Beam hardening effects of lead shielding during bone scintigraphy in the horse

by

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To Dominic, Biggi and Steffi

"For the Lord gives wisdom,
and from His mouth comes knowledge and understanding"

Prov.2:6

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List of Abbreviations

ALARA	as low as reasonably achievable
ANOVA	analysis of variance
Ave	average
B	bladder
C	charge
Bq	Becquerel
Ci	Curie
DNA	deoxyribonucleic acid
FWHM	full width half maximum
γ–ray	gamma ray
Gy	Gray
HC	head cheek
HDP	disodium oxydronate
HF	head front
HVL	half-value layer
IAEA	International Atomic Energy Association
ICRP	International Commission for Radiation Protection
IRU	increased radiopharmaceutical uptake
keV	kiloelectron volts
LET	linear energy transfer
LiF	lithium fluoride
µm	micrometer
MCA	multi-channel analyser
MDP	methylene diphosphonate
MHDP	methylene hydroxydiphosphonate
NaI:TI	sodium iodide
OVAH	Onderstepoort Veterinary Academic Hospital
P	pelvis
PHA	pulse height analyzer
PMT	photomultiplier tube
Rad	radiation absorbed dose
R	Roentgen
RBE	relative biologic effectiveness
ROI	region of interest
S	shoulder

SCA	single-channel analyser\
SD	standard deviation
Sv	Sievert
SD	standard deviation
$T_{1/2}$	half-life
^{99m}Tc	^{99m}technetium
TcO4-	technetium pertechnetate
TLD	thermoluminescent dosimeter
WOH	without any form of lead shielding on horse
WSH	with lead shielding on horse
WOH+0.25	without shielding on horse, 0.25mm lead equivalent shield on personnel
WOH+0.35	without shielding on horse, 0.35mm lead equivalent shield on personnel
WOH+0.5	without shielding on horse, 0.5mm lead equivalent shield on personnel
WSH0.35	with 0.35mm lead equivalent shield on horse
WSH0.5	with 0.5mm lead equivalent shield on horse
WSH0.35+0.25	with 0.35mm lead equivalent shield on horse, 0.25mm lead equivalent shield on personnel
WSH0.35+0.35	with 0.35mm lead equivalent shield on horse, 0.35mm lead equivalent shield on personnel
WSH0.35+0.5	with 0.35mm lead equivalent shield on horse, 0.5mm lead equivalent shield on personnel
WSH0.5+0.25	with 0.5mm lead equivalent shield on horse, 0.25mm lead equivalent shield on personnel
WSH0.5+0.35	with 0.5mm lead equivalent shield on horse, 0.35mm lead equivalent shield on personnel
WSH0.5+0.5	with 0.5mm lead equivalent shield on horse, 0.5mm lead equivalent shield on personnel

Summary

Beam hardening effects of lead shielding during bone scintigraphy in the horse
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Lameness in the horse is one of the most common clinical entities encountered in equine veterinary practice. Obscure lamenesses, equivocal radiographic findings or non–definable lameness that does not respond to regional anaesthesia, often warrant the use of further, more advanced diagnostic imaging modalities such as nuclear scintigraphy.

Bone scintigraphy in the horse is a useful diagnostic imaging modality to help identify sites of active bone metabolism, identified as increased radiopharmaceutical uptake (IRU) in the affected area on a scintigram. The radioactive nuclide, ^{99m}technetium (^{99m}Tc), is bound to freeze-dried and specially prepared pharmaceutical compounds such as methylene-diphosphonate (MDP) or disodium-oxydronate (HDP) and methylene-hydroxy-diphosphonate (MHDP), resulting in radiopharmaceuticals which are readily absorbed in areas of increased osteogenic activity. Usually, ^{99m}Tc–MDP is injected into a horse intravenously and the bone phase initiated approximately 2.5 to 3 hours later. Depending on the presenting complaint and clinicians' requests, the procedure may involve extensive parts of the horse's anatomy and thus personnel may be subjected to at least 1.5 to 2 hours of scanning time.

^{99m}Technetium is a metastable compound which decays by means of gamma ray emission, the majority of which are at an energy peak of 140.5keV. Once injected into the horse, there is extensive interaction within various tissues of the patient, but especially within large masses of muscle and bone. The resulting emitted polychromatic beam emanating from the horse has a vast spectrum of radiation energies. These energies emitted from the surface of the patient reach bystanding personnel with resultant radiation exposure. It is thus of paramount importance to establish the amount of radiation to which personnel are subjected, and whether conventional lead shielding as used in radiography, decreases the exposure during scintigraphic examinations. Due to the fact that there is interaction of the emitted radiation energies within the lead apron itself, resultant characteristic radiation produced by this interaction may theoretically be more harmful than the polychromatic spectrum emitted from the horse. The removal of lower energy radiation and thereby increasing the average energy of a spectrum is known as beam hardening.

Five average sized horses were scanned without lead shields and using combinations of lead shields of varying lead thicknesses on the horse and lead aprons as would be worn by personnel. All resultant energy spectra were measured with a spectrometer and recorded.

The energies emitted from horses injected with ^{99m}Tc–MDP differed from the energy spectrum of the pure, non–injected radiopharmaceutical. A large component of lower energies was emitted as a result of patient physical matter interaction. These energies averaged at 88–90keV. Once lead shielding was applied, two energy peaks were seen, one at 83–88keV and another at the typical gamma peak of 140.5keV for ^{99m}Tc. Depending on the thickness of the lead shielding, the heights of the two peaks varied. Generally, the thicker the lead coats, or combined lead coats (on the patient and on personnel), the smaller the 140.5keV peak and the higher the 83–88keV peak. This finding was attributed to characteristic x-rays emitted from the lead shielding through the interaction with the 140.5keV of ^{99m}Tc. Surprisingly, there was no evidence of the expected beam hardening, the average energy of the spectrum before lead shielding was higher (up to 94.1keV) than the average energy of the spectrum recorded behind lead shielding (up to 88keV). Instead, lead shielding resulted in slight "softening" of the typical ^{99m}Tc gamma spectrum. The 140.5keV peak from technetium is theoretically biologically safer than the 83–88keV peak emitted by characteristic radiation of lead coats. Personnel were exposed to lower energy scatter emitted from the horse at any rate, regardless of any application of lead shielding. The overall intensity of radiation exposure behind lead shielding, however, was reduced by 90%.

Therefore, despite altering the gamma spectrum of ^{99m}Tc into a biologically potentially more harmful lower peak of 83keV, the wearing of lead shielding during bone scintigraphy is strongly recommended, as it not only reduced the intensity of radiation considerably, but also removes the harmful lower energy scatter emitted from the patient that would otherwise reach bystanding personnel.

Further studies are needed to assess the ability of non-leaded shields to effectively shield the polychromatic energy spectrum emitted from horses during bone scintigraphy, and analyse the characteristic energy spectra emitted by these shields.

Chapter 1: Introduction

1.1   Background

Lameness in the horse is one of the most common clinical presentations with which an equine veterinarian is faced. Identifying the source of lameness is a skill that often requires a careful workup, considerable expertise and extensive experience. Even then, there are many cases that have confusing, equivocal findings clinically, radiographically or ultrasonographically. Such cases may benefit from bone scintigraphy using ^{99m}Tc–MDP. Due to the nature of the procedure, animal handlers and radiographers need to be present and mobile during the examination. Horses are unpredictable and may damage equipment or suffer further injuries if left unattended. Since these patients often require an extensive examination, attending personnel may be exposed to radiation for a considerable length of time. There are two opposing schools of thought on how to protect, and thereby reduce radiation to bystanding personnel: those that advocate the use of lead aprons and those that do not. Those that recommend the use of lead aprons do so based on studies that have been performed previously, demonstrating that the wearing of lead aprons reduces the intensity of personnel exposure considerably (Dyson *et al.* 2003; Steyn *et al.* 2005). One such study (Dyson *et al.* 2003) was performed with custom–made lead aprons placed on the patient and standard 0.5mm lead equivalent lead aprons worn by attending personnel. Those that do not advise wearing lead aprons do so based on the supposition that lead interacts with the emitted radiation, removes the "softer", weaker scatter energies and results in a "harder" more energetic spectrum, by emission of characteristic x–rays, which, upon interaction with bystanding personnel, would potentially be more harmful. There are no studies that prove the latter theory. This study will partially address this discrepancy and attempt to rectify some of this lack in knowledge.

1.2   Problem statement

Very little knowledge is available regarding the energy spectrum emitted from the horse 2–3 hours after injection of ^{99m}Tc during bone scintigraphy and no literature is available regarding the potential change of the emitted energy spectrum of ^{99m}Tc behind lead aprons, either on the patient or on bystanding personnel. This knowledge may be vital in implementing correct and adequate shielding of attending personnel during bone scintigraphy in the horse.

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1.3 Research questions

1. What is the appearance of the energy spectrum of ^{99m}Tc emitted from an equine patient approximately 2-3 hours post injection <u>without</u> lead shielding?

2. How does the energy spectrum, emitted from the patient behind lead shields of varying thicknesses, change?

3. Is there a significant difference in the recorded energy spectrum with lead shielding on the patient and /or personnel?

4. Should lead shields be recommended during bone scintigraphy in the horse?

5. If so, which combination of shields would be best to use?

1.4 Hypotheses

We hypothesize that:

1. The emitted energy spectrum from an equine patient without any form of lead shielding is broad and contains a large proportion of potentially harmful energies that reach attending personnel during scintigraphic examinations

2. The emitted polychromatic gamma spectrum of ^{99m}Tc–MDP, commonly used for bone scintigraphy in horses, would change significantly behind lead shielding worn by the patient and/or personnel with varying lead thicknesses

3. This change would result in a less potential harmful radiation spectrum behind the lead aprons than that emitted by the patient

4. The lower energies (60 to 100keV range), which are harmful, will be absorbed by the lead aprons

5. "Beam hardening" effects, if present, would not be enough to preclude the use of lead aprons during bone scintigraphy of the horse

1.5   Objective

The main objective of the study is to determine how the energy spectrum of ^{99m}Tc emitted gamma radiation changes behind lead aprons placed on the horse and worn by personnel with different lead thicknesses. This information serves to determine whether "beam hardening" effects take place. If it does, a further objective is to determine at what level of shielding (and/or which distance from the horse) this phenomenon is most obvious. The nature of the research to be undertaken is predominantly qualitative. Quantitative measurements of radiation exposure will also be included for interest, but have already been established and documented in the literature (Dyson *et al.* 2003; Steyn *et al.* 2005).

1.6   Benefits

1.   Determining the effect of shielding on the pulse height spectrum of ^{99m}Tc–MDP (qualitative analysis)

2.   Determining the amount of radiation exposure to personnel with and without lead shielding (quantitative analysis)

3.   Potential future radiation exposure reduction of personnel during bone scintigraphy of the horse due to routine use of lead aprons

Chapter 2: Literature review

2.1 Introduction

2.1.1 Basic radiation physics

To best understand the background to the study, the basics of radiation physics, radiation biology, radiation protection and nuclear scintigraphy follows.

Radiation is defined as energy that emanates from a source and travels through material, tissue or space. Ionising radiation is produced by unstable atoms and results in the removal of an orbital electron of an atom in the target material or tissue, and may be classified into two categories: particulate and electromagnetic radiation. Particulate radiation is associated with alpha and beta particles in radioactive decay. X–rays and gamma (γ) rays are forms of electromagnetic radiation. Gamma rays are produced within the nucleus of a radioisotope and x–rays are produced outside the nucleus in the electron shells. X- and γ–rays are often referred to as photons. Photons have no mass or charge. Photon radiation loses intensity with distance but theoretically intensity never reaches zero (Bushberg 2011).

Electromagnetic radiation interacts with matter in five different ways, of which only two, Compton scattering and photoelectric effect are important in diagnostic imaging (Bushong 2008). In the Compton effect, the incident photon interacts with an outer-shell (valence) electron of the target matter and ejects it from the atom, thereby ionising the atom. The ejected electron is called a Compton electron or a secondary electron. The incident photon continues in a different direction with less energy. Both the scattered photon and the Compton electron may have sufficient energy to undergo additional ionising interactions before losing all their energy. Ultimately, the scattered photon is absorbed photoelectrically. Compton scattered photons can be deflected in any direction, including 180° from the incident photon. Scattered photons from Compton reactions pose a serious radiation exposure hazard in diagnostic imaging. As radiation energy increases, Compton scattering increases relative to the photoelectric effect (Bushberg 2011).

The photoelectric effect describes incident photons that undergo ionising interactions with inner–shell electrons. The incident photon disappears, and the inner–shell electron, now called a photoelectron, is ejected from the atom. Characteristic x–rays may be produced after a photoelectric effect. Ejection of the inner–shell electron by the incident photon results in a vacancy within that shell. This unnatural state is immediately corrected when an outer– shell electron drops into the vacancy. This electron transition is accompanied by the

emission of an x–ray whose energy is equal to the difference between binding energies of the shells involved. The characteristic x–rays consist of secondary radiation and behave in the same manner as scattered radiation (Bushberg 2011).

The K–edge describes a sudden increase in the attenuation (= reduction in radiation intensity that results from absorption and scattering) coefficient of photons occurring at a photon energy just above the binding energy of the K–shell electron of the atoms interacting with the photons. The sudden increase in attenuation is due to photoelectric absorption of the photons.

Beam hardening refers to a process whereby the average energy level of an ionizing radiation beam (x– or γ–ray) is increased by filtering out (for example, by a lead apron) the low energy photons. This process results in a "harder" (ie. average higher energy) beam that is potentially more harmful than the original beam. The average energy increases with absorber (ie. lead apron) thickness (Cherry *et al*. 2012)

Röntgen (R) (or Gray (Gy)) is the unit of radiation exposure or intensity. It is expressed in terms of electric charge per unit mass of air (1R = 2.58 x 10^{-4}C/kg) Charge (C) refers to the electrons liberated by ionisation.

The rad (centi Gy) is the unit of radiation absorbed dose (Rad), most often used when describing the amount of radiation received by a patient. The rad is used for any type of ionising radiation and any exposed matter.

The rem (centi Sievert (Sv)) is the unit of occupational radiation exposure. It is used to express the quantity of radiation received by radiation workers and the general population. Some types of radiation produce more damage than γ- or x-rays. The rem accounts for these differences in biological effectiveness.

The Curie (Ci) (or Becquerel (Bq)) is the unit of quantity of radioactive material, commonly expressed as millicuries (mCi). One Curie is that quantity of radioactivity in which 3.7 x 10^{10} nuclei disintegrate every second. One Bq = 37mCi (Bushong 2008).

2.2 Radiation biology

There are many factors that determine the biologic response to radiation exposure. These factors may be related to the radiation source and the biological system being irradiated.

Radiation–related factors include absorbed dose (quantity), dose rate and the type and energy of the radiation.

Biological system–related factors include variables inherent to the cells themselves (some cells are more radiation resistant than others, (see below) and the condition of the cells at the time of irradiation.

Some responses to radiation exposure appear instantaneously or within minutes to hours, whilst others take weeks, years or even decades to appear (Bushberg 2011).

2.2.1   Classification of radiation biology

Biological effects of radiation exposure may be classified as *stochastic* or *deterministic* effects (non-stochastic in nature).

Stochastic effects are those that may or may not happen and in which the probability of the effect occurring increases with dose. Stochastic effects are believed to not have a dose threshold, therefore even a minor exposure may carry some, albeit small increased risk of an effect occuring. Examples of stochastic effects are radiation induced cancer and hereditary effects.

Deterministic effects require much higher doses to produce a clinically observable effect and there is a threshold dose below which the effect will not occur. An increase in dose results in an increase of severity of the effect. Examples of deterministic effects are skin erythema, fibrosis, and haematopoetic damage due to large radiation exposures (Bushberg 2011).

2.2.2   Interaction of radiation with tissue

As described above, x–ray and gamma ray photon interaction with matter, result in the production of energetic electrons. These electrons transfer their kinetic energy to their environment via excitation, ionisation and thermal heating. This triggers a cascade of events whereby secondary ionisations set more (sometimes as many as 1000) low–energy electrons (referred to as delta rays) in motion, causing additional excitation and ionisation along the path of the original energetic electron. This chain of ionisations ultimately gives rise to subexcitation electrons that become thermalized as they transfer their remaining kinetic energy by vibrational, rotational and collisional energy exchanges with water molecules (Bushberg 2011).

Cellular injury can occur in three ways:

1. Division delay: a dose dependent delay in cell division. Mitotic division is delayed but returns to near normal for unknown reasons. This is seen in doses greater than 0.5 Gy (50 rads) up to 3 Gy (300 rads).

2. Reproductive failure: cells fail to complete mitosis either immediately or after one or more generations. At levels at or below 1.5 Gy (150 rads), this type of failure is random and linear. At doses above 1.5 Gy (150 rads) it is non-linear and non-random. As the dose increases, so does reproductive death.

3. Interphase death: a relative prompt death caused by apoptosis. It can occur many generations from the initial radiation exposure. It depends on the type of affected cell and the dose to the cell. Rapidly dividing undifferentiated cells exhibit interphase death at lower doses (Bolus 2001).

If ionising events occur near the deoxyribonucleic acid (DNA) of a cell, they can produce multiple sites of damage. Repair of radiation damage occurs via a complex series of enzymes and co-factors which repair most of the radiation-induced DNA lesions within hours. However, clinical manifestation of radiation–induced damage, may take months or even years to appear. Only a fraction of the radiation energy deposited brings about chemical changes, most of it deposited as heat. The heat produced is of little biological consequence (Bushberg 2011).

Cells vary in their susceptibility to radiation damage. The response to radiation is related to cell type. Metabolically active (rapidly dividing cells) are the most sensitive, whilst well–differentiated cells are the least sensitive to the effects of radiation. Embryological tissue, due to the high metabolic rate and rapid division, is highly sensitive to radiation damage (Bushong 2008). See Table 1 below.

Linear Energy Transfer (LET) is a measure of the rate at which energy is transferred from ionising radiation to soft tissue. It is expressed in units of kiloelectron volt of energy transferred per micrometer of track length in soft tissue (keV/µm).

Relative Biologic Effectiveness (RBE): as the LET of radiation increases, the probability of biologic damage also increases. This relative effect is quantitively described by the relative biologic effectiveness by the following equation:

$$RBE = \frac{\text{Dose of reference radiation necessary to produce a given effect}}{\text{Dose of test radiation necessary to produce the same effect}}$$

Diagnostic x–rays, for example, have a LET of 3keV/µm and a RBE of 1. The RBE is a useful tool that helps characterise the potential damage from the various types and energies of ionising radiation (Bushberg 2011; Bushong 2008).

Table 1: Relative radiosensitivity of various cell types

Radiosensitivity	Cell type	Effects
High	Lymphoid tissue	Atrophy
	Spermatogonia	Atrophy
	Erythroblasts	Suppression
	Intestinal crypt cells	Atrophy
	Embryological cells	Atrophy
Intermediate	Osteoblasts	Growth arrest
	Spermatids	Atrophy
Low	Muscle cells	Fibrosis
	Nerve cells	Necrosis

Adapted from Bushong (2008) Chapter 32, p 510

Hormesis

Hormesis is defined as the process in which exposure to a low dose of a chemical agent or environmental factor, such as radiation, that is damaging at higher doses induces an adaptive beneficial effect on the cell or organism. This suggests that low–dose radiation is beneficial and stimulates hormonal and immune responses to other toxic agents (Bushong 2008; Mattson 2008; Rattan 2008). Studies have shown that all-cause mortality and all-cause cancers (leukaemia and prostate cancer) were significantly lower for nuclear workers than for non–radiation workers (Rattan 2008), thus emphasizing the fact that low-dose radiation has a beneficial, protective, effect to radiation workers.

2.3 Radiation detection

Instruments were designed to detect radiation or to measure radiation, or to do both. Those designed for detection are used to indicate the presence of radiation. Instruments that measure the intensity of radiation are used to measure total radiation exposure.

2.3.1 Types of detectors

Three types of radiation detection devices are of particular importance in diagnostic imaging:

1. The gas–filled radiation detector is widely used to measure radiation intensity and to detect radioactive contamination. An example of this is the Geiger–Müller counter.

2. Thermoluminescence dosimetry is used for both patient and personnel radiation monitoring.

3. Scintillation detection forms the basis for the gamma camera, computed tomography detector arrays and spectrometers. It involves coupling a scintillator (light emitter) to an

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electronic light sensor such as a photomultiplier tube (PMT), photodiode, or silicon PMT. PMTs absorb the light emitted by the scintillator and re–emit it in the form of electrons via the photoelectric effect. The subsequent multiplication of those electrons (also called photo–electrons) results in an electrical pulse, which can then be analyzed and yield quantitative and qualitative information about the particle that originally struck the scintillator (Bushberg 2011).

2.3.2   Personnel dosimetry

The radiation exposures of radiation personnel must be monitored for both safety and regulatory purposes. Three main types of individual radiation recording devices (called *personnel dosimeters*), are used in diagnostic and nuclear imaging:

1. Film badges: consist of a small sealed packet of radiosensitive film that can be clipped to clothing. Radiation striking the film emulsion will subsequently darken the film. The amount of darkening is directly proportional to the absorbed dose. The film emulsion contains silver bromide, resulting in a higher effective atomic number than biological tissue, therefore, the dose to the film is not equal to the skin dose. Most film badges record doses from about 100µSv to 15Sv for photons and 500µSv to 10Sv for beta radiation.

2. Thermoluminescent (TLD) dosimeters: these dosimeters contain storage phosphors (most commonly lithium fluoride (LiF)) with effective atomic numbers closer to that of tissue. They can record doses in the region of 100µSv to 15Sv and are re–usable but are more expensive than film badges.

3. Pocket dosimeters: the major disadvantage of the first two dosimeters is that the accumulated dose is not displayed immediately. Pocket dosimeters measure radiation exposure and can be read immediately. The analogue version is a pocket ion chamber, which can detect energies greater than 20keV. Single ionising events can be accurately recorded. These are the most expensive dosimeters. The most commonly used models measure exposures from 10µSv to 100mSv.

A dosimeter is typically worn on the part of the body that is expected to receive the heaviest radiation dose, or is most sensitive to radiation damage. Most personnel wear them at waist or shirt–pocket level. A study has shown that readings obtained from the collar or waist level were similar (Lundberg *et al.* 2002).

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Common problems associated with dosimetry include contamination of the dosimeter, not worn, lost and damaged dosimeters and dosimeters left in radiation fields (Bushberg 2011; Bushong 2008).

The International Commission for Radiation Protection (ICRP) defines the rules for radiation exposures and issue recommendations to world's regulators. It is therefore compulsory to wear a dosimeter so that legal limits for radiation exposure to personnel can be carefully monitored and appropriate actions taken should any limits be exceeded. Members of the ICRP meet every seven years to review and recommend changes if necessary.

All International Atomic Energy Association (IAEA) members (including South Africa) are bound by international treaties to implement these recommendations. Table 2 lists the annual recommended exposure limits for radiation workers.

Table 2: Recommended ICRP dose limits to various body regions per annum.

Body region	Recommended exposure limit / annum
Whole body (deep dose)	50 mSv (but < 100 mSv per 5 years, which averages to 20 mSv per annum)
Skin (shallow dose)	500 mSv
Extremities (hands and feet)	500 mSv
Lens of the eye (cornea)	150 mSv
Internal dose	5 mSv

Adapted from Bushong (2008) Chapter 40, p619; ICRP = International Commission for Radiation Protection

It is up to the facility working with radiation to determine if it wants to accept the above limits as their own, or to set limits below the recommendations. As an example, our co-worker facility, iThemba LABS in Stellenbosch, South Africa, use 60% of the recommended legal limits as in–house limits for personnel. The South African Department of Health issues a "Red Flag" (which prohibits further exposure to radiation for at least one "Wearing Period" = one month) to anybody who records more than 4mSv on their dosimeter in a single Wearing Period (personal communication with iThemba LABS medical biophysicist).

2.3.3   Spectrometer

Spectroscopy is the study of the energy distribution of a radiation field. A spectrometer is a detector that yields information about the energy distribution of the incident radiation. A typical spectrometer is a scintillator operated in pulse mode, which means, the signal from each interaction is processed individually. The amplitude of each pulse is proportional to the energy deposited in the detector by the interaction causing that pulse. It is important to note

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that only a fraction of incident radiation interacts with the scintillator: most of it does not interact at all or passes right through.

A pulse height spectrum is usually depicted as a graph of the number of interactions depositing a particular amount of energy in the spectrometer as a function of energy. Scattered incident radiation may not be measured and therefore the pulse height spectrum is not completely identical to the actual energy spectrum of the incident radiation.

Scintillation detectors may be used with pulse height analysers (PHAs) which are electronic systems that may be used to perform pulse height spectroscopy and energy-selective counting. In energy-selective counting, only interactions that deposit energies within a certain energy range are counted.

Two types of PHAs are used: single–channel analysers (SCA) and multi–channel analysers (MCA), the latter determining energy spectra more efficiently than the former (Bushberg 2011).

There are a number of mechanisms by which, for example, a γ–ray can deposit energy in the detector, several of which deposit only a fraction of the incident photon energy.

Fig 1, below, shows that an incident photon can deposit its full energy by a photoelectric interaction (A) or by one or more Compton scatters followed by a photoelectric effect (B). If it interacts by Compton scattering and the scattered photon escapes the detector (C), then only a fraction of its energy will be deposited. The energy deposited depends on the scattering angle, with larger angles depositing larger energies. If an incident photon interacts by the photoelectric effect but a characteristic x–ray is formed which escapes the detector (D), then a fraction of the total energy will be lost. Most of the detectors are shielded to reduce interaction of natural background radiation and other nearby radiation sources. Incident photons may interact by Compton scattering in the shield, with the scattered photon striking the detector (E), or a characteristic x–ray may interact with the detector (F).

Most interactions of x–rays and gamma rays with a NaI:TI (sodium iodide activated with thallium) detector are with iodine atoms, because iodine has a much larger atomic number than sodium.
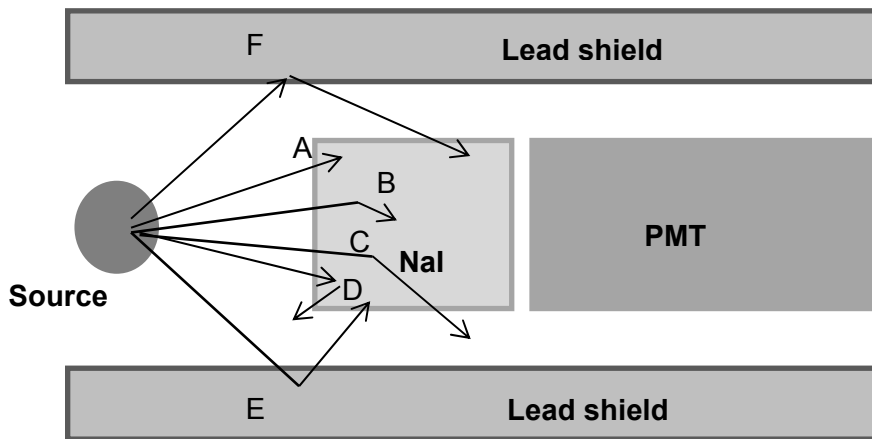
Fig 1. Interactions of x-rays and gamma rays with a NaI:TI detector.

A = complete absorption by photoelectric effect, B = Compton scatters followed by the photoelectric effect, C = Compton scatter and scattered photon escapes detector, D = photoelectric effect with escape of characteristic x-ray, E = Compton scatter with scattered photon striking the detector, F = Compton scatter and characteristic x-ray interacts with detector

NaI = sodium iodide; PMT = photomultiplier tube (Adapted from Bushberg 2011, Chapter 17, p655)

2.3.3.1 Performance characteristics of spectrometers

a. Energy resolution: this is the ability of a spectrometer to differentiate between photons or particles of different energies. The shape of the peak determines the resolution, that is, the wider the peak, the poorer the resolution and vice versa. The width is usually measured at half the maximum height of the peak, which is called the full width at half maximum (FWHM). The FWHM (from 635 to 682keV) is then divided by the pulse amplitude corresponding to the maximum of the peak (in this case 662keV) and multiplied by 100 to depict the energy resolution of a system as a percentage. (Fig 2)
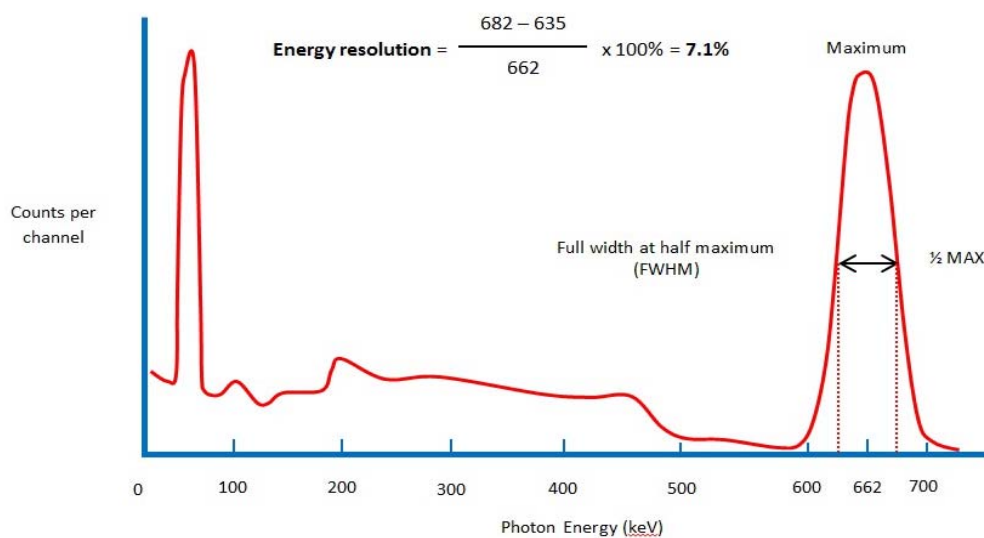
Fig 2 Energy resolution of a pulse height spectrometer.

The spectrum shown is that of ^{137}Cs, obtained by a NaI:TI scintillator coupled to a photomuliplier tube. Adapted from Bushberg 2011, Chapter 17, p657

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b. <u>Count-Rate effects in spectrometers</u>: these are best understood as a count pileup (= number of counts is too high). Dead time describes count pileup to the extent that the detector can no longer record a new event. Therefore dead time is the time after each event during which the system is not able to record another event.

c. <u>Paralyzing the spectrometer</u>: a detector, or detection system, can be characterized by paralyzable or non–paralyzable behaviour. In a non-paralyzable detector, an event happening during the dead time since the previous event is simply lost, so that with an increasing event rate the detector will reach a saturation rate equal to the inverse of the dead time. In a paralyzable detector, an event happening during the dead time since the previous one will not just be missed, but will restart the dead time, so that with increasing rate the detector will reach a saturation point where it will be incapable of recording any event at all.

Due to the above-described artefacts and the non-incident radiation that may contribute to recordings, a spectrometer is not designed to give accurate readings with regards to exposure rates and count reductions. It may provide a very rough estimation of count reduction, behind lead shielding for example, but for a more accurate exposure rates analysis, a dosimeter, which is specifically designed for such purposes, should be used.

2.3.4   Gamma camera

The gamma camera (also known as a scintillation camera) functions to detect γ–rays emitted by the radiopharmaceutical after its administration to the patient and to produce an image reflecting the distribution pattern of the radiopharmaceutical within the patient.

A gamma camera consists of one or more flat crystal planes (or detectors) optically coupled to an array of photomultiplier tubes, the assembly is known as a "head", mounted on a gantry. The gantry is connected to a computer system that both controls the operation of the camera as well as acquisition and storage of acquired images. The system accumulates counts of gamma photons that are absorbed by the crystal in the camera. Usually a large flat crystal of sodium iodide with thallium doping (NaI:Tl) in a light–sealed housing is used. The crystal scintillates (emits light) in response to incident gamma radiation. When a gamma photon interacts with an electron from an iodine atom in the crystal, a faint flash of light is produced. This process has been described in detail in paragraph 2.3.3 above.

2.4　Radiation protection

It is incumbent upon all individuals who work with radiation to strive for an optimal compromise between clinical need/utility of radiation and radiation doses to patients, staff and public. The success of radiation protection programs relies on the development of procedures that ensure safe use of radiation and radioactive material and on the education of staff about radiation safety principles, risks associated with radiation exposure and contamination, and the procedures for safe use.

2.4.1　The ALARA principle

This is the driving force for many policies, procedures and practices in a radiation working environment and represents a commitment by both employee and employer to minimise radiation exposure to staff and the public. This doctrine also incorporates the three most important aspects of radiation exposure control: time, distance, and shielding.

1. <u>Time</u> – minimise the time spent working with radiation

2. <u>Distance</u> – maximise the distance from the source of radiation

3. <u>Shielding</u> – use applicable protective apparel wherever possible to keep the intensity of radiation exposure to a minimum

With specific reference to radiation safety of personnel working in nuclear medicine, it has been established that the radiation emitted from patients and resultant exposure to personnel occurs mainly to the front of the body, with higher exposures (more than double) recorded during injection of the radiopharmaceutical (Lundberg *et al.* 2002). It is therefore recommended in human facilities that susceptible personnel (such as pregnant women) do not inject patients with radiopharmaceuticals.

2.5　Nuclear scintigraphy

2.5.1　Radionuclides

The basic principle of nuclear scintigraphy is the detection of gamma rays, emitted from the decay of a radionuclide, by a gamma camera. When the radionuclide is attached to a specific radiopharmaceutical which targets a specific organ, physiological function, shape, size and position of the target organ can be assessed. In the horse, scintigraphy has been used predominantly for the detection of bone pathology, particularly stress fractures and early degenerative joint disease. The improved diagnosis of stress fractures in the horse has

been of great benefit in reducing the mortality rate from these injuries (Dyson *et al.* 2003). Scintigraphy is not only more sensitive in the detection of stress fractures than radiography, but allows imaging of sites in which radiography would be difficult or contra–indicated, such as the pelvis. It also assists in monitoring of the progress of the condition, helping with therapy and indication of suitability for return to work (Dyson *et al.* 2003).

The most common form of radionuclide imaging uses elements that emit γ–ray photons at single or multiple energies. These are then detected by the gamma camera, which is a position sensitive γ–ray detector.

The ideal radionuclide (also known as radioisotope) should have the following properties (Dyson *et al.* 2003):

1. It must easily attach to a pharmaceutical, then known as a radiopharmaceutical

2. It must have a short half–life ($T_{1/2}$) to limit radiation dose to patient and facilitate early and safe disposal

    o Half-life is defined as the time required for one half of atoms in a group of radioactive atoms to decay

        ▪ Physical half-life is characteristic for an element, independent of external conditions

        ▪ Biological half-life depends on physiological conditions (eg. Increased fluid input)

        ▪ Effective half-life: $T_{1/2\,eff} = T_{1/2\,phys} + T_{1/2\,biol}$ (Bushberg 2011)

3. It should interact minimally with body tissues, minimising patient dose and allowing radiation to escape the patient so it can easily be detected

4. It should possess sufficiently low energy to minimise scatter, which would compromise spatial information and thus reduce image quality

5. Its energy must be suitable for efficient detection by the scintillating crystal of the gamma camera

Radionuclides that have short half–lives and produce γ–rays with energies between 80-247keV are preferentially used.

<u>99mTechnetium (99mTc)</u>

99mTechnetium is the most commonly used radioisotope in equine scintigraphy.

The fact that both its physical and biological half–life (6.02 hours) are short leads to very fast clearing from the body after an imaging process. Its biological half-life is one day, thus its calculated effective half-life using the formula above, is 4.8 hours. A further advantage is that the emitted gamma ray (electromagnetic decay) is a single energy, not accompanied by beta emission, permitting more precise alignment of imaging detectors.

99mTechnetium is produced by bombarding uranium with neutron targets to produce molybdenum (^{98}Mo). The resultant ^{99}Mo decays with a half–life of 66 hours to the metastable state of technetium. This process permits the production of ^{99m}Tc for medical purposes. Since ^{99}Mo is a fission product of ^{235}U fission, it can be separated from the other fission products and used to generate ^{99m}Tc. For medical purposes, ^{99m}Tc is used in the form of pertechnate, TcO_4^-.

The Tc isotope ^{99m}Tc is unusual in that although its half–life for gamma emission is a short time biologically and physically, it is extremely long for an electromagnetic decay, more typical decay of other radioactive nuclides is 10^{-16} seconds (Bushberg 2011). With such a long half–life for the excited state leading to this decay, this state is called a metastable state, ergo the designation "99m". Some aspects of the complex decay of this radioisotope are shown in Fig 3 below. The dominant decay mode results in the clinically useful gamma ray at 140.5keV.
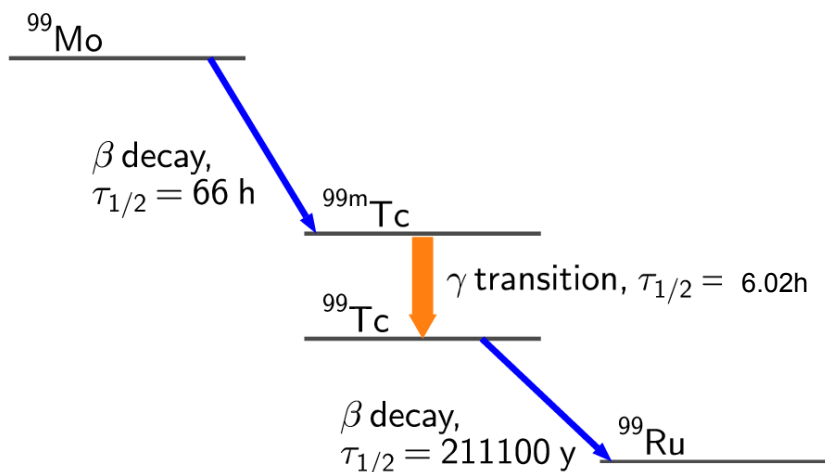
Fig 3 .Diagram of technetium decay. Adapted from Bushberg 2011, Chapter 15, p 592

While the 140.5keV gamma transition happens 98.6% of the time, not all of those actually emit a gamma ray photon. A process called internal conversion always competes with

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gamma photon emission. This involves transfer of the transition energy to one of the electrons in the K, L or M shell. Gamma photon yield constitutes approximately 87.87% of all transitions.

The short effective half–life of ^{99m}Tc results in a low radiation dose for the patient, but is long enough to maintain sufficient radioactivity to produce diagnostic images. The energy value of 140.5keV allows a significant amount of radiation to escape the patient, as 50% of γ–rays will escape from a depth of 4.6cm of soft tissue, the half–value layer (HVL), but are of sufficiently low energy to be absorbed easily by lead (HVL 0.3mm). The HVL of radiation is the amount or thickness of absorbing material or filtration that must be placed in the beam to reduce the transmission of the beam by one half. ^{99m}Technetium can also be readily attached to a wide range of clinically useful radiopharmaceuticals (Bushberg 2011).

In bone scintigraphy, the most commonly used nuclear medicine application in the horse, ^{99m}Tc is labelled with several of the diphosphonate salts, as they selectively localise in the bone. These include methylene–diphosphonate (MDP), disodium–oxydronate (HDP) and methylene–hydroxydiphosphonate (MHDP). Diphosphonate salt binds to exposed hydroxyapatite in the bone and its uptake is relative to the osteoblastic/osteoclastic activity or metabolism of the bone and the blood flow to the bone in a specific region (McDougall 1979, Dyson *et al.* 2003). Increased radiopharmaceutical uptake (IRU) will be present with increased osteoblastic/osteoclastic activity or blood flow. (McDougall 1979, Dyson *et al.* 2003)

The normal energy spectrum of ^{99m}technetium

The pulse height spectrum of ^{99m}Tc is shown in Figs 4 and 5. ^{99m}Technetium decays to ^{99}Tc by means of isomeric transition, where a stable form of ^{99m}Tc is produced by emitting a gamma ray of 140.5keV. In 11% of the transitions, a conversion electron (an electron released from the atomic shell by transferring the energy of a gamma photon emitted from the same nucleus to this electron, the kinetic energy of which is equal to the energy of the gamma photon reduced by the binding energy of the electron) is emitted instead of a gamma ray (Bushberg 2011).

In Fig 4, the photopeak (A) is caused by the total absorption of the 140.5keV gamma rays. The escape peak (B) is caused by the 140.5keV gamma rays that interact with the crystal by the photoelectric effect but with resultant characteristic x–rays of the iodine within the crystal (of energies ranging from 20 to 33keV) escaping the crystal. There is also a photopeak (C) caused by the absorption of lead characteristic x-rays produced from the shield. The Compton effect is quite small because the photoelectric effect predominates in iodine at

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140.5keV (Bushberg 2011). In Fig 5 the A peak is well-defined but the B and C peaks are not distinct due to the Compton scatter continuum of this particular device being much shorter with resultant superimposition (and thus masking) of these peaks compared to the device used to record the spectrum in Fig 4.
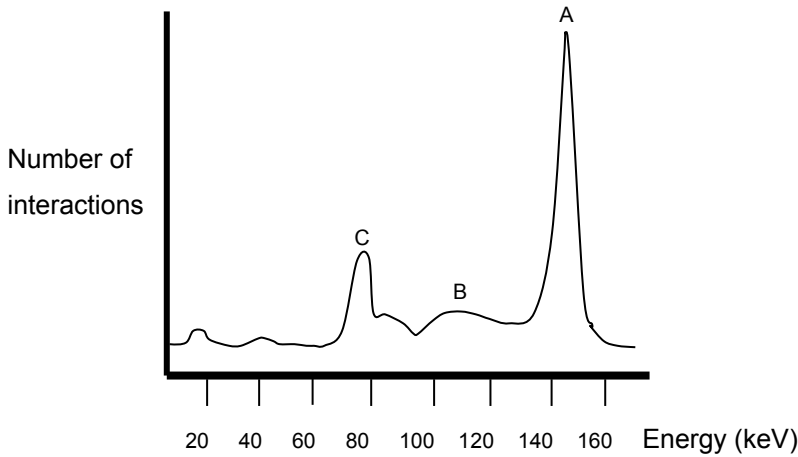
Fig 4. Pulse height spectrum of ^{99m}*technetium*

A = photopeak, B = escape peak caused by photopeak gamma rays that interact with crystal via photoelectric effect with resultant escaping characteristic x-rays of iodine within crystal, C = photopeak caused by absorption of lead characteristic x-rays produced from shield. (Adapted from Bushberg 2001, Chapter 20, p657)
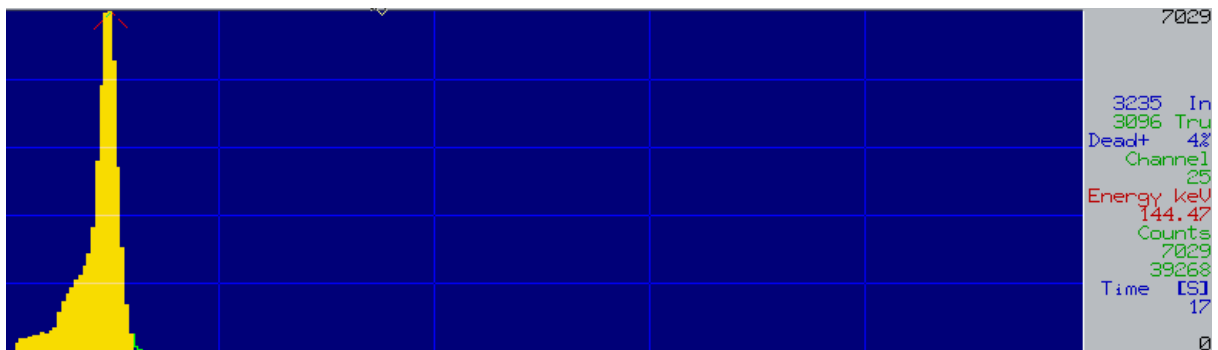
Fig 5. Pulse height spectrum of ^{99m}*technetium as measured with the spectrometer from iThemba LABS.*

The Y-axis shows the number of counts (events) for a specific energy level, the X-axis the different energy levels.

In the grey area to the right, the energy marked in red corresponds to the red cross on the spectrum.

Pertaining to the information in the grey area to the right of the spectrum:

Number in the top right hand corner (in black) = computational number of no relevance

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

Tru (in green) = number of recorded ionising events (counts)

Dead+ (in blue) = the dead time of the device (the lower the percentage, the better)

Channel (in green) = channel number used for this particular recording

Energy keV (in red) = energy recorded in that particular channel

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

Time (in blue) = acquisition time (in seconds)

2.5.2   Radiation exposure during scintigraphy

The primary sources of radiation exposure associated with equine bone scintigraphy are preparing and administering the radiopharmaceutical, handling and imaging the patient and contact with the patient's urine (Didierlaurent *et al.* 2005; Whitelock *et al.* 1997, Voute *et al.* 1995). The radiopharmaceutical is usually shielded for handling to reduce exposure during injection. In one study it was found that contaminated urine, rather than the patient, was an important source of exposure in equine nuclear imaging (Didierlaurent *et al.* 2005). Furosemide is injected intravenously approximately an hour after radioisotope injection to facilitate bladder emptying before delayed phase images are acquired. This has been shown to significantly reduce radiation exposure to personnel (Steyn *et al.* 2005).

Personnel are in the room during the acquisition process which may take up to 90 minutes depending on which and how many areas of the skeleton need to be scanned, as well as the compliance of the patient. During this time, personnel are exposed to the ionising effects of the γ–rays emitted from the patient.

Though ancillary equipment has been developed and its use recommended to limit radiation to personnel (Neuwirth *et al.* 2000), the highest amount of radiation from the equine patient was measured over the rump (at 50µSv/h) (Dyson *et al.* 2003), and this area is not shielded using the recommended equipment. The use of lead aprons specifically designed to fit over the horse's body, thereby reducing radiation from the rump, has been recommended (Dyson *et al.* 2003).

A study measuring exposure rates (quantity of radiation) at different distances from various sites of the horse at varying times post-injection with lead shielding, concluded that a 0.5mm equivalent lead apron significantly decreased radiation exposure (Steyn *et al.* 2005). It has been suggested that protective shielding is not commonly worn because the 140.5keV emitted from the ^{99m}Tc is too high to be stopped by a 0.5mm lead apron, and lead shielding would result in "beam hardening" which is more dangerous for personnel (Steyn *et al.* 2005).

The 140.5keV gamma ray emitted from ^{99m}Tc is no longer monochromatic when it exits the horse because of bone and soft tissue attenuation and scatter. Although beam hardening by 0.5mm lead equivalent of protective clothing is allegedly inevitable, the γ–photons most likely to be attenuated by the lead would be those in the lower keV range, which are also the photons that would most likely be attenuated or absorbed by personnel. In human nuclear medicine, where lower (average of 20mCi) doses of ^{99m}Tc are used, several studies have recommended wearing lead aprons during a scintigraphic examination (Bolus *et al.* 2008; Huda *et al.* 1989; Lundberg *et al.* 2002).

A study that measured the external radiation of staff during and after soft tissue as well as bone scintigraphy in horses (Didierlaurent *et al.* 2005) showed that 140.5keV constituted a rather small portion of the emitted measured spectrum of ^{99m}Tc (See Fig 6). The gamma spectrum of ^{99m}Tc emitted from a horse was measured 10 minutes (soft tissue phase) and 3 hours (bone phase) post injection, and revealed that a large portion of the attenuated polychromatic gamma rays were found within the 60 to 100keV range (Didierlaurent *et al.* 2005). This finding was most likely as a result of Compton scatter within the patient.

Based on the fact that the scatter energy spectra were similar in the soft tissue and bone phase, it was decided that this study focused predominantly on the bone phase as it was the most common and most time–consuming part of the scintigraphic examination in the horse.

The investigator also considered that the extra time it would take to obtain all the proposed measurements in the soft tissue phase would subject by standing personnel to unnecessary additional radiation exposure.

Soft tissue phase: 10 minutes after radiopharmaceutic injection

Bone phase: 3 hours after radiopharmaceutic injection
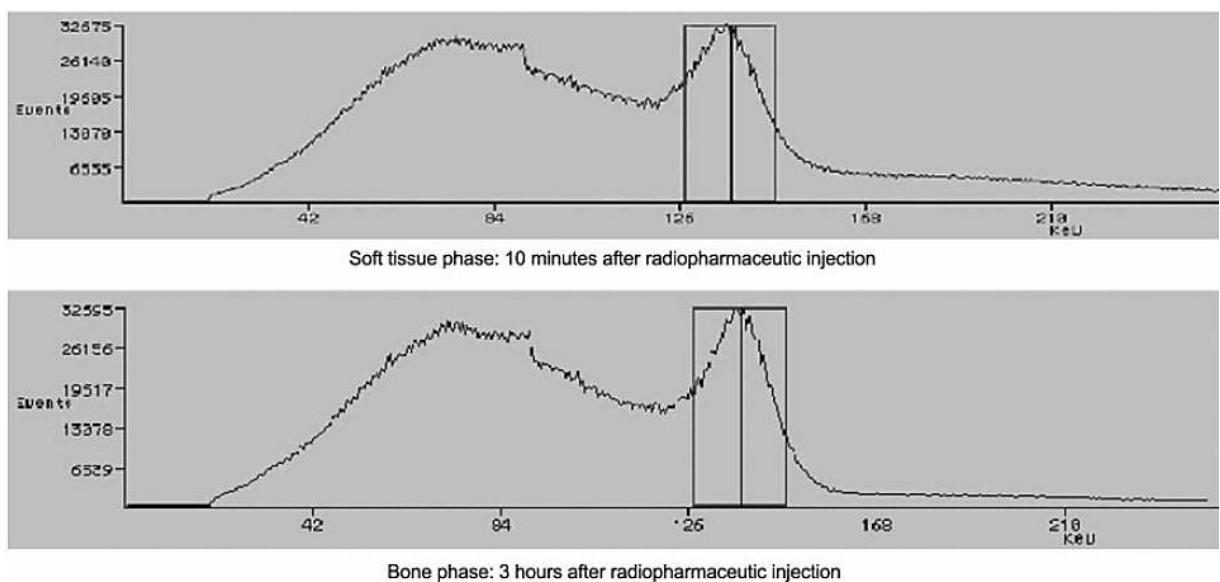
Fig 6. Energy spectrum of ^{99m}technetium emitted from a horse during a soft tissue and bone phase scintigraphic examination.

Counts (events) are present on the Y-axis and the energy spectrum is shown on the X-axis. These two graphs show the emitted spectra from the equine patient undergoing a soft tissue and bone phase scintgraphicv examination to be similar in appearance. (Didierlaurent et al. 2005) Used with permission.

The broad spectrum of Compton scatter within the lower energy range implies that lead aprons worn by personnel or the patient or both, would absorb these lower energy rays and in doing so considerably reduce exposure to personnel. However, no mention is made of beam hardening effects and the potential impact they may have on personnel wearing lead aprons.

The above study also does not investigate changes in the gamma spectrum of ^{99m}Tc behind lead shielding. Since beam hardening effects are potentially more harmful to personnel than the original polychromatic beam emitted from the horse (Cherry *et al.* 2012), it is important to establish how big an impact on radiation dose such a process would have, if any at all. Should beam hardening effects result in significantly altering the emitted beam thereby making it more harmful to bystanding personnel, then the wearing of lead aprons during bone scintigraphy of the horse would not be recommended.

2.6   Conclusions drawn from the literature review

Vital information is lacking regarding the effect lead shielding has on the polychromatic energy spectrum emitted from a horse during bone scintigraphy. No such energy spectra have been recorded and analysed.

Thus, it is not currently known, whether the wearing of lead-shields during bone scintigraphy of horses result in beam hardening effects that may result in increased radiation exposure to those wearing them. This study is designed to assist in answering the following questions:

1. Do beam hardening effects behind lead shielding, worn by patient and personnel, exist and do they increase radiation exposure to personnel and patients wearing them?

2. Should lead aprons be used routinely during routine bone scintigraphy of horses and if so, which thickness of lead should be recommended?

3. Would it be beneficial if lead shielding were used on personnel or the patient or both?

4. How does personnel radiation exposure differ behind the varying lead thicknesses, with and without additional lead shielding on the patient?

5. Can a position (with the least radiation exposure) for the handler holding the horse be identified?

Chapter 3: Materials and Methods

3.1   Experimental design

Five Thoroughbred and similar sized experimental horses were included in the study.

Inclusion criteria:

1. Thoroughbred, Thoroughbred-type healthy horse

2. 450–500kg body weight

3. No signs of disease on clinical examination

The horses were admitted at approximately 9am each day to be ready for injection with the radioisotope at roughly 10:30am the same day. All horses underwent a brief, clinical evaluation (which included temperature, pulse, respiration measurements and thoracic ausculation) by the primary investigator. All findings were documented on an examination form, and tabulated in Table 3 (Chapter 4), along with the activity of ^{99m}Tc–MDP, time of injection and the commencement time of data collection.

Horses were weighed on the Onderstepoort Veterniary Academic Hospital (OVAH) equine clinic scale.

The horse was placed into the designated scintigraphy stable with normal feed and water. An indwelling jugular catheter was placed by an experienced equine clinic sister.

Each horse was given a number consisting of H (horse) and a digit, i.e. H1-H5.

3.2   Experimental procedures

3.2.1   Measurement procedure

The OVAH has two isolation stables specifically reserved for equine scintigraphy patients that house these animals for a period of at least 24 hours (4 half–lives of technetium) until these animals are safe to be released into a public environment (= skin surface radiation of less than 10mSv/hr). The animals were fed and handled as normal equine clinic patients and during working hours clinically monitored by the primary investigator. Stables were mucked

out after 24 hours by an assistant staff member of the Equine Clinic. Data was collected from one horse per day.

^{99m}Technetium–MDP (150mCi in a 2ml syringe) was ordered the previous day from Axim Medical (121 Gazelle Avenue, Corporate Park South, Midrand, South Africa) to be delivered to the Diagnostic Imaging Section by the following morning. The primary investigator and all personnel involved wore the currently required protective clothing which consists of dedicated white coats, disposable latex gloves and gumboots whenever dealing with the radiopharmaceutical or the injected horse. The wearing of lead aprons, thyroid shields and lead glasses was optional. However, the primary investigator recommended that the person holding the horse wear a 0.35mm lead apron after the first day.

Delivery of the radioisotope took place in the early hours of the same day and was calibrated to be approximately 150 (+/- 10) mCi by 10.30am.

On the first day of the study, the scintigraphy gamma camera was calibrated and peaked, thereafter only peaked every day for the use of ^{99m}Tc. This was performed in order to acquire a single standard 60 second lateral abdominal view of the bladder region to assess bladder filling and to confirm proper normal uptake of the injected ^{99m}Tc–MDP.

At approximately 10.25am, the primary investigator donned the prescribed protective clothing and opened the sealed lead container holding the ordered dose of ^{99m}Tc–MDP.

At 10.30am, the syringe filled with ^{99m}Tc–MDP was placed into a calibrator (Capintec CRC®-15R radioisotope dose calibrator, CAPINTEC, INC.6 Arrow Road, Ramsey, New Jersey 07446), the radioactivity measured and documented on the data sheet (values are tabulated in Table 3). A lead syringe cover was placed over the syringe and the content injected into the horse and immediately flushed with 20ml of sterile saline. The time of injection was documented on the data sheet. Radioactivity within the horse was confirmed over the cranial thorax (heart area) and abdomen with a digital Geiger-Müller counter (RadEye™ G/G-10 Personal Dose Rate Meter, Thermo Fisher Scientific Inc, United Kingdom) after which the horse was placed back into the stable.

Furosemide was not injected to induce urination, as has been recommended previously (Dyson *et al* 2003). A full bladder was welcomed in order to measure the "worst case" scenario as far as radiation exposure to bystanding personnel was concerned.

Approximately two and a half hours post injection, the horse was led into the OVAH scintigraphy room and sedated with 0.1mg/kg detomidine (0.1ml/100kg Domesedan®,

Novartis SA, P.O.Box 92, Isando, 1600, South Africa) intravenously and topped up as required.

A single standard 60 second lateral abdominal view of the bladder region was imaged with the gamma camera and recorded. This was done to assess bladder filling and to confirm uptake of the injected ^{99m}Tc–MDP into bone (seen on adjacent ribs and vertebrae).

Spectrometer readings:

Gamma-ray spectroscopy measurements were conducted using a portable digital multi-channel radiation analyser (made available by iThemba Labs in Stellenbosch, Western Cape, South Africa) (TGI Net MCA-3 Transgalactic Intruments, Bulgaria). A sensitive 1 inch NaI:TI detector that could be placed close to animals to read radiation characteristics was connected to a dedicated portable computer accompanying the spectrometer to analyse radiation spectra with high precision. The very high resolution of energy channels provided accurate information about changes in radiation quality from the isotope at different anatomical sites. See Figs 7 and 8.

Fig 7. The portable NaI:TI spectrometer detector.

Calibration was performed every day with ^{137}Cs (item on the left) and peaked at 662 keV (which is standard for the measurement of gamma rays).
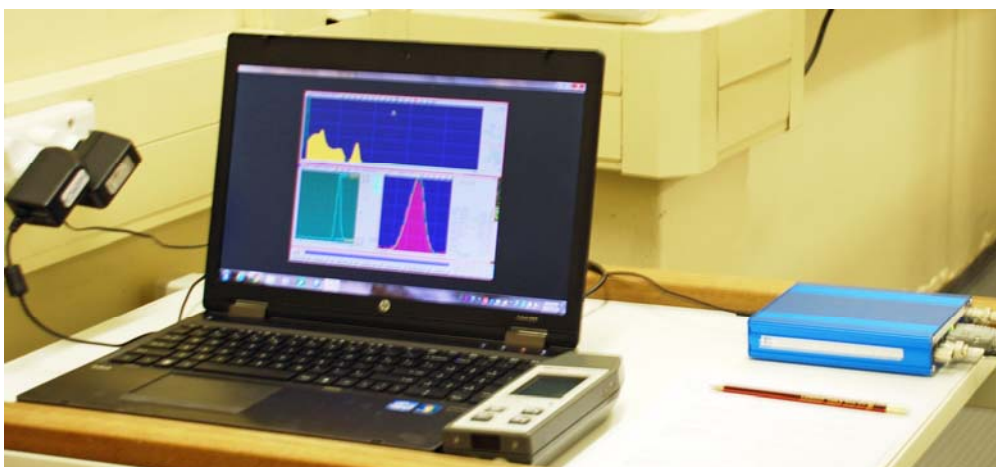
Fig 8. A dedicated notebook containing all the necessary software accompanied the NaI:TI crystal.

The blue box to the right is the multichannel analyzer that connected the crystal to the notebook.

The assisting radiation biophysicist Mr Philip Beukes (iThemba LABS) set up the spectrometer near a power point within the scintigraphy room.

Every day, the equipment was calibrated. Since ^{99m}Tc was the target source, it is considered good practice to calibrate with completely different sources, so a ^{137}Cs sample was used, followed by re–calibration with a second source (^{99m}Tc) of a different peak (energy) to confirm the energy calibration. Gamma spectrometers are usually employed to measure between 0 and 2000keV. Most of the energies fall within the 0 to 1200keV range, ^{137}Cs with an energy peak of 662keV falls in the middle of this range. This makes it the ideal calibration source.

The horse was walked to the middle of the room and held still. Measurements with the spectrometer were taken in the following way (see Fig 9):

Location:

Measurements were made on the right or the left hand side of the patient:

1. Directly (within 10–30cm of the patient) in front of the head (where a handler would conceivably stand) (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 (bulk of the pelvic and hindlimb musculature) (P)

Fig 9. Schematic representation of ^{99m}technetium–MDP pulse height spectrum measurement points.

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<u>Lead shielding</u>*:*

For the first readings, no lead shielding was applied. Measurements were taken at all the above-mentioned locations to determine if and how the spectrum of gamma rays, emitted directly from the horse, changed at the various locations. These measurements are documented as WOH (= without shielding on horse) in tables and figures.

Thereafter, standard lead aprons of 0.25mm, 0.35mm and 0.5mm lead equivalent were handheld with coat hangers or hung on drip stands approximately 30cm from the patient. See Fig 10. The distance of the measurements varied up to 100cm from the horse according to the intensity of the emitted spectrum, as the spectrometer dead time increased to a paralysed state if the number of counts measured was too high. This effect became less problematic during the two-hour 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. Measurements were taken at the different locations (See Fig 9) and recorded electronically as counts or events per second and as graphs in which counts were depicted on the Y- and energy levels on the X–axes. These measurements are documented as WOH plus the shields of varying lead thicknesses described above. For example WOH+0.25 = without shield on horse plus 0.25mm lead equivalent on personnel.

After these measurements were completed, a 0.35mm lead equivalent and 0.5mm lead equivalent shield was draped over the horse (Fig 11). Measurements with these shields and those described hereafter were only taken at three locations, S, B and P as the head could not effectively be draped. These measurements are documented as WSH (with shielding on horse) with the various lead thicknesses (0.35mm and 0.5mm) added without a "+" sign. For example WSH0.5 = with 0.5mm lead equivalent shielding on horse.

 Additional measurements at the same three measurement points were taken behind the hanging lead aprons, but this time with lead shielding (using only 0.35 mm, then 0.5 mm lead equivalent) draped over the horse as described above. These measurements are documented as WSH with added various lead shields on hangers denoted by the "+" sign. For example WSH0.35+0.5 = with 0.35mm lead equivalent shielding on horse and 0.5mm equivalent lead shield on hanger (personnel). See Fig 11.

Although data collection with lead shielding on the horse in the head regions may have yielded useful information, due to radiation safety concerns, it was decided to minimize the time spent collecting data and thus these measurements were omitted.

Fig 10. Spectrometer recordings behind lead aprons of varying thicknesses with no additional shielding on the

Fig 11. Spectrometer recordings with additional lead shielding on the horse (WSH)

<u>Distances for radiation exposure</u>: Radiation exposures, using two different TLD dosimeters, a Thermo Scientific™ ESM FH 20G-L10 and a Thermo Scientific™ ESM FH40G-L10 multi-purpose digital survey meters were measured.

Recordings at variable distances, ranging from 20-100cm from the skin surface of the horse, directly behind the hanging lead shielding (of varying thicknesses as described above) were measured.

If the lead apron or any part of it worn by the horse became contaminated through sweat, urine or faeces, it was placed in the decay room and rinsed off with water and dried until the following day, before its use on the next horse.

If a horse urinated during the evaluation this was noted and coloured on excel sheets as green.

3.2.2   Data measurements and calculations

Counts recorded during a 30 second period were collected for each individual measurement and entered into an Excel spreadsheet (Microsoft Excel 2010, Microsoft Corp, Redmond, WA, USA). Graphs of all the measured spectra were drawn electronically and saved.

Spectra for the scatter and photopeak were recorded in colour format and saved for each measurement. The most representative examples are documented under the relevant sections below. The information contained within the grey area described in Fig 5 was omitted to reduce the space required for the spectra and to place them next to each other for easier comparison.

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1. Average counts: the counts of all five horses added together and divided by five, standard deviation was omitted due to large variability in the recordings and the fact that in most cases the standard deviation approximated the original value itself.

2. Absolute counts: recorded ionizing events (counts) by the spectrometer

3. Net counts: absolute counts recorded in a specific region of interest (ROI)

4. Fit counts: a distribution function fitted over the ROI to smooth the curve and give a better approximation of its true value when repeating measurements

5. Percentage reduction was calculated using the following formula: (a – b) / a x 100, with a being the non-shielded counts and b the shielded counts.

3.2.3   Data and Statistical Analysis

GraphPad prism 4 was used to plot the gamma spectrum results of the different measurement locations and to calculate the mean and standard deviation (SD) of the different data sets.

Tukey's test, a single–step multiple comparison procedure and statistical test, was used in conjunction with a Repeated Measures analysis of variance (ANOVA) to find statistical significant differences within the cohort of measurements performed for the different locations and attenuation media combinations. The ANOVA is a hypothesis test used to compare the means of more than two populations.

3.3   Ethical considerations

Experimental animals were used for this study. The injected radioisotope bore little health risk and animals were returned to their previous facilities within 24 hours (4 physical half–lives of ^{99m}Tc) of the procedure.

As per regulations, all persons handling the radioisotope and radioactive animals wore dedicated protective clothing at all times. 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 unauthorized 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 by Axim Medical 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 (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).

3.4   Biosecurity measures

All handling of radioactive material and animals were 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 adhered to at all times.

Chapter 4: Results

4.1 Study population

The five horses' particulars and measurement times are given in Table 3.

Table 3: Horse particulars and measurement times

	H1	H2	H3	H4	H5
Date	25/11/13	26/11/13	27/11/13	28/11/13	29/11/13
Breed	Boerperd	TB	TB	TB	TBx
Body weight	520kg	500kg	480kg	480kg	450kg
Temperature	37.8°C	38°C	38.2°C	37.8°C	38.1°C
Respiration rate	18	18	16	16	20
Heart rate	36	42	32	42	48
^{99m}Tc-MDP activity	142.7 mCi	148 mCi	150.5 mCi	140.4 mCi	144.2 mCi
Time of injection	10:32 am	10:35 am	10:35 am	10:35 am	10:40 am
Commencement of measurements	13:00 pm	13:00 pm	13:00 pm	13:00 pm	13:00 pm

TB = English Thoroughbred; TBx = English Thoroughbred cross
H1 = Horse on day 1
H2 = Horse on day 2
H3 = Horse on day 3
H4 = Horse on day 4
H5 = Horse on day 5

4.2 Data acquisition

The time to acquire a full set of spectrometer readings varied from 90 to 120 minutes depending on the tractability of the horse and expertise of the handler, as well as the ongoing experience of the researcher (time was reduced with horses 3, 4 and 5 due to adaptation of the lead shielding sequence to minimise time spent around the radioactive patient). The first few horses generally took longer, since the technique of correct positioning was uncertain and the original sequence of the lead shielding was initially proposed by the primary researcher to follow a thickness– and positioning–based chronological order. As time progressed, however, less repeat measurements with regards to exact positioning were required, and the lead shielding order was adapted to reduce time spent in the radioactive field.

Sedation doses ranged from 0.5 to 0.9ml detomidine (0.1ml/100kg Domesedan®, Novartis SA, P.O.Box 92, Isando, 1600, South Africa) intravenously, depending on the compliance of the horse and the time needed for all the readings. None of the horses showed any adverse

reactions to the sedation or the injected radioisotope. The activity measured, the time of injection and the time taken for all measurements for each horse are documented in Table 3.

All recorded measurements of the spectrometer are recorded on Excel spreadsheets (Appendices B – F).

The radiation exposure measurements taken from horse 5 using two different dosimeters are recorded in Table 16. A full set of exposure rate readings took approximately 30 minutes and thus was only possible once a fastest measurement protocol was established on the last horse.

A single horse urinated during the course of measurement recording and this was noted and post voidance counts were recorded in green on the relevant Excel spreadsheet (Day 3). The recordings affected the shoulder, bladder and pelvis regional counts (See Appendix D). See also comments under 4.3.4 and Tables 7, 9 and 11.

4.3   Data sets analysed

The energy spectra emitted from the horses injected with ^{99m}Tc were evaluated with two particular areas of interest around which all the results and points for discussion are based. The first, and most important area of interest for the purpose of this study, was the roughly estimated quantity and quality of scatter radiation emitted from the horses. The second area of interest was the quantity and quality of the emitted ^{99m}Tc peak, as it formed that part of the spectrum which is useful in nuclear imaging.

As expected, the characteristic monophasic 140.5keV peak of ^{99m}Tc (see Figs. 4 and 5) before injection into the patient was no longer apparent 2.5 hours after injection, as previously illustrated in Fig 6. A similarly appearing polychromatic spectrum, seen as a wider range of scatter energies (from 60–140keV), was emitted from the horses due to the interaction of the radioisotope within their bodies (ie. Compton scatter radiation). With the application of lead shielding, the appearance of the emitted spectrum changed once more, with total net counts recorded by the spectrometer now roughly concentrated around two peaks, the first around a 83-86keV scatter peak (the centroid (equivalent to the midpoint of the x–axis in a normal distribution) average) and the second around the ^{99m}Tc photopeak of 140.5keV. The quantity and quality of the scatter and ^{99m}Tc net counts varied considerably depending on location and the combinations of lead shielding (Fig 12).
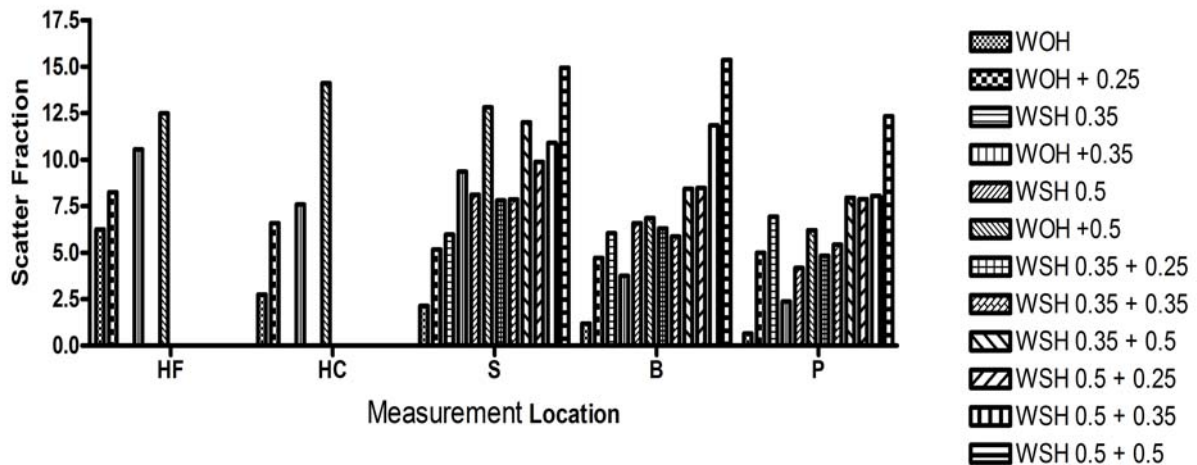
Fig 12. The scatter fraction of the various lead combinations at the 5 different anatomical locations.

HF = head front
HC = head cheek
S = shoulder
B = bladder
P = pelvis
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel

4.3.1   Spectra emitted from horses – general

Without any lead shielding placed on horse or personnel, the scatter fraction of the spectrum displayed average energy peaks ranging from 86.5keV (S) to 94.2keV (HF).

Both HF and HC sets of data were only recorded behind lead aprons hanging on stands, without added lead shielding on the horse, for reasons mentioned above in point 3.2.1.

Average scatter net counts (very rough estimates of exposure) of the various regions without lead shielding and with the varying lead combinations are tabulated at each region. The corresponding average net counts of ^{99m}Tc are tabulated beneath each value in brackets. For all regions (Tables 4 to 11), net counts decreased disproportionately with increasing lead equivalent thicknesses behind the lead aprons draped over horses and those hanging on stands.

The histograms after the tables in each region show the total combined net counts on the Y- and the various shielding combinations on the X–axes. The first recording on the left hand side is the unshielded measurement on each histogram (Figs 13, 15, 17, 19, 21). Typical

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spectra of unshielded measurements as well as several combinations of lead shields are also shown for each region after the above–mentioned graphs (Figs 14, 16, 18, 20, 22).

4.3.2   Spectra emitted from horses at location HF

Refer to Table 4 and Figs 13 and 14 below. Table 4 shows total, unshielded ^{99m}Tc net counts ranging from 3494 (H1) to 38217 (H2) with an average of 23581 counts, whilst total, unshielded scatter counts ranged from 243527 (H1) to 543370 (H5) with an average of 377397 counts. The average combined total counts of ^{99m}Tc and scatter peaks for 5 unshielded horses were 400978 counts. The average energy of the scatter peaks in this region was 92.1keV (Fig 14A).

Table 4: Total number of net scatter and ^{99m}Tc (in brackets) counts recorded at HF without added lead shielding on the horse

H	WOH (^{99m}Tc)	WOH + 0.25 (^{99m}Tc)	WOH + 0.35 (^{99m}Tc)	WOH + 0.5 (^{99m}Tc)
1	243527 (3494)	395008 (36348)	275429 (28063)	156403 (21327)
2	357388 (38217)	192664 (12827)	137867 (12497)	100323 (9855)
3	493797 (34154)	104466 (5714)	75857 (3811)	----- (---)
4	248901 (5264)	204777 (14659)	101434 (11977)	96658 (11178)
5	543370 (36778)	273214 (26322)	145450 (20681)	141662 (19127)
Average	377397 (23581)	232356 (19174)	146050 (15406)	123073 (15372)
Standard deviation	137776 (17601)	109029 (12122)	77220 (9174)	61078 (5704)

H = Horse number
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
---- = values absent due to unexpected power surges corrupting non-retrievable data

The ^{99m}Tc net counts behind 0.25mm of lead equivalent ranged from 5714 (H3) to 36348 (H1) (average of 19174 counts), whilst net scatter counts ranged from 104466 (H3) to 395008 (H1) (average of 232356 counts) (Fig 14B). A further reduction in net counts was noted behind 0.35mm lead equivalent aprons with ^{99m}Tc net counts ranging from 3811 (H3) to 28063 (H1) (average of 15406 counts) and scatter net counts ranging from 75857 (H3) to 275429 (H1) (average of 146050) (Fig 14C). ^{99m}Tc net counts ranged from 9855 (H2) to

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21327 (H1), behind 0.5mm lead equivalent aprons, the minimum count was higher compared to the thinner lead aprons due to the error reading of H3 which represented the lowest counts of all the other recordings. The resulting average ^{99m}Tc net counts (from only the remaining 4 horses) were 15371.75, which are only marginally less than behind the 0.35mm lead equivalent apron (Fig 14D). The scatter net counts, however, ranged from 96658 (the only net scatter recording to break below 100000 in this region) to 156403 and the average of 123073 is 16% less than that recorded behind the 0.35mm lead equivalent aprons. Total combined net counts behind 0.25mm, 0.35mm and 0.5mm lead equivalent aprons were 251530, 161456 and 138445 respectively.

The percentage of total combined net count reduction between unshielded recordings and those taken behind 0.25mm lead equivalent aprons was 37.2%, whereas those between 0.25mm, 0.35mm and 0.5mm lead equivalent aprons was 35.8% and 14.3% respectively.

The percentage of total combined net count reduction between unshielded recordings and 0.35mm was 60%, whilst the difference between unshielded recordings and behind 0.5mm lead equivalent aprons was 65.4%. See Table 15.

An increased peak at 140.5 keV was recorded behind 0.5mm lead equivalent aprons. In some horses this peak dominated the lower energy 86 keV peak.
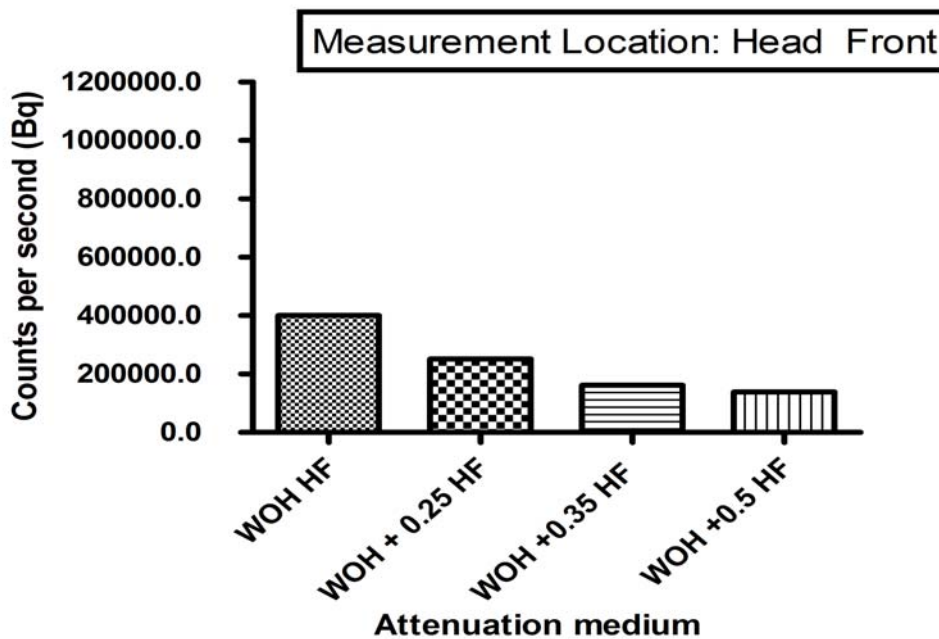
Fig.13. Histogram of average counts per second recorded at HF.
Counts recorded without shielding (WOH HF) and different levels of shielding (WOH + 0.25, 0.35 and 0.5mm lead equivalent aprons) hanging on stands are shown.

HF = head front
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel

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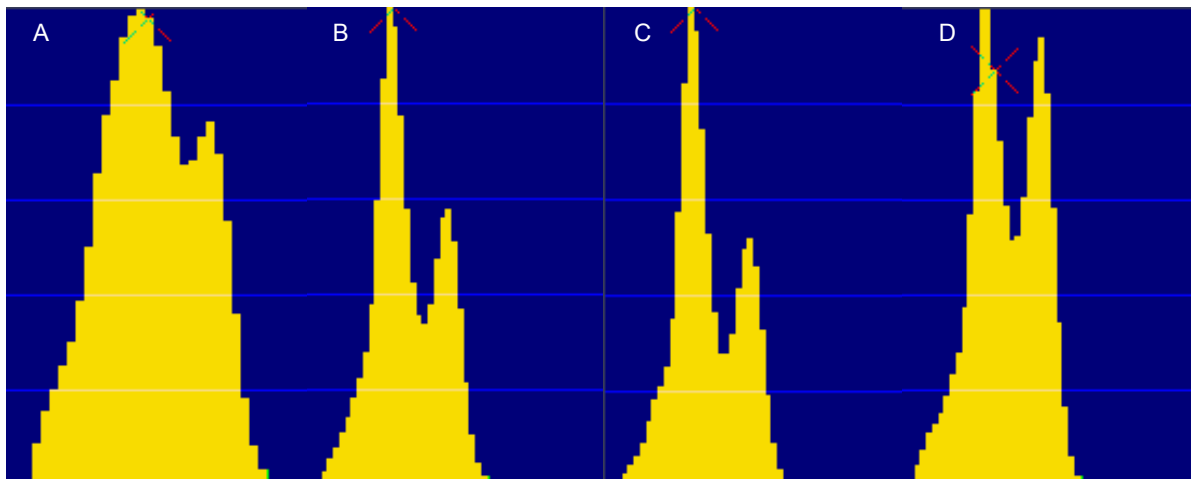
Fig.14. Unshielded and various lead shields on personnel at location HF.
*A. **No shielding:** The unshielded spectrum recorded at HF. The scatter peak is marked with a red cross at 94.21keV.*
*B. **0.25mm lead shielding on personnel:** An obvious peak at 81keV with a mild reduction in the ^{99m}Tc peak is seen. Spectral narrowing and shrinkage of the entire spectrum indicates a marked reduction in net combined counts. C. **0.35mm lead shielding on personnel:** A mild further reduction in the ^{99m}Tc peak and combined net counts is noted. D. **0.5mm lead shielding on personnel:** An obvious rise in the ^{99m}Tc peak is apparent. Absolute combined net counts were not always reduced compared to a 0.35mm lead equivalent apron as in this case.*

4.3.3 Spectrum emitted from horses at location HC

Refer to Table 5 and Figs 15 and 16 below. In this region, there was a slight decrease of the average net ^{99m}Tc counts compared to the "head front" region, but a moderate increase in the average net scatter counts. Unshielded ^{99m}Tc net counts ranged from 9849 (H4) to 28672 (H5) with an average of 20006 counts, whilst total, unshielded scatter counts ranged from 454885 (H2) to 885248 (H5) with an average of 726553 counts, almost double the unshielded scatter net counts compared to the "head front" region. The average combined total counts of ^{99m}Tc and scatter peaks for 5 unshielded horses were 756490 counts. The average energy of the scatter peaks in this region was 91keV (Fig 16A).

The average counts reduced in a similar fashion to the HF region, with addition of lead shielding. A disproportionate percentage reduction of 45.8% and 16.7% between 0.25mm, 0.35mm and 0.5mm respectively, was seen (Figs 16 B-D).

The percentage of total combined net count reduction between unshielded recordings and 0.25mm, 0.35mm, 0.5mm lead equivalent aprons was 43%, 69%, 74.3% respectively. See Table 15. Similar to the HF region, an increased 140.5keV peak was recorded behind 0.5mm lead equivalent aprons.

Table 5: Total number of net scatter and ^{99m}Tc (in brackets) counts recorded at HC without added lead shielding on the horse

H	WOH (^{99m}Tc)	WOH + 0.25 (^{99m}Tc)	WOH + 0.35 (^{99m}Tc)	WOH + 0.5 (^{99m}Tc)
1	755305 (18577)	513590 (37707)	366153 (22725)	277851 (38069)
2	454885 (22925)	299086 (14850)	160497 (9854)	142935 (23373)
3	727220 (---)	271018 (9801)	273119 (---)	79788 (8059)
4	810108 (9849)	387852 (17836)	205014 (28011)	152436 (26547)
5	885248 (28672)	526430 (51474)	276491 (36690)	189065 (22805)
Average	726553 (20006)	399595 (26334)	256255 (24320)	168415 (23771)
Standard deviation	163398 (7934)	118168 (17598)	78369 (11232)	72736 (10725)

H = Horse number
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
--- = values absent due to unexpected power surges corrupting non-retrievable data
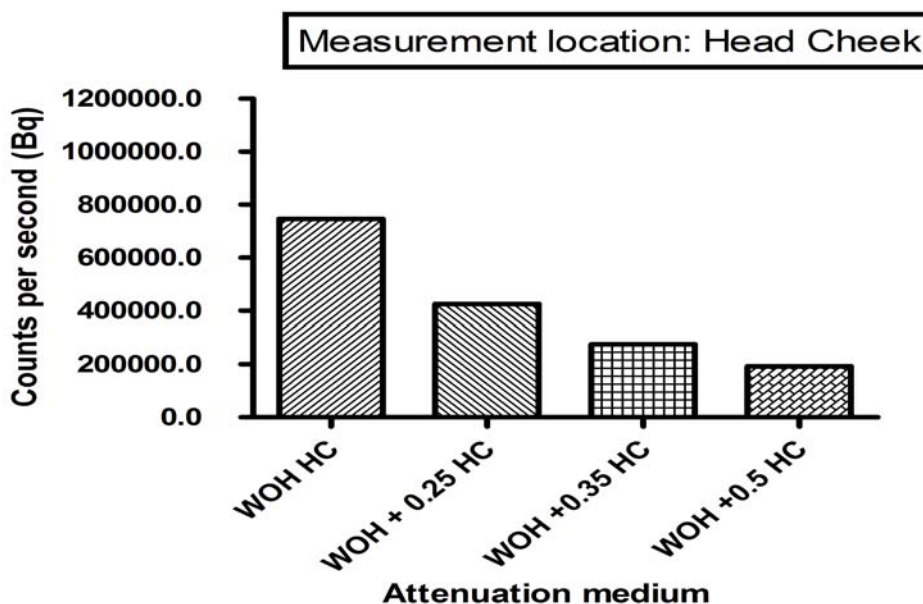
Fig 15. Histogram of average counts per second recorded at HC.
Counts recorded without shielding (WOH HC) and different levels of shielding (WOH + 0.25, 0.35 and 0.5mm lead equivalent aprons) hanging on stands are shown.

HC = Head cheek
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel

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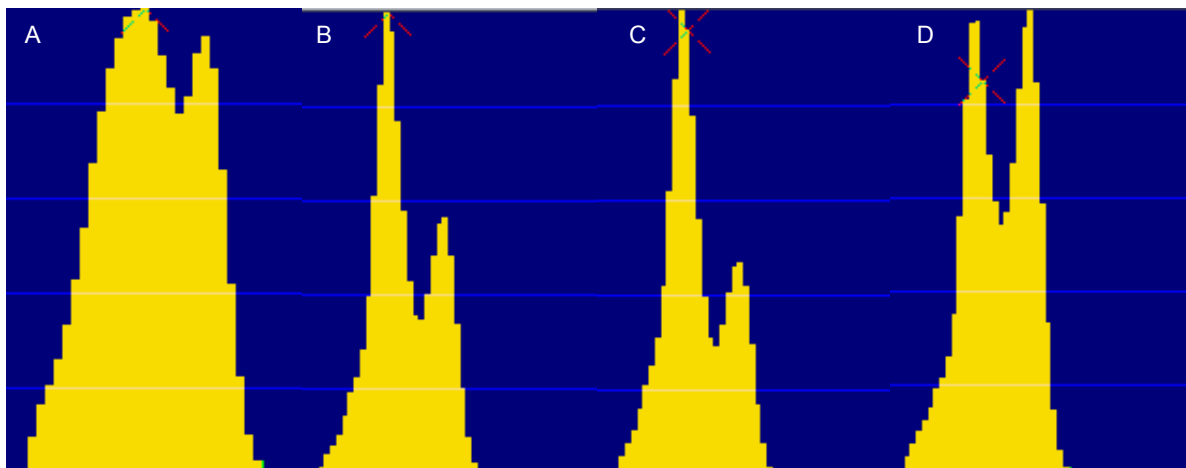
Fig 16. Unshielded recordings and those of various lead shields on personnel at location HC.
*A. **No shielding:** The unshieldedspectrum recorded at „head cheek". The scatter peak is marked with a red cross at 94.21keV(as in previous region). B. **0.25mm lead shielding on personnel:** An obvious peak at 81keV with a mild reduction in the ^{99m}Tc peak is seen. Spectral narrowing and shrinkage of the entire spectrum indicates a marked reduction in net combined counts. Spectrum very similar to Fig 14B. C. **0.35mm lead shielding on personnel:** A mild further reduction in the ^{99m}Tc peak and combined net counts is noted. Similar to Fig 14C. D. **0.5mm lead shielding on personnel:** An obvious rise in the ^{99m}Tc peak, which even surpasses the scatter peak, is apparent. Compare with Fig 14D.*

4.3.4   Spectrum emitted from horses at location S (Shoulder)

See Table 6 and 7; and Figs 17 and 18 below.

The sets of data from the shoulder, bladder and pelvic region were measured with and without lead shielding on the horse. The results are thus displayed in two separate tables.

The shoulder region showed a marked increase in the number of scatter counts compared to the head regions. Unshielded ^{99m}Tc net counts ranged from 19641 (H1) to 31541 (H4) with an average of 24942 counts, whilst total, unshielded scatter counts ranged from 908106 (H1) to 1391433 (H5) with an average of 1164679 counts. The average combined total counts of ^{99m}Tc and scatter peaks for 5 unshielded horses were 1189621 counts. The average energy of the scatter peaks in this region was 86.5keV (Fig 18A).

With lead shielding draped over the horse alone, combined net counts experienced a greater percentage reduction behind 0.35mm lead equivalent aprons (59%) compared with 0.5mm lead equivalent aprons (55%) (Fig 18B).

When measurements were recorded behind lead aprons hanging on stands, there was again a greater percentage reduction between the 0.25mm and 0.35mm lead equivalent aprons (35%) compared with 0.35mm and 0.5mm lead equivalent aprons (24%). The percentage of total combined net count reduction between unshielded recordings and 0.25mm, 0.35mm, 0.5mm lead equivalent aprons hanging on stands was 48%, 66% and 74.3% respectively.

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Table 6: Total number of net scatter and ^{99m}Tc (in brackets) counts recorded at S without added lead shielding on the horse

H	WOH (^{99m}Tc)	WOH + 0.25 (^{99m}Tc)	WOH + 0.35 (^{99m}Tc)	WOH + 0.5 (^{99m}Tc)
1	908106 (19641)	--- (---)	--- (36245)	289155 (27204)
2	1202070 (24804)	471912 (21322)	259150 (15561)	194672 (35191)
3	944429 (20961)	386118 (7683)	252965 (9104)	190113 (14210)
4	1377356 (31541)	769782 (35271)	317658 (33902)	291411 (45329)
5	1391433 (27763)	733708 (57799)	654471 (78797)	400947 (53026)
Average	1164679 (24942)	590380 (30519)	371061 (34722)	273260 (33825)
Standard deviation	230426 (4885)	311177 (21392)	234410 (27245)	86567 (15204)

H = Horse number
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
--- = values absent due to unexpected power surges corrupting non-retrievable data

When 0.35mm lead shielding on the horse was combined with lead shielding on personnel (hanging on stands), the greatest reduction was achieved with a 0.5mm lead equivalent apron on personnel (85%). When a 0.5mm lead equivalent apron was draped over the horse, up to 90% reduction in total combined counts could be achieved with a 0.5mm lead equivalent apron on personnel (Figs 18D, E).

The characteristic 140.5 keV peak seen with 0.5mm lead equivalent aprons on personnel only in the previous regions was most prominent with the 0.5mm (horse) and 0.5mm (personnel) combination.

Though the combined sum of lead equivalent thicknesses was equal, there was a slight difference in the reduction in total combined net counts between 0.35mm on the horse and 0.5mm on personnel (85%) and 0.5mm on the horse and 0.35mm on personnel (84%). See Table 15.

Table 7: Total number of net scatter and ^{99m}Tc (in brackets) counts recorded at S with added lead shielding on the horse

H	WSH.35 (^{99m}Tc)	WSH.5 (^{99m}Tc)	WSH.35+.25 (^{99m}Tc)	WSH.35+.35 (^{99m}Tc)	WSH.35+.5 (^{99m}Tc)	WSH.5+.25 (^{99m}Tc)	WSH.5+.35 (^{99m}Tc)	WSH.5+.5 (^{99m}Tc)
1	522304 (29269)	462608 (33733)	215419 (17687)	252560 (20980)	157009 (19898)	259481 (20662)	148298 (14618)	136485 (16395)
2	322930 (21516)	358455 (40674)	226644 (27782)	162922 (15476)	86392 (13917)	188821 (21995)	156219 (21192)	117025 (17073)
3	438051 (14491)	493548 (18147)	252824 (18779)	151250 (13196)	148562 (16199)	197338 (19830)	110689 (15367)	104691 (---)
4	460113 (27998)	560981 (52442)	193952 (---)	175744 (22603)	179352 (25995)	308669 (26587)	200107 (18695)	143846 (32411)
5	564886 (44446)	456377 (44160)	404907 (53026)	263609 (6874)	200304 (16675)	310054 (35822)	216919 (20929)	223556 (20822)
Ave	461657 (27544)	466394 (37831)	258749 (20205)	201217 (15826)	154324 (18537)	252873 (24979)	166572 (18160)	145120 (21675)
SD	92384 (6794)	73228 (12902)	84416 (5131)	52775 (6318)	42999 (4684)	58338 (6599)	42429 (3061)	46509 (7417)

H = Horse number
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel
--- = values absent due to unexpected power surges corrupting non-retrievable data
Ave = average (scatter)
SD = standard deviation (scatter)
Mint-coloured sections of horse number 3 = net counts post urination

During the course of the study, a single horse (horse number 3) urinated during data collection. The recorded counts affected the shoulder, bladder and pelvis regions from the combination of 0.35mm shielding on the horse and 0.35mm lead shields on personnel onwards. There was an obvious reduction of net scatter counts following voidance of urine, not of the recorded net ^{99m}Tc counts. The affected counts are highlighted in mint in Tables 7, 9 and 11 and are seen in Appendix D.
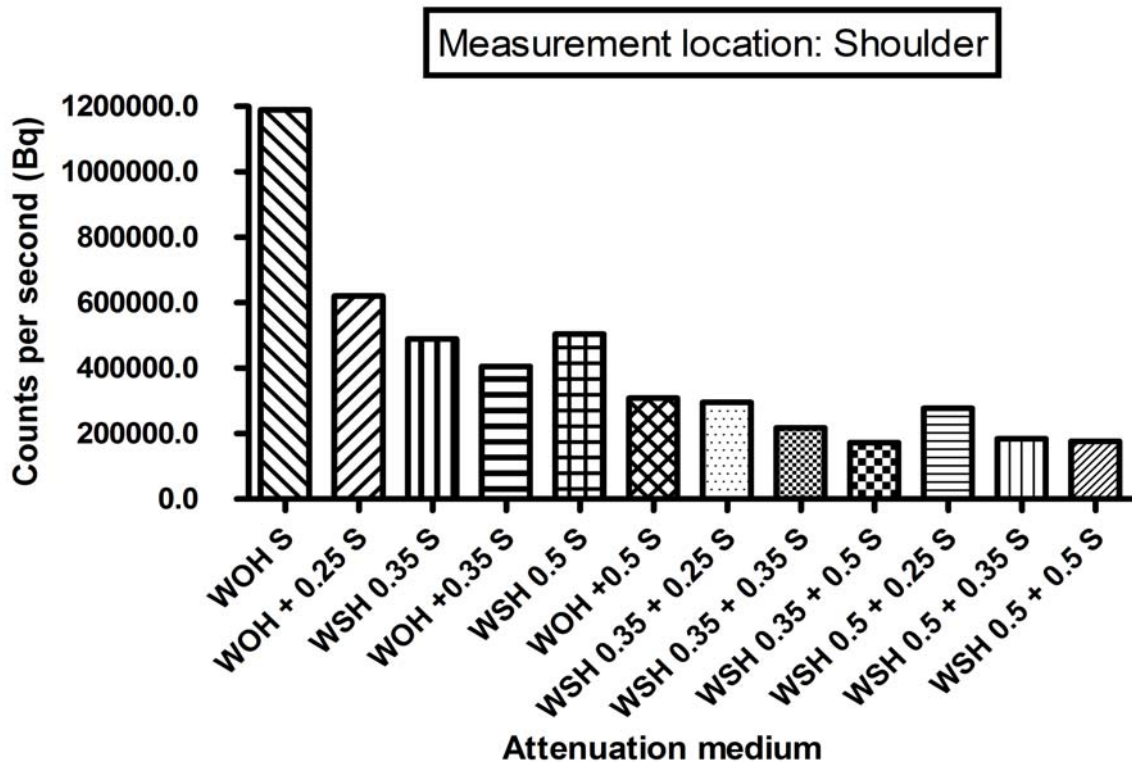
Fig 17. Histogram of average counts per second recorded at S.
Counts recorded without shielding and different levels of shielding on the horse or personnel alone, and in combination.

WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel

Fig 18. Unshielded recording and those of various lead shields on personnel and horse at location S.
*A. **No shielding:** The spectrum looks similar to previous regions, the scatter peak is at 82keV. B. **0.35mm lead shielding on the horse:** The ^{99m}Tc peak is reduced but total combined net count reduction is less than behind lead aprons on personnel alone. C. **0.5mm lead shielding on the horse:** The ^{99m}Tc peak is elevated compared to Fig 18B, but total combined net counts are slightly reduced. D. **0.5mm on the horse and 0.25mm lead shielding on personnel:** An obvious decrease in total combined net counts as well as a marked reduction of the ^{99m}Tc peak is seen. E. **0.5mm on the horse and 0.5mm lead shielding on personnel:** The ^{99m}Tc peak is elevated again. Most reduction of total combined net counts compared to other combinations, was seen.*

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4.3.5 Spectrum emitted from horses at location B (Bladder)

See Tables 8 and 9; and Figs 19 and 20 below.

This was the region with the most scatter net counts, as expected, due to accumulation of the radioisotope within the bladder. Unshielded ^{99m}Tc net counts ranged from 8144 (H2) to 26705 (H3) with an average of 15100 counts, whilst total, unshielded scatter counts ranged from 900576 (H2) to 1665754 (H5) with an average of 1269154 counts. The average combined total counts of ^{99m}Tc and scatter peaks for 5 unshielded horses were 1284254 counts. The average energy of the scatter peaks in this region was 87.9keV (Fig 20A).

With lead shielding draped over the horse alone, combined net counts experienced a 60% reduction behind 0.35mm, and another further 60% reduction behind 0.5mm lead equivalent aprons, compared with unshielded net counts (Fig 20B).

Table 8: Total number of net scatter and ^{99m}Tc (in brackets) counts recorded at B without added lead shielding on the horse

H	WOH (^{99m}Tc)	WOH + 0.25 (^{99m}Tc)	WOH + 0.35 (^{99m}Tc)	WOH + 0.5 (^{99m}Tc)
1	944640 (14364)	496369 (28341)	417295 (23696)	337447 (27044)
2	900576 (8144)	942205 (---)	390189 (15241)	343229 (27062)
3	1214685 (26705)	790222 (12519)	344062 (13543)	312041 (20541)
4	1620116 (11507)	1048378 (29582)	432279 (26348)	451138 (32503)
5	1665754 (14780)	907146 (55270)	605832 (65304)	508807 (---)
Average	1269154 (15100)	836864 (31428)	437931 (28826)	390532 (26787)
Standard deviation	362144 (7011)	211475 (17691)	99673 (21102)	84968 (4893)

H = Horse number
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
--- = values absent de to unexpected power surges corrupting non-retrievable data

When measurements were recorded behind lead aprons hanging on stands, there was a 46% reduction between the 0.25mm and 0.35mm lead equivalent aprons, but only an 11% reduction between the 0.35mm and 0.5mm lead equivalent aprons. The percentage of total

combined net count reduction between unshielded recordings and 0.25mm, 0.35mm, 0.5mm lead equivalent aprons hanging on stands was 32%, 64% and 68% respectively (Fig 20C).

When 0.35mm lead shielding on the horse was combined with lead shielding on personnel (hanging on stands), the greatest reduction was achieved with a 0.5mm lead equivalent apron on personnel (84%) (Fig 20D). When a 0.5mm lead equivalent apron was draped over the horse, up to 89% reduction in total combined counts could be achieved with a 0.5mm lead equivalent apron on personnel. See Table 15.

The characteristic 140.5keV peak seen with 0.5mm lead equivalent aprons on personnel and on the horse is similarly increased as in other regions.

Though the combined sum of lead equivalent thicknesses was equal, there was a difference in reduction of total combined net counts between 0.35mm on the horse and 0.5mm on personnel (84%) and 0.5mm on the horse and 0.35mm on personnel (88%) (Fig 20E).

Table 9: Total number of net scatter and ^{99m}Tc (in brackets) counts recorded at B with added lead shielding on the horse

H	WSH.35 (^{99m}Tc)	WSH.5 (^{99m}Tc)	WSH.35+.25 (^{99m}Tc)	WSH.35+.35 (^{99m}Tc)	WSH.35+.5 (^{99m}Tc)	WSH.5+.25 (^{99m}Tc)	WSH.5+.35 (^{99m}Tc)	WSH.5+.5 (^{99m}Tc)
1	407733 (---)	331151 (22164)	233081 (16654)	195337 (15325)	140117 (15987)	236403 (19010)	132602 (---)	109081 (14319)
2	446793 (21717)	392596 (33733)	241842 (20602)	338131 (14270)	199580 (12239)	193135 (23168)	127279 (14419)	95618 (14514)
3	509413 (18115)	525859 (31632)	262738 (21138)	145013 (10745)	151427 (15574)	254915 (27384)	92490 (13687)	96242 (21016)
4	462671 (28837)	559600 (41250)	226005 (17972)	192899 (16460)	120586 (13830)	304655 (18735)	120806 (16756)	113464 (24802)
5	648450 (24820)	624284 (21545)	536092 (18231)	660588 (32844)	319822 (21037)	441089 (32891)	205016 (19457)	194025 (18866)
Ave	495012 (23372)	486698 (29394)	299952 (18919)	306394 (17990)	186318 (15728)	286039 (24238)	135639 (16080)	121686 (18703)
SD	93192 (5417)	121273 (8069)	132724 (1888)	210784 (8586)	80104 (3322)	95460 (5990)	41756 (2604)	41190 (4454)

H = Horse number
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel
--- = values absent due to unexpected power surges corrupting non-retrievable data
Ave = average (scatter)
SD = standard deviation (scatter)
Mint-coloured sections of horse number 3 = net counts post urination

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Fig 19. Histogram of average counts per second recorded at B.
Counts recorded without shielding and different levels of shielding on the horse or personnel alone, and in combination.

WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel

Fig 20. Unshielded recording and those of various lead shields on personnel and horse at location B.
A. **No shielding:** The spectrum looks similar to previous regions, the scatter peak is at 88.2keV. B. **0.5mm lead shielding on horse:** The ^{99m}Tc peak at 138keV is more prominent compared to Fig 20A but total combined net counts are reduced. C. **0.25mm lead shielding on personnel:** An obvious decrease in total combined net counts as well as a marked reduction of the ^{99m}Tc peak is seen. D. **0.35mm on the horse and 0.5mm lead shielding on personnel:** An increase in the ^{99m}Tc peak is seen, compared to Fig 20C. This was consistently seen with 0.5mm lead aprons on personnel. E. **0.5mm on the horse and 0.35mm lead shielding on personnel:** A reduction in the ^{99m}Tc peak is seen, compared to Fig 20D. This combination, although equal in sum to that in Fig 20D, had the consistently lower total combined net counts.

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4.3.6   Spectrum emitted from horses at location P (Pelvis)

Refer to Tables 10 and 11; and Figs 21 and 22.

This was the region with the lowest total combined net scatter counts outside of the head regions. Unshielded ^{99m}Tc net counts were lowest of all regions and ranged from 2686 (H2) to 9856 (H1) with an average of 5941 counts. Total unshielded scatter counts ranged from 624191 (H2) to 1239913 (H5) with an average of 921441 counts. The average combined total counts of ^{99m}Tc and scatter peaks for 5 unshielded horses were 927382.45 counts. The average energy of the scatter peaks in this region was 86.8keV (Fig. 22A).

With lead shielding draped over the horse alone, combined net counts experienced a 44% reduction behind 0.35mm, and another further 50% reduction behind 0.5mm lead equivalent aprons, compared with unshielded net counts (Figs. 22B, C).

Table 10: Total number of net scatter and ^{99m}Tc (in brackets) counts recorded at P without added lead shielding on the horse

H	WOH (^{99m}Tc)	WOH + 0.25 (^{99m}Tc)	WOH + 0.35 (^{99m}Tc)	WOH + 0.5 (^{99m}Tc)
1	810831 (9856)	376972 (13444)	384324 (15588)	270378 (17648)
2	624191 (2686)	549583 (9166)	341907 (8369)	288285 (---)
3	1042655 (5046)	437358 (2331)	260608 (5689)	167059 (16066)
4	889616 (---)	1132407 (22478)	497614 (20130)	578918 (30830)
5	1239913 (6177)	627965 (26597)	379362 (28206)	365700 (18297)
Average	921441 (5941)	624857 (14803)	372763 (15597)	334070 (20710)
Standard deviation	233303 (2987)	299952 (9838)	85580 (9082)	154107 (6811)

H = Horse number
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
--- = values absent due to unexpected power surges corrupting non-retrievable data

Measurements recorded behind lead aprons hanging on stands revealed a 39% reduction between the 0.25mm and 0.35mm lead equivalent aprons, but only an 8% reduction between the 0.35mm and 0.5mm lead equivalent aprons. The percentage of total combined

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net count reduction between unshielded recordings and 0.25mm, 0.35mm, 0.5mm lead equivalent aprons hanging on stands was 31%, 58% and 62% respectively (Fig 22D, E).

When 0.35mm lead shielding on the horse was combined with lead shielding on personnel (hanging on stands), the greatest reduction was achieved with a 0.5mm lead equivalent apron on personnel (82%). When a 0.5mm lead equivalent apron was draped over the horse, up to 86% reduction in total combined counts could be achieved with a 0.5mm lead equivalent apron on personnel.

The characteristic 140.5 keV peak seen with 0.5mm lead equivalent aprons on personnel was less prominent compared with other regions.

The combinations of 0.35mm lead shielding on the horse and 0.5mm on personnel and 0.5mm on the horse and 0.35mm on personnel yielded 82% reduction of total combined net counts. See Table 15.

Table 11: Total number of net scatter and ^{99m}Tc (in brackets) counts recorded at P with added lead shielding on the horse

H	WSH.35 (^{99m}Tc)	WSH.5 (^{99m}Tc)	WSH.35+.25 (^{99m}Tc)	WSH.35+.35 (^{99m}Tc)	WSH.35+.5 (^{99m}Tc)	WSH.5+.25 (^{99m}Tc)	WSH.5+.35 (^{99m}Tc)	WSH.5+.5 (^{99m}Tc)
1	289053 (15003)	222195 (14820)	269123 (15079)	153046 (8083)	112582 (8873)	166344 (10422)	119053 (6537)	81185 (7507)
2	365771 (18017)	381105 (27099)	248910 (15902)	178555 (10159)	109275 (9967)	181763 (17492)	81584 (9962)	135684 (19245)
3	473588 (23078)	435896 (29831)	185224 (13013)	110569 (7334)	90434 (9571)	225355 (19393)	63868 (7262)	62040 (10641)
4	707005 (30744)	534850 (30115)	212458 (8794)	158836 (11815)	87900 (8874)	277466 (21735)	118747 (10937)	94024 (16910)
5	654296 (37669)	609585 (49615)	738284 (27244)	475316 (21012)	387802 (25425)	268510 (19197)	381705 (26902)	195426 (15809)
Ave	497943 (24902)	436726 (30296)	330800 (16006)	215264 (11681)	157599 (12542)	223888 (17648)	152992 (12320)	113672 (14022)
SD	180174 (9298)	148851 (12482)	230082 (6858)	147471 (5506)	129155 (7217)	49874 (4312)	130073 (8354)	533093 (4814)

H = Horse number
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel
--- = values absent due to unexpected power surges corrupting non-retrievable data
Ave = average (scatter)
SD = standard deviation (scatter)
Mint-coloured sections of horse number 3 = net counts post urination

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Fig 21. Histogram of average counts per second recorded at P.
Counts behind no shielding and different levels of shielding on the horse or personnel alone, as well as combinations thereof, are shown.

WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
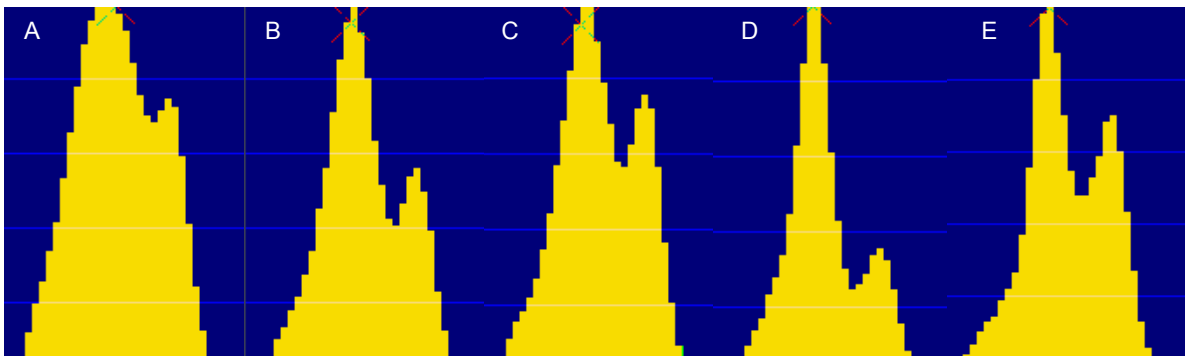
Fig 22. Unshielded recording and those of various lead shields on personnel and horse at location "Pelvis".
A. **No shielding:** The spectrum looks similar to previous regions, the scatter peak is at 88.32keV. B. **0.35mm lead shielding on horse:** Although scatter counts were markedly reduced, the ^{99m}Tc peak as well as total combined net counts were moderately increased compared with Fig 22D. C. **0.5mm lead shielding on horse:** The familiar spectrum of the 0.5mm lead shield, with the increased ^{99m}Tc peak but counts considerably more than in Fig 22E. .D. **0.35mm lead shielding on personnel:** The spectrum shows a reduction of counts compared with Fig 22B and a markedly reduced ^{99m}Tc peak. E. **0.5mm lead shielding on personnel:** Less scatter and ^{99m}Tc counts, though spectrum looks similar in shape to Fig 22C.

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4.3.7　Correlation of spectra changes behind lead shielding of different lead thicknesses

Histograms showing summaries of the recorded counts and scatter fractions with the various lead shielding combinations (attenuation media) at the different anatomical locations can be seen in Figs 23 and 24. The difference between the 0.25mm and 0.35mm lead equivalent aprons was generally greater than that between the 0.35mm and 0.5mm lead equivalent aprons.

Fig. 23. The total combined net counts are on the Y-axis and the various attenuation media are depicted on the X-axis. This graph shows the 0.35mm and 0.5mm lead equivalent shield on the horse combined with the 0.35mm and 0.5mm lead equivalent shielding on personnel to have the lowest counts.

HF = Head Front
HC = Head Cheek
S = Shoulder
B = Bladder
P = Pelvis
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel

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The histogram in Fig 25 shows the average unshielded ^{99m}Tc, scatter and total combined net counts. The bladder region had the highest scatter net counts compared with other regions.

The summaries of average regional net counts for all five horses with different lead shields on personnel only are tabulated in Table 12, for different lead shields on the horses only in Table 13, and for the various thicknesses of lead shields on personnel and horses in Table 14.
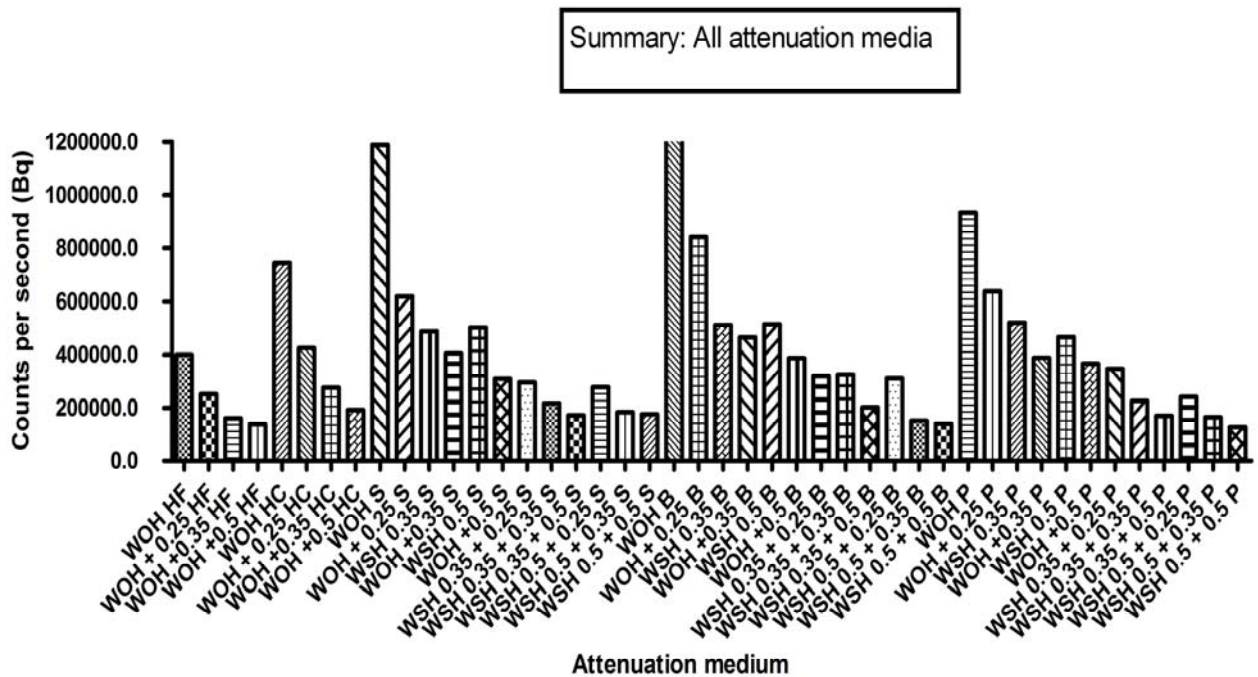
Fig 24. The total combined net counts are on the Y-axis and the various regional attenuation media are depicted on the X-axis. This graph shows the head front region to have the lowest shielded and unshielded total combined net counts compared to all the other regions.

HF = Head Front
HC = Head Cheek
S = Shoulder
B = Bladder
P = Pelvis
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
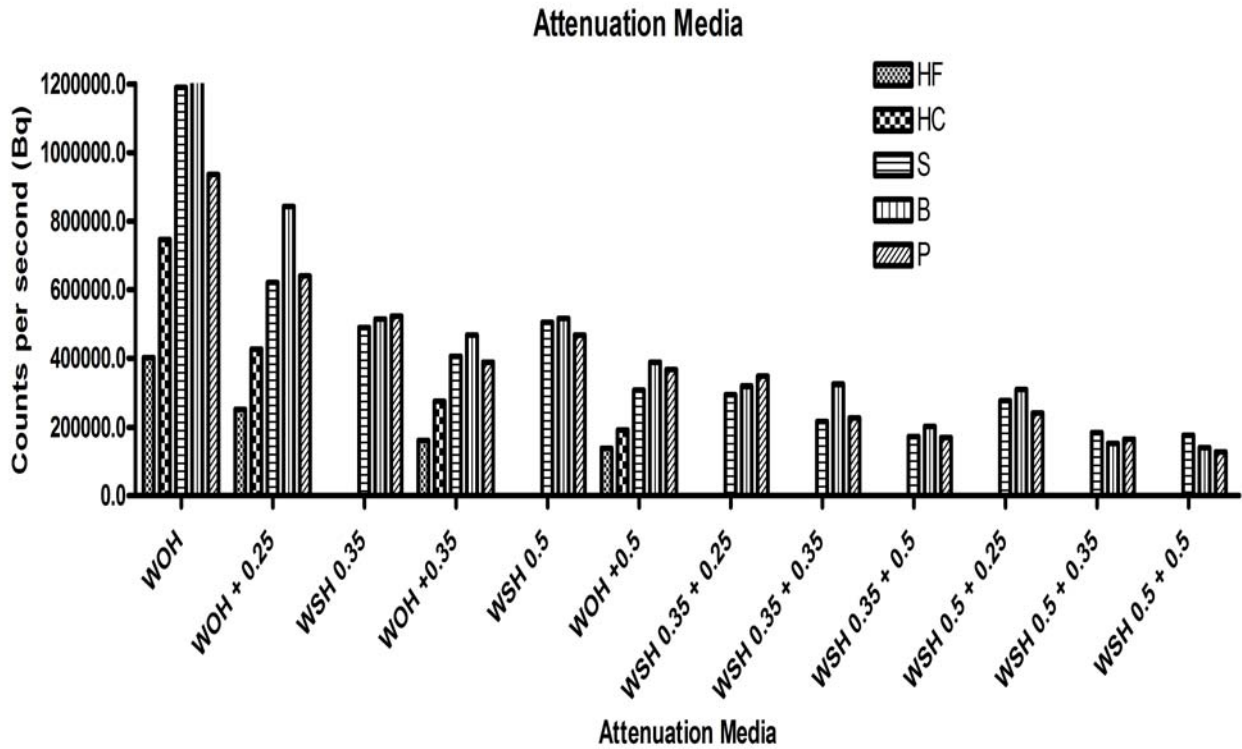*WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel*
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel

Average unshielded ^{99m}Tc, scatter and total combined regional counts
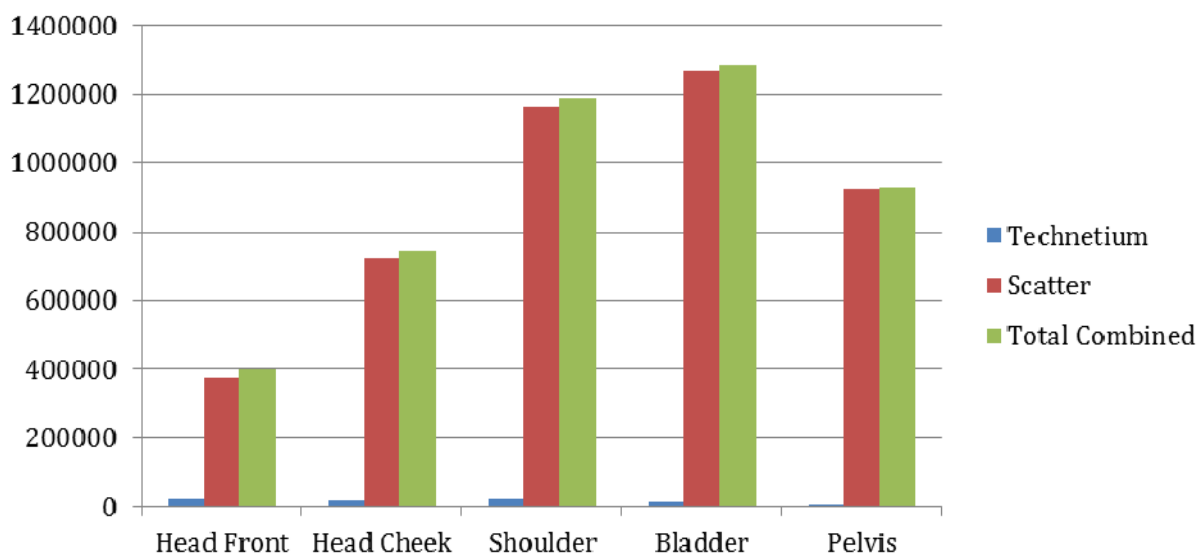
Fig 25. Histogram of average unshielded ^{99m}Tc, scatter and total combined regional counts.

High portion of scatter counts are shown compared to the useful ^{99m}Tc counts used to create a scintigram. The bladder region had the highest scatter counts and the pelvic region the lowest ^{99m}Tc counts.

Table 12: Average 0.25, 0.35 and 0.5mm lead equivalent apron shielded ^{99m}Tc, scatter and total combined regional counts on personnel only

Average counts	Head front	Head cheek	Shoulder	Bladder	Pelvis
^{99m}Tc 0.25mm	19174	26333.6	30518.75	31428	14803.2
Scatter 0.25mm	234025	399595.2	590380	836864	624857
Total 0.25mm	**253199.8**	**425928.8**	**620898.75**	**868292**	**639660.2**
^{99m}Tc 0.35mm	15404.8	24320	34721.8	28826	15596.4
Scatter 0.35mm	147207.4	206486.4	371061	437931.4	372763
Total 0.35mm	**162613.2**	**230806.4**	**405782.8**	**466757.8**	**388359.4**
^{99m}Tc 0.5mm	15371.75	23770.6	34992	26787.5	20710.25
Scatter 0.5mm	123761.5	168415	273259.8	390532.4	334068
Total 0.5mm	**139133.25**	**192185.6**	**308251.6**	**417319.9**	**354778.25**

^{99m}Tc 0.25mm = average ^{99m}Tc net counts recorded behind a 0.25mm lead equivalent shield
Scatter 0.25mm = average net scatter counts recorded behind a 0.25mm lead equivalent shield
Total 0.25mm = total number of average recorded net counts behind a 0.25mm lead equivalent shield
^{99m}Tc 0.35mm = average ^{99m}Tc net counts recorded behind a 0.35mm lead equivalent shield
Scatter 0.35mm = average net scatter counts recorded behind a 0.35mm lead equivalent shield
Total 0.35mm = total number of average recorded net counts behind a 0.35mm lead equivalent shield
^{99m}Tc 0.5mm = average ^{99m}Tc net counts recorded behind a 0.5mm lead equivalent shield
Scatter 0.5mm = average net scatter counts recorded behind a 0.5mm lead equivalent shield
Total 0.5mm = total number of average recorded net counts behind a 0.5mm lead equivalent shield

Table 13: Average regional ⁹⁹ᵐTc, scatter and total combined counts with 0.35 and 0.5mm lead equivalent horse shielding only

Average counts	Shoulder	Bladder	Pelvis
⁹⁹ᵐTc 0.35mm	27544	23372.25	24902.2
Scatter 0.35mm	461656.8	495012	497942.6
Total 0.35mm	**489200.8**	**518384.25**	**522844.8**
⁹⁹ᵐTc 0.5mm	37831.2	30064.8	30296
Scatter 0.5mm	466393.8	486698	436726.2
Total 0.5mm	**540225**	**516762.8**	**467022.2**

⁹⁹ᵐTc 0.35mm = average ⁹⁹ᵐTc net counts recorded behind a 0.35mm lead equivalent shield
Scatter 0.35mm = average net scatter counts recorded behind a 0.35mm lead equivalent shield
Total 0.35mm = total number of average recorded net counts behind a 0.35mm lead equivalent shield
⁹⁹ᵐTc 0.5mm = average ⁹⁹ᵐTc net counts recorded behind a 0.5mm lead equivalent shield
Scatter 0.5mm = average net scatter counts recorded behind a 0.5mm lead equivalent shield
Total 0.5mm = total number of average recorded net counts behind a 0.5mm lead equivalent shield

Table 14: Average regional ⁹⁹ᵐTc, scatter and total combined counts with 0.35 and 0.5mm lead equivalent horse shielding and 0.25, 0.35 and 0.5mm lead equivalent aprons

Average counts	Shoulder	Bladder	Pelvis
⁹⁹ᵐTc 0.35+0.25mm	29318.5	18919.4	16006.4
Scatter 0.35+0.25mm	258749.2	251951.6	330799.8
Total WSH0.35+0.25mm	**288067.7**	**270871**	**346806.2**
⁹⁹ᵐTc 0.35+0.35mm	15825.8	17928.8	11680.6
Scatter 0.35+0.35mm	201217	306393.6	215264.4
Total WSH0.35+0.35mm	**217042.8**	**324322.4**	**226945**
⁹⁹ᵐTc 0.35+0.5mm	18538.8	15733.4	12542
Scatter 0.35+0.5mm	154323.8	186306.4	157598.6
Total WSH0.35+0.5mm	**172860.6**	**202039.8**	**170140.6**
⁹⁹ᵐTc 0.5+0.25mm	24979.2	24230.4	17647.8
Scatter 0.5+0.25mm	252872.6	286039.4	175555.6
Total WSH0.5+0.25mm	**277851.8**	**310269.8**	**193203.4**
⁹⁹ᵐTc 0.5+0.35mm	18160.2	16079.75	12320
Scatter 0.5+0.35mm	166466.4	135638.6	152991.4
Total WSH0.5+0.35mm	**184606.6**	**151718.35**	**165311.4**
⁹⁹ᵐTc 0.5+0.5mm	21675.25	18703.4	14022.4
Scatter 0.5+0.5mm	145120.6	121686	113671.8
Total WSH0.5+0.5mm	**166795.85**	**140389.4**	**127694.2**

WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel

Table 15: Comparative percentage reduction of net scatter counts between unshielded and various shielded regions

Shielding	Head front	Head cheek	Shoulder	Bladder	Pelvis
WOH + 0.25	37%	43%	48%	32%	31%
WOH + 0.35	59%	69%	66%	64%	58%
WOH + 0.5	65%	74%	74%	68%	62%
WSH 0.35	-	-	59%	60%	44%
WSH 0.5	-	-	55%	60%	50%
WSH 0.35 + 0.25	-	-	76%	71%	63%
WSH 0.35 + 0.35	-	-	82%	75%	76%
WSH 0.35 + 0.5	-	-	85%	84%	82%
WSH 0.5 + 0.25	-	-	77%	76%	79%
WSH 0.5 + 0.35	-	-	84%	88%	82%
WSH 0.5 + 0.5	-	-	90%	89%	86%

WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel

Percentage reduction was derived from the formula in 3.2.2. The average recorded net scatter counts from the five horses behind different lead shield thicknesses and different personnel/horse shielding combinations were subtracted from the average recorded net scatter counts of the unshielded horses to obtain the percentages tabulated above.

4.3.8   Recording of exposure rates

The radiation exposure rate, in microsievert per hour (µSv/hr) was measured with the two different dosimeters on the last horse, the results of which are tabulated in Table 16 below.

Table 16: Comparative exposure rates (measured in µSv) of two different dosimeters between unshielded and various shielded regions

Shielding	Head front	Head cheek	Shoulder	Bladder	Pelvis
Unshielded	21 29.3*	27 43*	33.9 74.5*	73 213*	90 267*
0.25mm on personnel	3.7 5.3*	2.1 11.3*	16.4 29*	23 61.2*	28.6 55.8*
0.35mm on personnel	2.6 2.86*	2.9 12.4*	7.3 16.2*	11.3 60.8*	20.9 24.7*
0.5mm on personnel	2.6 8.1*	2.87 11.4*	9.4 18.9*	16.9 54.9*	21.9 32.6*
0.35mm on horse	21 29.3*	27 43*	14.8 25.4*	14.7 28*	9.7 17.3*
0.5mm on horse	21.2 29.3*	27 43*	13.4 22.6*	11 25.4*	8.8 17.7*
0.35mm (horse) + 0.25mm (personnel)	-	-	6.2 12.3*	12 18.2*	9.5 23.2*
0.35mm (horse) + 0.35mm (personnel)	-	-	2.4 10.3*	5.3 26.2*	6 6.5*
0.35mm (horse) + 0.5mm (personnel)	-	-	3.6 7.3*	6.6 12.3*	5.5 7.4*
0.5mm (horse) + 0.25mm (personnel)	-	-	5.3 9*	6.5 11.1*	5.5 14*
0.5mm (horse) + 0.35mm (personnel)	-	-	3.3 5.1*	2.2 5.5*	4.9 9.3*
0.5mm (horse) + 0.5mm (personnel)	-	-	3.2 5*	3.5 5.8*	4.3 10.5*

Dosimeter used: Thermo ESM FH 40G-L10 Multi-purpose Digital Survey Meter

*Dosimeter used: Thermo ESM FH 20G-L10 Multi-purpose Digital Survey Meter (routinely used at the OVAH)

The dosimeter routinely used at the OVAH measured consistently higher exposure rates when compared to the device from iThemba LABS. Another dosimeter (Thermoelectron Corporation (UK) Electronic Personal Dosimeter (Easy EPD2)) used on Mr Philip Beukes and on the primary investigator for the last horse, measured > 10µSv/hr ambient exposure rates, 33µSv/hr deep absorbed dose and 44µSv/hr shallow skin dose for the duration of the exposure period on one day. Exposure rate measurements were only recorded on the last

day, as the previous days were spent attempting to reduce already long exposure times of 90-120 minutes to at least 90 minutes in order to include the extra 30 minutes of exposure time these measurements subjected personnel to.

In total, the measurements of the horses took approximately 1.5 to 2 hours to complete, with a slight decrease in time in the last two horses due to a routine that was devised after the first three horses. Some measurements were taken in reverse order to reduce the time it took to change the lead shields.

4.4 Statistical analysis

For statistical evaluation, a one way ANOVA of different shielding thicknesses at predefined measurement locations was used.

Table 17: Repeated Measures ANOVA and Tukey's Multiple Comparisons Test derived from data of all regions and lead shield combinations as illustrated in Fig 24

Tukey's Multiple Comparison Test	Mean Diff.	Q	P value	95% CI of diff
WOH vs WOH + 0.25	435600	12.19	P < 0.001	251600 to 619500
WOH vs WSH 0.35	627800	17.57	P < 0.001	443900 to 811800
WOH vs WOH +0.35	716200	20.05	P < 0.001	532300 to 900200
WOH vs WSH 0.5	640600	17.93	P < 0.001	456700 to 824600
WOH vs WOH +0.5	782300	21.9	P < 0.001	598400 to 966300
WOH vs WSH 0.35 + 0.25	816100	22.84	P < 0.001	632200 to 1000000
WOH vs WSH 0.35 + 0.35	880300	24.64	P < 0.001	696300 to 1064000
WOH vs WSH 0.35 + 0.5	954700	26.72	P < 0.001	770800 to 1139000
WOH vs WSH 0.5 + 0.25	859800	24.07	P < 0.001	675900 to 1044000
WOH vs WSH 0.5 + 0.35	968900	27.12	P < 0.001	784900 to 1153000
WOH vs WSH 0.5 + 0.5	988100	27.66	P < 0.001	804100 to 1172000
WOH + 0.25 vs WSH 0.35	192300	5.381	P < 0.05	8298 to 376200
WOH + 0.25 vs WOH +0.35	280700	7.856	P < 0.001	96710 to 464600
WOH + 0.25 vs WSH 0.5	205100	5.74	P < 0.05	21100 to 389000
WOH + 0.25 vs WOH +0.5	346800	9.706	P < 0.001	162800 to 530700
WOH + 0.25 vs WSH 0.35 + 0.25	380600	10.65	P < 0.001	196600 to 564500
WOH + 0.25 vs WSH 0.35 + 0.35	444700	12.45	P < 0.001	260800 to 628700
WOH + 0.25 vs WSH 0.35 + 0.5	519200	14.53	P < 0.001	335200 to 703100
WOH + 0.25 vs WSH 0.5 + 0.25	424300	11.88	P < 0.001	240300 to 608200
WOH + 0.25 vs WSH 0.5 + 0.35	533300	14.93	P < 0.001	349400 to 717300
WOH + 0.25 vs WSH 0.5 + 0.5	552500	15.46	P < 0.001	368600 to 736500
WSH 0.35 vs WOH +0.35	88410	2.475	P > 0.05	-95540 to 272400
WSH 0.35 vs WSH 0.5	12810	0.3584	P > 0.05	-171200 to 196800
WSH 0.35 vs WOH +0.5	154500	4.325	P > 0.05	-29450 to 338500
WSH 0.35 vs WSH 0.35 + 0.25	188300	5.271	P < 0.05	4353 to 372300
WSH 0.35 vs WSH 0.35 + 0.35	252500	7.067	P < 0.01	68510 to 436400
WSH 0.35 vs WSH 0.35 + 0.5	326900	9.15	P < 0.001	142900 to 510900

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WSH 0.35 vs WSH 0.5 + 0.25	232000	6.495	P < 0.01	48070 to 416000
WSH 0.35 vs WSH 0.5 + 0.35	341100	9.547	P < 0.001	157100 to 525000
WSH 0.35 vs WSH 0.5 + 0.5	360300	10.08	P < 0.001	176300 to 544200
WOH +0.35 vs WSH 0.5	-75610	2.116	P > 0.05	-259600 to 108300
WOH +0.35 vs WOH +0.5	66100	1.85	P > 0.05	-117900 to 250100
WOH +0.35 vs WSH 0.35 + 0.25	99900	2.796	P > 0.05	-84060 to 283900
WOH +0.35 vs WSH 0.35 + 0.35	164000	4.592	P > 0.05	-19910 to 348000
WOH +0.35 vs WSH 0.35 + 0.5	238500	6.675	P < 0.01	54530 to 422400
WOH +0.35 vs WSH 0.5 + 0.25	143600	4.02	P > 0.05	-40340 to 327600
WOH +0.35 vs WSH 0.5 + 0.35	252700	7.072	P < 0.01	68710 to 436600
WOH +0.35 vs WSH 0.5 + 0.5	271800	7.609	P < 0.01	87890 to 455800
WSH 0.5 vs WOH +0.5	141700	3.966	P > 0.05	-42250 to 325700
WSH 0.5 vs WSH 0.35 + 0.25	175500	4.912	P > 0.05	-8453 to 359500
WSH 0.5 vs WSH 0.35 + 0.35	239700	6.708	P < 0.01	55700 to 423600
WSH 0.5 vs WSH 0.35 + 0.5	314100	8.792	P < 0.001	130100 to 498100
WSH 0.5 vs WSH 0.5 + 0.25	219200	6.136	P < 0.05	35270 to 403200
WSH 0.5 vs WSH 0.5 + 0.35	328300	9.188	P < 0.001	144300 to 512200
WSH 0.5 vs WSH 0.5 + 0.5	347500	9.725	P < 0.001	163500 to 531400
WOH +0.5 vs WSH 0.35 + 0.25	33800	0.9461	P > 0.05	-150200 to 217800
WOH +0.5 vs WSH 0.35 + 0.35	97950	2.742	P > 0.05	-86000 to 281900
WOH +0.5 vs WSH 0.35 + 0.5	172400	4.825	P > 0.05	-11560 to 356300
WOH +0.5 vs WSH 0.5 + 0.25	77520	2.17	P > 0.05	-106400 to 261500
WOH +0.5 vs WSH 0.5 + 0.35	186600	5.222	P < 0.05	2613 to 370500
WOH +0.5 vs WSH 0.5 + 0.5	205700	5.759	P < 0.05	21790 to 389700
WSH 0.35 + 0.25 vs WSH 0.35 + 0.35	64150	1.796	P > 0.05	-119800 to 248100
WSH 0.35 + 0.25 vs WSH 0.35 + 0.5	138600	3.879	P > 0.05	-45360 to 322500
WSH 0.35 + 0.25 vs WSH 0.5 + 0.25	43720	1.224	P > 0.05	-140200 to 227700
WSH 0.35 + 0.25 vs WSH 0.5 + 0.35	152800	4.276	P > 0.05	-31190 to 336700
WSH 0.35 + 0.25 vs WSH 0.5 + 0.5	171900	4.813	P > 0.05	-12010 to 355900
WSH 0.35 + 0.35 vs WSH 0.35 + 0.5	74440	2.084	P > 0.05	-109500 to 258400
WSH 0.35 + 0.35 vs WSH 0.5 + 0.25	-20430	0.5719	P > 0.05	-204400 to 163500
WSH 0.35 + 0.35 vs WSH 0.5 + 0.35	88620	2.48	P > 0.05	-95340 to 272600
WSH 0.35 + 0.35 vs WSH 0.5 + 0.5	107800	3.017	P > 0.05	-76160 to 291800
WSH 0.35 + 0.5 vs WSH 0.5 + 0.25	-94870	2.656	P > 0.05	-278800 to 89080
WSH 0.35 + 0.5 vs WSH 0.5 + 0.35	14180	0.3968	P > 0.05	-169800 to 198100
WSH 0.35 + 0.5 vs WSH 0.5 + 0.5	33350	0.9336	P > 0.05	-150600 to 217300
WSH 0.5 + 0.25 vs WSH 0.5 + 0.35	109000	3.052	P > 0.05	-74910 to 293000
WSH 0.5 + 0.25 vs WSH 0.5 + 0.5	128200	3.589	P > 0.05	-55730 to 312200
WSH 0.5 + 0.35 vs WSH 0.5 + 0.5	19180	0.5368	P > 0.05	-164800 to 203100

WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel
WSH 0.35 = with 0.35mm lead equivalent shield on horse
WSH 0.5 = with 0.5mm lead equivalent shield on horse
WSH 0.35 + 0.25 = with 0.35mm lead shield on horse AND 0.25mm lead shield on personnel
WSH 0.35 + 0.35 = with 0.35mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.35 + 0.5 = with 0.35mm lead shield on horse AND 0.5mm lead shield on personnel
WSH 0.5 + 0.25 = with 0.5mm lead shield on horse AND 0.25mm lead shield on personnel

WSH 0.5 + 0.35 = with 0.5mm lead shield on horse AND 0.35mm lead shield on personnel
WSH 0.5 + 0.5 = with 0.5mm lead shield on horse AND 0.5mm lead shield on personnel

Table 18: Repeated Measures ANOVA and Tukey's Multiple Comparisons Test from data derived from Table 4 (Number of counts recorded at HF without added lead shielding on the horse)

Table Analyzed 4				
One-way analysis of variance				
P value	0.0098			
P value summary	**			
Are means significantly different? (P < 0.05)	Yes			
Number of groups	4			
F	5.444			
R squared	0.5213			
ANOVA Table	SS	df	MS	
Treatment (between columns)	2.007E+11	3	66910000000	
Residual (within columns)	1.844E+11	15	12290000000	
Total	3.851E+11	18		
Tukey's Multiple Comparison Test	Mean Diff.	q	P value	95% CI of diff
WOH HF vs WOH + 0.25 HF	147800	2.981	P > 0.05	-54300 to 349900
WOH HF vs WOH +0.35 HF	238400	4.808	P < 0.05	36280 to 440400
WOH HF vs WOH +0.5 HF	261800	4.979	P < 0.05	47500 to 476200
WOH + 0.25 HF vs WOH +0.35 HF	90590	1.827	P > 0.05	-111500 to 292700
WOH + 0.25 HF vs WOH +0.5 HF	114100	2.169	P > 0.05	-100300 to 328400
WOH +0.35 HF vs WOH +0.5 HF	23480	0.4465	P > 0.05	-190900 to 237800

HF = Head Front
WOH = without shielding on horse
WOH + 0.25 = without shielding on horse AND 0.25mm lead equivalent shield on personnel
WOH + 0.35 = without shielding on horse AND 0.35mm lead equivalent shield on personnel
WOH + 0.5 = without shielding on horse AND 0.5mm lead equivalent shield on personnel

Chapter 5: Discussion

5.1   Introduction

Measurements of energy spectra and number of ionising events (counts) within the spectrometer were made in order to establish whether the energy spectra emitted from five horses undergoing bone scintigraphy changed in quality behind the various types of lead

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shields. Additionally, exposure rates during the measurement period at the various anatomical locations were recorded on the last horse. This section discusses the technique, the measurements, the energy spectra and exposure rates at different anatomical locations, with varying combinations of lead shields, the pitfalls and limitations of the study, and the applications that the findings of this study could have clinically, and suggestions of further research.

5.2   Study population

Initially, the evaluation of ten horses were planned, but previous records of patients undergoing bone scintigraphy at the University of Pretoria, documented by radiation safety officer at the time (Ms Yolanda Bekeur), showed that using ten animals would result in an estimated personnel radiation exposure level of 7mSv for the duration of measurements (this excludes the radiation dose received during injection). Considering that the legal limit for a radiation worker is 20mSv per annum, and radiology staff members are regarded as "normal public" in South Africa, with legal limits of 5mSv per annum, the number of horses included in this study was halved to comply with the local legal radiation exposure requirements. All animals were treated in the same manner as clinical cases admitted to the equine clinic of the OVAH for bone scintigraphy would be. Thoroughbreds and thoroughbred crosses were used in the study because they represented the majority of patients admitted for scintigraphic examinations at our facility.

5.3   General data collection - devices

Due to the technical nature of this study, the quality of instrumentation was paramount to its successful outcome. A state of the art spectrometer was sought to obtain the most accurate measurements with the least amount of electronic noise that may have hampered interpretation of results. Fortunately, such a device was available and thus the recorded spectra are regarded as accurate representations of energy spectra emitted from the horses. Two dosimeters were used to measure exposure rates behind varying lead shield combinations, as the medical physicist accompanying the spectrometer had a device that was far more expensive and accurate than the one routinely used at the OVAH, therefore a comparison of the two devices was considered useful for future use and interpretation of the OVAH device. Additionally a personal electronic dosimeter measured the shallow skin and deep absorbed doses during the measurement period of approximately 1.5–2 hours.

5.4   Measurement technique

For the recording of energy spectra, it was not possible to standardise a distance from the horse surface, as the distance was dependent on the dead time of the system. Thus a

variable distance was required and adhered to in order to minimise this technical problem. The variability in the distance would not affect the recorded energy spectra in any way. The recording of ionising events (counts per second) was secondary and due to the fact that any spectrometer, even a high quality one, has a roughly 10% efficiency (Bushberg 2011) at best, the absolute total number of counts could not be recorded in any case, making the exact measuring distance from the horse less important.

The measuring of spectra initially took approximately 90 to 120 minutes to complete. This was reduced to about 90 minutes after the first two days due to increased efficiency of the placement and strategic rotation of lead shields. Locations were not measured in any specific order, but were randomized. As the effective half-life of ^{99m}Tc (4.8hrs) exceeded measurement time (2.5hr delay + maximum of 2 hour measuring time = 4.5hrs), random variation in measurement location order was not considered problematic. In addition, the spectrum recorded behind lead shields was not expected to change with decreasing radioisotope activity within the patient.

The additional exposure rate measurements took another 30 minutes to complete for all the anatomical locations and various combinations of lead shielding.

Unfortunately, due to unexpected occasional power surges, a few recorded data sets were corrupt and could not be repeated as this was detected in the post–processing phase of the study, thus recordings were no longer retrievable.

5.5   Energy spectra without lead shields

The spectrometer generally measured the least counts in front of the horses' heads. As previously determined by investigators (Didierlaurent *et al* 2005), the energy spectrum acquired from the surfaces of horses 2.5 hours after the intravenous injection of ^{99m}Tc is vastly different from the monophasic peak of non–injected ^{99m}Tc. The counts around the 140.5keV peak of ^{99m}Tc are reduced. The ^{99m}Tc peak is accompanied by a large amount of lower energies, which had an average of 86.5 (shoulder region) to 92.1keV (head front region). The reason for the higher average energy peaks of the head regions is unknown, but it may be speculated that there is little soft tissue coverage of the head region, relative to the underlying skull, and this may result in a relatively harder scatter energy peak to due reduced Compton scattering of the 140.5keV ^{99m}Tc peak by soft tissue. In the regions where more soft tissue mass is present due to muscle and internal organs, the energy peaks are lower, the shoulder, bladder and pelvic regions all have scatter energy peaks of less than 88keV.

5.6　　Energy spectra with varying lead shield combinations

As soon as lead shielding is introduced, there is an immediate reduction of ionising events and a shift of the energy spectrum to the left of the graph. There was an emergence of lower energy (86keV) peaks, which most likely resulted from the photoelectric effect of lead shielding and resultant characteristic x–rays derived from lead.The scatter peaks are predominantly centred at 82–88keV, which coincide with the different K – edges of lead (88.008, 87.367, 84.936, 84.450, 74.969 and 72.804 from the K shell transitions to the N, M, M, L and L shells respectively) (Robinson 1976). There was consistently less reduction in scatter when lead shielding was placed on the horse alone, in comparision with personnel wearing lead aprons. The maximum reduction achieved with lead shielding on horses alone was 60% compared to 74% reduction with lead shielding on personnel alone (see Table 15). Since the distance of measurements behind lead shielding on horses alone also varied from the horse's surface due to technical limitations of the dead time of the equipment, it is unlikely that the mild increase in distance from the horse's surface behind hanging lead shields played a role in this obvious difference in the recorded energy spectrum.

The ^{99m}Tc peaks were variably reduced depending on the lead shield combination employed. It was lowest with 0.25mm and 0.35mm lead equivalent aprons and highest with 0.5mm lead equivalent aprons. Why the latter occurred is unclear. It may be due to a relatively higher efficiency of the thicker lead to remove scatter radiation, thus resulting in a relatively higher radioisotope peak, or it may be due to characteristic x–rays from the photoelectric effect of unknown alloys mixed with the lead. Although the manufacturers of the lead aprons used in the study were approached, information regarding the mixture of metals within the aprons was not disclosed.

The above–described second peak of ^{99m}Tc was markedly reduced as soon as 0.25mm or 0.35mm lead equivalent lead aprons were added as shields. This effect was less obvious when a 0.5mm lead equivalent apron was used.

The lowest second high peak combined with lowest recorded counts was measured behind 0.5mm lead shields on the horse and 0.35mm lead aprons on personnel, thus was regarded as being the ideal combination to use in a clinical setting.

5.7　　Energy spectra at different anatomical locations

In the regions with less soft tissue covering, there was understandably less scatter radiation and the energy peaks also differed accordingly. Higher scatter peaks were recorded with higher scatter counts and the second higher energy peak recorded with 0.5mm lead shields was also higher in the regions with increased scatter, especially the shoulder and bladder regions. It is unknown why the pelvic region, which has subjectively more muscle mass than the shoulder region, had consistently narrower peaks and less counts than the shoulder or bladder regions. It is speculated that because ^{99m}Tc–MDP localises in bone; and the

shoulder region may have more bone mass due to the shoulder girdle and underlying ribs, the scatter counts in this region (with an equivalent soft tissue mass) could thus be higher than the pelvic region.

5.8   Scatter radiation emitted from horses

Scatter radiation was markedly increased at the shoulder and bladder regions, compared to the head regions. This correlated with soft tissue coverage as mentioned above. The pelvic region surprisingly had an intermediate amount of scatter radiation. The highest counts were measured in the bladder region and were mild to moderately reduced (as expected) post voidance. A single horse that urinated during the recording of data showed a moderate reduction of particularly net scatter counts after urination when compared to the other horses and to counts before voidance. It is therefore recommended that urination is encouraged before the commencement of the scintigraphic examination and to prevent personnel from standing too close to that region. The administration of furosemide an hour after injection of the radionuclide may thus be a useful adjunct to the scintigraphic examination procedure.

5.9   Exposure rates with different dosimeters at various anatomical locations

Table 16 demonstrates the discrepancy in dosimeter readings. The TLD routinely used at the OVAH (Thermo ESM FH 20G-L10 Multi-purpose Digital Survey Meter) consistently but variably overestimated exposure rates at the different anatomical locations and behind the various lead shields. It is unknown, at this stage, why this is the case. No specific pattern regarding locations or lead–shield combinations could be identified.

5.10   Application of these results in the clinical scenario

Maximal lead shielding significantly reduced absolute scatter counts by almost 90% thus is strongly advised. The best and most effective lead shield combination to use was a 0.5mm lead equivalent apron on the horse and 0.35mm lead equivalent aprons worn by personnel.

From this study it appears that the best position for handler to stand in is directly at the front of the head, and not at the side. It is strongly advised that the handler wear a 0.35mm lead equivalent apron.

Personnel assisting in shielding of opposite limbs to avoid the "shine–through" effect during scintigraphic examination, should stand as far away as possible from the bladder region and face the limb whilst wearing a 0.35mm lead equivalent apron.

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The ALARA principle should be adhered to at all times. Even though lead shields reduced the radiation exposure rates considerably, the resultant characteristic x–rays produced by the lead shields are biologically hazardous and contact time should still be minimized.

5.11   Limitations of the study

Limitations of this study include the small number of horses measured, the variation in the distance from the horse whilst measurements were recorded, unfortunate power outages that occurred and rendered some non–retrievable recordings useless. Additionally, exposure rates were only measured on one horse, which also happened to be the smallest and lightest of the group and thus may under–estimate average exposure rates in a normal clinical setting, in which the larger breeds predominate. Due to radiation constraints, the randomization of data collection could not be adhered to. Instead, the quickest possible route of measurement collection was developed. The distance from the horse was also variable due to the dead time of the system. The fat and water content of the slightly different sized horses was not recorded or taken into account and would also affect the scatter counts.

Lastly, the radioisotope was delivered with different activity every day, so that another variable would have influenced the counts recorded.

5.12   Future studies

Further studies would be needed to evaluate the energy spectra of non–leaded shields to determine their clinical usefulness in equine bone scintigraphy. Since characteristic x – rays produced by lead are biologically more hazardous (albeit with a markedly reduced intensity when used with the correct lead shield combination), alternatives to leaded shields may need to be investigated and perhaps pursued in future.

Further studies are also necessary to evaluate a range of commonly used dosimeters to determine their variability in measuring exposure rates. In our case, we have established that our dosimeter over–estimates exposure. However, it is unknown whether others might underestimate exposures and also, which is the dosimeter with the most accurate recording of all.

It may also be useful to determine radiation exposure rates at varying distances from the horse with different types of dosimeters and different lead shield combinations, though this has to some degree already been documented (Steyn *et al* 2005).

5.13 Null hypotheses

The results of this study have shown that:

- The null hypothesis that suggests emitted energy spectrum from an equine patient without any form of lead shielding is harmless for attending personnel during scintigraphic examinations may be rejected.

- The null hypothesis that suggests emitted polychromatic gamma spectrum of ^{99m}Tc–MDP, commonly used for bone scintigraphy in horses, would not change significantly behind lead shielding worn by the patient and/or personnel with varying lead thicknesses may be rejected.

- The null hypothesis that suggests "beam hardening" effects of lead would preclude the use of lead aprons during bone scintigraphy of the horse may be rejected.

Chapter 6: Conclusion

The following conclusions were deduced from this study:

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- The wearing of lead shields during bone scintigraphy of the horse is strongly advised.

- Personnel should wear 0.35mm lead equivalent lead aprons, whilst patients should be draped with 0.5mm lead equivalent coats.

- The handler should stand directly in front of the horse's head, wearing a 0.35mm lead equivalent apron.

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18. Personal communication with Mr Philip Beukes of iThemba LABS, Somerset West, RSA

APPENDIX A

DATA COLLECTION SHEET

Horse _____Date _____ Mass _____ Breed _____

Clinical examination:

Temperature_____ Respiration rate (per minute) _____ Heart rate (per minute) _____

Blood collected _____

Technetium^{99m} – MDP activity injected _____mCi   Time injected: _____   Time scanned_____

Furosemide injection time: _____   Amount: _____

MEASUREMENTS:

    1. Without lead shielding on the horse =   Head front (HF) _____

WOH

Cheek side (HC) _____

Shoulders (S) _____

Bladder (B) _____

Pelvis (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

1.   Without lead shielding on horse and with lead apron on stand **(0.25mm)** =

WOH+0.25P

Head front (HF) _____

Cheek (HC) _____

Shoulder (S) _____

Bladder (B) _____

Pelvis (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

2.   Without lead shielding on horse and with lead apron on stand **(0.35mm)** =

WOH+0.35P   Head: Front (HF) _____

Cheek (HC) _____

Shoulder (S) _____

Bladder (B) _____

Pelvis (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

3.   Without lead shielding on horse with lead apron on stand **(0.5mm)** =

WOH+0.5P

Head front (HF) _____

Cheek (HC) _____

Shoulder (S) _____

Bladder (B) _____

Pelvis (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

4.   With lead shielding on the horse = **0.35 mm** lead apron

WSH0.35

Shoulder (S) _____

Bladder (B) _____

Pelvis (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

5.   With lead shielding on the horse = **0.5mm** lead apron

WSH0.5   Shoulder (S) _____

Bladder (B) _____

Pelvis (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

6.   With lead shielding on horse **(0.35mm)** and with lead apron on stand **(0.25mm)** =

WSH0.35+0.25P   Shoulder (S) _____

Bladder (B) _____

Pelvis (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

7.   With lead shielding on horse **(0.35mm)** and with lead apron on stand **(0.35mm)** =

WSH0.35+0.35P   Pelvis (S) _____

Bladder (B) _____

Shoulder (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

8.   With lead shielding on horse **(0.35mm)** and with lead apron on stand **(0.5mm)** =

WSH0.35+0.5P

Shoulder (S) _____

Bladder (B) _____

Pelvis (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

9.   With lead shielding on horse **(0.5mm)** and with lead apron on stand **(0.25mm)** =

WSH0.5+0.25P

Shoulder (S) _____

Bladder (B) _____

Pelvis (P) _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

10.   With lead shielding on horse **(0.5mm)** and with lead apron on stand **(0.35mm)** =

WSH0.5+P0.35   Pelvis _____

Bladder _____

Shoulder _____

65

Exposure: HF _____ HC _____ S _____ B _____ P _____

Exposure: HF _____ HC _____ S _____ B _____ P _____

11.   With lead shielding on horse **(0.5mm)** and with lead apron on stand **(0.5mm)** =

WSH0.5+P0.5

Shoulder _____

Bladder _____

Pelvis _____

Exposure: 30cm HF _____ HC _____ S _____ B _____ P _____

Exposure: 100cm HF _____ HC _____ S _____ B _____ P _____