 mm on personnel produced a consistently higher ^{99m}Tc peak than the 0.5 mm placed on the horse and the other two thicknesses placed on personnel (Figures 4D, 5D and 5E).

All energy spectra recorded at the shoulder (S) showed a broadening of the spectrum along the X-axis compared to those made in the head regions (Figures 4A–E). The ^{99m}Tc peak was generally slightly higher in this region than the bladder or pelvic regions, a higher peak was recorded with 0.5 mm lead equivalent shielding on the horse than on pre-shielding spectra (Figures 4A and 4C).

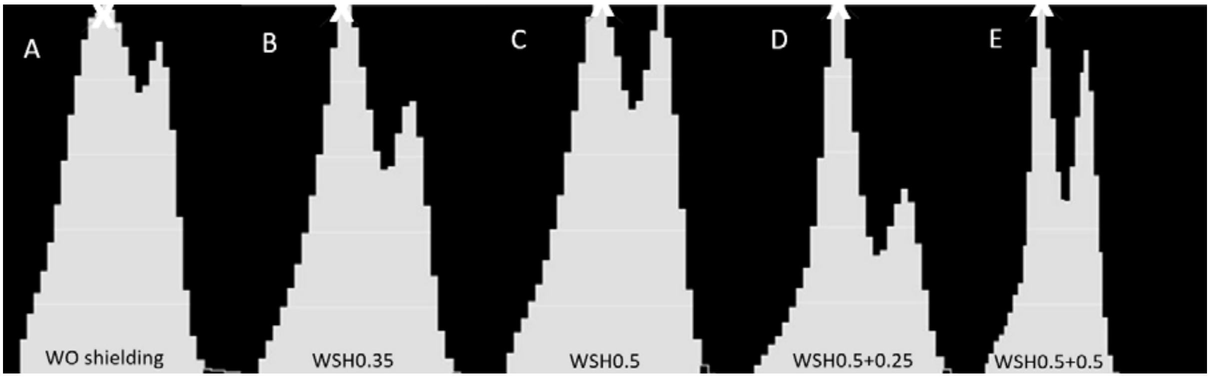
The broadest spectra were recorded in the bladder region, though the overall shape of the spectra at the various locations was similar in appearance to both the bladder and the pelvic regions (Figures 5A–E). Like other regions, the addition of a



Figures 2A–D: A qualitative representation of polychromatic radiation spectra recorded without or behind various lead shields at location Head Front (HF).
A. **No shielding:** The unshielded spectrum recorded at HF. The scatter peak is marked with a white cross at 94.21 keV.
B. **0.25 mm lead shielding on personnel:** A scatter peak at 81 keV and reduction in the ^{99m}Tc peak is seen. Spectral narrowing and shrinkage of the entire spectrum indicates a substantial reduction in net combined counts of ionising events.
C. **0.35 mm lead shielding on personnel:** A mild further reduction in the ^{99m}Tc peak and combined net counts is noted.
D. **0.5 mm lead shielding on personnel:** A marked rise in the ^{99m}Tc peak is apparent.



Figures 3A–D: A qualitative representation of polychromatic radiation spectra recorded without or behind various lead shields at location Head Cheek (HC).
A. **No shielding:** The unshielded spectrum recorded at HC. The scatter peak is marked with a white cross at 94.21 keV (same as in 2A). Note the higher ^{99m}Tc peak than in 2A. This is most likely due to increased bone mass in this region.
B. **0.25 mm lead shielding on personnel:** The appearance of the recorded spectrum is very similar to 2A.
C. **0.35 mm lead shielding on personnel:** A slightly lower ^{99m}Tc peak compared to 2C is seen, the reason for this is unknown.
D. **0.5 mm lead shielding on personnel:** The ^{99m}Tc peak is higher at the HC level than at 2D. This is most likely due to the increased uptake of ^{99m}Tc in bone.



Figures 4A–E: A qualitative representation of polychromatic radiation spectra recorded without or behind various lead shields at location Shoulder (S).

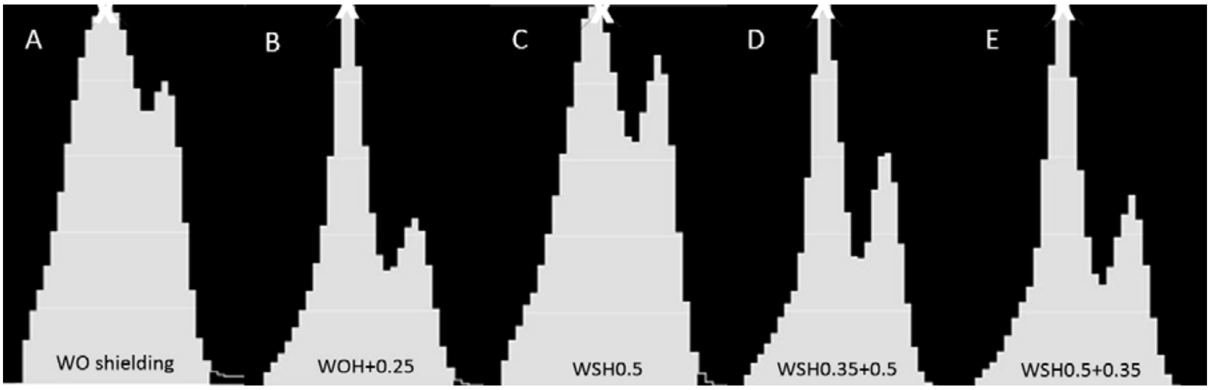
A. **No shielding**: The non-shielded spectrum is very similar in appearance to the spectrum recorded at the HC position (Figure 3A), with a high ^{99m}Tc peak indicating high bone mass.

B. **0.35 mm lead shielding on the horse:** The scatter peak was measured at 86 keV and the height of the ^{99m}Tc peak is reduced relative to the pre-shielding emissions.

C. **0.5 mm lead shielding on the horse:** The height of the ^{99m}Tc peak is increased compared to Fig. 4A. The overall spectrum is slightly broader than A. This indicates more recorded ionising events over a broader spectrum of energies.

D. **0.5 mm on the horse and 0.25 mm lead shielding on personnel:** An obvious narrowing of the spectrum, mild shift to the right as well as a marked reduction of the ^{99m}Tc peak height is apparent.

E. **0.5 mm on the horse and 0.5 mm lead shielding on personnel:** Although this spectrum is the narrowest of all combinations here, the height region of the ^{99m}Tc peak is increased again, increasing the trough between the two peaks.



Figures 5A–E: A qualitative representation of polychromatic radiation spectra recorded without or behind various lead shields at location Bladder (B).

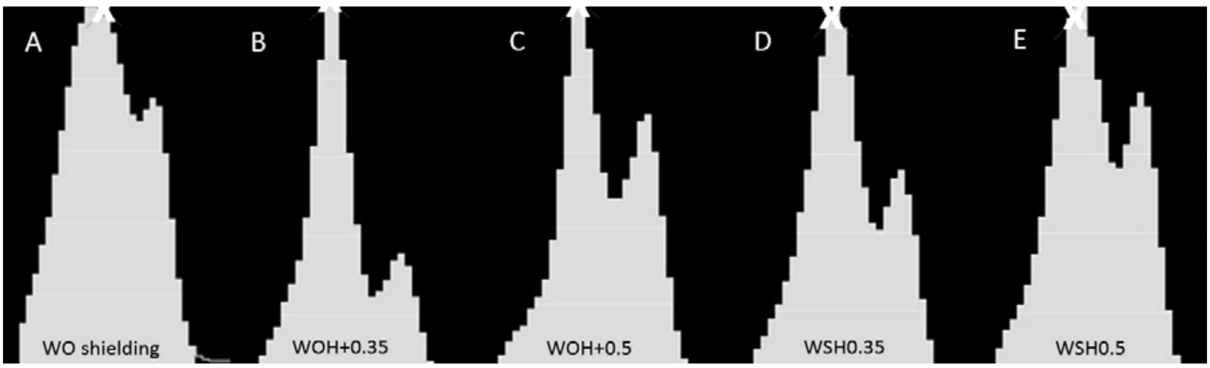
A. **No shielding**: Similar in appearance to the other non-shielded recorded spectra.

B. **0.25 mm lead shielding on personnel:** An obvious decrease in total combined net scatter counts as well as a marked reduction of the ^{99m}Tc peak height is seen.

C. **0.5 mm lead shielding on horse:** The height of the ^{99m}Tc peak is increased compared to Figures 5B–D. The overall spectrum is broad, the trough is high up in the spectrum indicating an increased number of ionising events.

D. **0.35 mm on the horse and 0.5 mm lead shielding on personnel:** A mild increase in the region of the ^{99m}Tc peak is noted, whilst the overall shape stays similar to B.

E. **0.5 mm on the horse and 0.35 mm lead shielding on personnel:** With the switching of 0.5 mm and 0.35 mm lead equivalent aprons on horse and personnel, a reduction of the ^{99m}Tc peak height is seen (compare to D).



Figures 6A–E: A qualitative representation of polychromatic radiation spectra recorded without or behind various lead shields at location Pelvis (P).

A. **No shielding:** The overall shape of this spectrum is similar to the other regions.

B. **0.35 mm lead shielding on personnel:** The spectrum is narrower and lower here with the lowest ^{99m}Tc peak than the other spectra.

C. **0.5 mm lead shielding on personnel:** Similar in appearance to D but the region of ^{99m}Tc peak is slightly lower.

D. **0.35 mm lead shielding on horse:** Note how much higher the scatter and ^{99m}Tc peaks are compared to when the lead shield is used on personnel (Figure 6B).

E. **0.5 mm lead shielding on horse:** Compared to D the ^{99m}Tc peak is higher and the spectrum has an overall broader appearance with a higher lying trough.

0.5 mm lead equivalent apron increased the height of the ^{99m}Tc peak (Figure 5C) compared to the recorded pre-shielded spectra (Figure 5A).

Discussion

The use of personal protective equipment is common practice during radiography of veterinary patients (Tyson et al. 2011; Mayer et al. 2018; Shirangi et al. 2007; Schürnbrand et al. 1982; Prussin et al. 1998). The use of lead aprons during bone scintigraphy of horses is not routinely employed, for fear that it may result in beam hardening effects as well as emitting characteristic x-rays through the K-edge of lead, and thus rendering the emitted scatter radiation biologically more hazardous than if lead shields were not used at all (Steyn & Uhrig 2005). Spectrometer recordings of energy spectra emitted from five horses undergoing bone scintigraphy showed how the quality and quantity of scatter (and also ^{99m}Tc) changed when using various thicknesses of lead shielding. While a Geiger-Müller counter merely determines count rates for radiation, gamma spectroscopy can determine both the count rate and the energy of the radiation. This is important as different radioisotopes emit many gamma rays of differing energies. A gamma spectrum is created by taking measurements of emitted gamma rays with a spectrometer detector and digitally processing them. Although it was not possible to standardise a distance from the horse surface to the recording detector, as the distance was dependent on the dead time of the system, and varied between horses, it was felt that this variation would not affect the qualitative component of recorded energy spectra in any way. Recording of spectra at the designated, randomised locations took between 90 to 120 minutes to complete. As the effective half-life of ^{99m}Tc (4.8 hrs) exceeded measurement time (2.5 hr delay and a maximum of two hours measuring time = 4.5 hrs), random variation in measurement location order was not considered problematic although some decay would have taken place. Again, this was not expected to affect the quality of the emitted energy spectrum at all.

As expected, and previously documented (Didierlaurent et al. 2005), the energy spectrum emitted from the surfaces of horses 2.5 hours after an intravenous injection of ^{99m}Tc was vastly different from the almost monochromatic recorded peak of pure ^{99m}Tc (Figure 1). In the former, the 140.5 keV peak was markedly reduced in height and overshadowed by a broader spectrum of lower energies, which had an average of 86.5 keV (shoulder region) to 92.1 keV (head front region). The spectrometer generally recorded the highest average scatter energy directly in front of the horses' heads (HF). The reason for this is thought to be due to scant soft tissue coverage of the underlying skull. This may result in a relatively harder (higher energy) scatter energy peak due to a reduced Compton scatter effect, normally seen in soft tissue, of the 140.5 keV gamma radiation emitted by the injected ^{99m}Tc. Compared to the head front region, the head cheek region had higher recorded ^{99m}Tc peaks. This finding was expected to be the result of the higher bone density at the latter location, compared to the rostral/dorsal aspects of the head, which contain largely air-filled paranasal sinuses and nasal passages. In the regions where more soft tissue mass is present due to muscle mass and internal organs, the energy peaks were lower and the spectrum broader due to an increase in the emitted scatter energy range. The shoulder, bladder and pelvic regions all had average scatter energy peaks of less than 88 keV. The ^{99m}Tc peak was higher in the shoulder region than the bladder or pelvis regions. This is most likely because the shoulder region is narrower than the bladder or pelvis regions and the bone to soft tissue ratio is higher than at the other two regions.

As soon as lead shielding was introduced, there was a slight left shift of the energy spectrum toward lower energies. There was an emergence of distinct lower energy (86 keV) peaks, most likely resulting from both the photoelectric effect of lead and the production of characteristic x-rays, as well as scatter radiation. The scatter peaks were predominantly centred at 82–88 keV, which coincides with the different K-edges of lead (88.008, 87.367, 84.936, 84.450, 74.969 and 72.804 keV from the K shell transitions to the N, M, M, L and L shells respectively) (Robinson 1976).

The ^{99m}Tc peak height was variably reduced depending on the lead shield combination used. It was lowest with 0.25 mm and 0.35 mm lead equivalent aprons and highest with 0.5 mm lead equivalent aprons. The most pronounced effect occurred when combining 0.5 mm lead equivalent shielding on horses with the same thickness on phantoms. Why the latter occurred is unclear. It is speculated that thicker lead has a higher efficiency in removing scatter radiation, thus resulting in a relatively higher radioisotope peak, or that unknown alloys in the thicker lead may produce characteristic x-rays in that specific (138–143 keV) energy range. Manufacturers were reluctant to release information regarding the mixture of metals within the lead aprons used in this study. A noticeable trend was that regions with higher recorded ^{99m}Tc peaks to begin with, also had higher recorded peaks with the 0.5 mm lead equivalent shields. The reason for this is unknown.

All spectra recorded behind lead shields demonstrated a slight slant of the lower energy scale towards the right on the X-axis, without affecting the peak energy recordings of 82–88 keV. This finding suggests that although the lower energies were absorbed by the lead shields, it did not result in an overall beam hardening effect. The latter would have been seen as a shift of the peak energy to the right on the X-axis.

The height of the ^{99m}Tc peak was markedly reduced when 0.25 mm or 0.35 mm lead equivalent lead aprons were added. The most effective reduction was achieved with 0.35 mm lead aprons, thus was regarded as being the ideal lead equivalent apron to use on personnel in a clinical setting.

In regions with greater soft tissue coverage (shoulder, bladder and to a lesser extent pelvis) broader and higher scatter peaks were recorded, the second peak seen with 0.5 mm lead shields was also increased.

Although the lower energy characteristic x-rays produced by lead are biologically more hazardous than the 140.5 keV gamma peak emitted by the radioisotope, the average scatter energy recorded by the spectrometer without any lead shielding of all anatomical regions used in this study showed a similar energy range to that of the K-edges of lead and thus would expose personnel to biologically more hazardous radiation in any event. The recorded individual ionising events provided a rough quantitative assessment. This means that each channel recording a specific energy from the emitted (scatter) energy spectrum also recorded the amount of ionising events occurring in that channel. These counts, along with the quality of the energy spectra produced by the varying lead shield combinations, were used to make deductions as to which lead shield combination would provide the best protection for bystanding personnel. A moderate to severe reduction in counts, when the combination of 0.5 mm was used on the horse, and 0.35 mm was used on the phantom, was noted, and is thus proposed as the best combination to use for protection of bystanding personnel. A study in humans (Warren-Forwardet al. 2007) using lead and lightweight aprons for shielding of ^{99m}Tc radiation concluded that lightweight aprons provided better reduction at energies < 95 keV, though lead was 35% more efficient at higher energies. Such studies may be useful to conduct in the veterinary field, given the at times lengthy equine scintigraphic procedures. The useful emitted 140.5 keV ^{99m}Tc peak needed to create the scintigraphic image plays a small part in the energy spectrum emitted by the horse.

Limitations of this study

The major limitations of this study were the small number of horses measured and the (albeit small) variation in the distance from the horse whilst measurements were recorded. Further studies are needed to evaluate the energy spectra of non-leaded (lightweight) shields to determine their clinical usefulness in equine bone scintigraphy.

Conclusion

The results of this study show that the use of any variation of lead shields, except where 0.5 mm lead equivalent is used on both the horse and on personnel, is encouraged. Draping a 0.5 mm lead equivalent apron over the horse and using a 0.35 mm lead equivalent apron on personnel likely provides the best protection against the potentially hazardous scatter effects of gamma radiation during scintigraphy in horses. The use of a 0.5 mm lead equivalent apron on personnel is discouraged due to a rise (of unconfirmed origin) in the second energy peak. Unequivocal evidence of beam hardening effects resulting from the use of lead shields in equine bone scintigraphy could not be demonstrated, which confirms our research hypothesis.

Acknowledgements

The authors wish to thank NRF iThemba LABS Old Faure Rd Cape Town, South Africa, for the generous use of the multichannel analyser and the expertise of their radiation biophysicist in this project, and Professor Eberhard Ludewig, University of Leipzig for reading through and assisting with the manuscript. The Flemish Inter University Council (VLIR) for financial support.

Conflict of interest

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article

Funding source

This research received grants from the Section of Diagnostic Imaging, Department of Companion Animal Clinical Studies, Department of Companion Animal Clinical Studies, Abe Bailey Trust Fund.

Ethical approval

The study was approved by the Animal Use and Care Committee of the University of Pretoria (V004/06).

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