THESIS

OCCUPATIONAL RADIATION DOSE TO PERSONS INVOLVED IN VETERINARY POSITRON EMISSION TOMOGRAPHY

Submitted by

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ABSTRACT

OCCUPATIONAL RADIATION DOSE TO PERSONS INVOLVED IN VETERINARY POSITRON EMISSION TOMOGRAPHY

Several studies have been conducted concerning the dose to hospital personnel from positron emission tomography (PET) radiopharmaceuticals, but to date no specific parallel studies have been done for veterinary PET technologists. Compared to human PET imaging, veterinary personnel are potentially interacting with animal patients for a longer time period, sometimes in close physical proximity, because of the need for anesthetizing patients. There is no equivalent data on personnel exposure from human PET imaging; human patients are not anesthetized and are kept in an isolated room after injection until their imaging procedure. Although veterinary personnel may be interacting more closely with animal patients undergoing PET imaging, radiopharmaceutical doses are generally smaller for animal patients because they weigh less on average. Considering these and other differences between human and veterinary practice, this study aimed to determine, on a per patient basis, the dose to personnel working with PET at Colorado State University's (CSU) James L. Voss Veterinary Teaching Hospital (VTH). Electronic personal dosimeters (EPDs) and supplemental optically stimulated luminescence (OSL) dosimeters were used (in addition to regular dosimetry) to determine radiation doses to veterinary personnel

over a period of four months. Participants in the study included nuclear medicine technologists, the on-duty anesthesiology technologist, and occasionally an observer. Individual doses, along with the details of the staff member's activities, were recorded for available personnel for each PET study. Twenty-five scans were conducted over the course of this study: thirteen different dogs, six different cats, and a sheep (with two cats and three dogs having repeat scans). The mass range of the animals was 2.8 to 76.5 kg, with an average of 28.9 kg. The average amount of activity injected was 6 MBq per kg. The dose range for the nuclear medicine technologists was 0 to 30 μSv (7.8 μSv average), for the anesthetist 1 to 22 μSv (8.3 μSv average), and for the observer 0 to 2 μSv (0.4 μSv average).

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Personal

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DEDICATION

To Peekaboo

4/9/2003 – 5/25/2011

The foot of my bed is empty

There's a knock without a bark

Forgetting, I still talk to you

Too soon we had to part

Until we meet again

In the light beyond the dark

I love you, I miss you

My little dog, my heart

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Background and Motivation [1-2]

Positron emission tomography (PET) is a diagnostic imaging modality used in the clinical setting for disease detection and treatment assessment. PET was developed in the 1970s [3-4] and although primarily used for research, it has become much more prevalent in the medical community for clinical use over the past 15 years. PET is both more sensitive and has higher resolution than gamma camera imaging or single photon emission computed tomography (SPECT). Additionally, since PET provides functional and metabolic information, it surpasses other diagnostic imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI) in the ability to detect malignant processes [5]. PET is often combined with CT, which enables simultaneous visualization of both physiologic and anatomical characteristics of a biological system. The first combined PET/CT became available clinically in 2001, further increasing the specificity and accuracy of the imaging modality, and again contributing to a rise in popularity. In 2005, more than 1.3 million patients received PET or PET/CT procedures in the United States alone. Double digit growth in the number of PET/CT procedures performed per year is predicted, with about 500 new PET/CT units being sold every year.

Veterinary PET/CT

Some of the early positron emission and PET imaging studies were conducted using dogs [6-9] and have contributed to the determination of the viability of translational application of these imaging techniques to humans. Now, with the increasing prevalence of PET (especially combined with CT) in human medicine over the past several years, PET/CT has been considered for use in the veterinary community [10-11]. Studies have been recently conducted in the veterinary community concerning the utility of PET [12-20], PET/CT [21-25], and even PET/MRI [26-28], but the extent of the literature is still somewhat limited. However, the dramatic increase in the number of veterinary PET studies published in the past few years indicates a growing interest in this imaging technique, with the first dedicated, on-site veterinary PET/CT installed at Colorado State University's (CSU) James L. Voss Veterinary Teaching Hospital (VTH) in 2009 [29]. The first PET/CT conducted at the VTH was on 27 October 2009 of a companion animal (a Boston Terrier, shown in Figure 1).

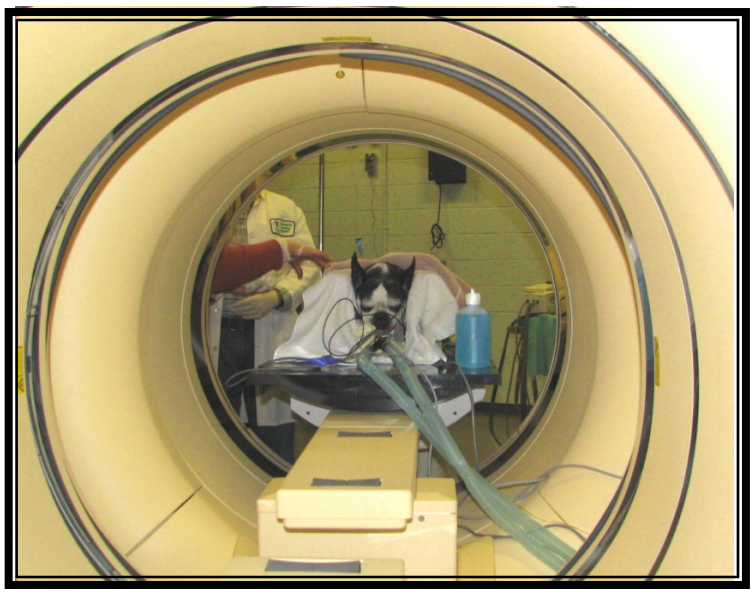


Figure 1: The first PET/CT patient at CSU VTH

To date (27 October 2009 through 09 June 2011), 48 animals have received PET/CT scans, with 70 total scans conducted, as summarized in Table 1.

Table 1: PET/CT study summary

Year	# Dogs	# Cats	# Sheep	Isotope
2009	9	0	0	^{18}F FDG
	1	0	0	^{18}F NaF
2010	21	8	0	^{18}F FDG
	4	0	0	^{18}F NaF
2011	14	10	1	^{18}F FDG
	2	0	0	^{18}F NaF
			Total number of animals:	48
			Total number of PET/CT scans:	70

With the widespread adoption of PET/CT into the medical community and its corresponding impact on cancer management [1], the popularity of the imaging modality is likely to continue to diffuse to the veterinary community. Veterinary PET provides phenomenal research opportunities as well as providing a new, accurate mode of diagnostic imaging in veterinary radiation oncology, and is likely to continue to increase in popularity as the veterinary community becomes more familiar with the technology and its application [10-11].

Along with the medical applications of PET are concurrent radiation safety considerations. Multiple studies have been conducted concerning radiation dose to human hospital personnel from PET radiopharmaceuticals [30-44], but to date no

specific parallel studies have been done for veterinary personnel. Veterinary patients present challenges not encountered with human patients. For example, veterinary patients undergoing PET procedures need to be anesthetized to insure the animal remains immobile for optimal image acquisition. Because animal patients under anesthesia require close monitoring, more time is generally spent near these patients than human patients. Additional differences include administered activities and patient throughput. Typical radiopharmaceutical doses for humans range from 370 to 740 MBq [45] (or about five to seven MBq kg^{-1}), with up to 30 patients being seen in one day [2]. In this study, injected doses to veterinary patients ranged from 20 to 417 MBq (about 5.9 MBq kg^{-1}), with 25 procedures performed over about four months (an average of 0.2 patients per day.)

This study aimed to determine the radiation dose, per patient, to VTH personnel working with veterinary PET at Colorado State University's James L. Voss Veterinary Teaching Hospital in Fort Collins, Colorado. Area monitoring has been conducted during certain PET scans at the VTH, but area monitoring is an indirect method for calculating dose, whereas this study determined doses from PET exposures directly. Electronic personal dosimeters (EPDs) were used to determine real-time radiation doses to VTH personnel over a period of four months. As a supplement to the EPDs, optically stimulated luminescence dosimeters were used that were identical (and in addition) to the VTH personnel's dosimeters of record. VTH personnel who participated in this study included nuclear medicine technologists, the on-duty anesthetist, and a student observing the procedures. Individual doses, along with the details of the participant's

activities, were recorded as available for each PET study. Upon completion of this study, radiation doses were compared to doses received by technologists performing conventional PET studies. This study consisted of twenty-five scans: sixteen dogs, eight cats, and one sheep.

The hypothesis was that the per patient radiation doses to VTH personnel from fluorine-18 (F-18) labeled radiopharmaceuticals would be comparable to the doses of conventional nuclear medicine technologists working in human hospitals.

Interaction of (Ionizing) Radiation with Matter [46-47]

For the purposes of this paper, the word "radiation" is used to mean specifically *ionizing* radiation, or radiation capable of producing ions in matter. Radiation interacts with matter through excitations (raising an electron to a higher energy level) and ionizations (creation of ion pairs), thus depositing some or all of its energy in the material through which it traverses. Photointeractions are interaction mechanisms specific to electromagnetic radiation (photons). The radiation of concern in this study, 511 keV positron-electron annihilation photons, interacts through Compton scattering (the primary interaction mechanism for these photons) or the photoelectric effect, as the energy of each photon is less than the energy required for pair production or for photodisintegration [47].

The absorption of radiation by a biological medium, like the human body, can result in biological effects as a consequence of DNA damage. Although photons do not typically damage DNA directly, their interaction with matter can produce charged particles (liberation of electrons leading to free radical formation) which in turn can

cause DNA damage, such as single or double chromosome strand breaks (SSB and DSB respectively). Low amounts of radiation exposure often result in SSB, which can result in DNA mutation, consequences of which are stochastic effects such as cancer. Large amounts of radiation can more frequently result in DSB, which, in addition to mutations, may lead to cell death. Excessive cell death is the source of deterministic effects like erythema.

Basic Physics of Radiation Protection – Band Theory of Solids [48]

There are discrete electron energy levels within solids (referred to as a band structure). These energy levels are dependent on the crystalline lattice structure of the particular solid, and can be grouped into two major categories: the conduction (higher energy) band and the valence (lower energy) band. Outer shell electrons, covalently bound in the solid, typically reside in the valence band. The conduction band, although normally empty, will contain any unbound electrons that are free to migrate through the solid. These energy bands are separated by an energy range referred to as the "forbidden gap." Solids can be classified as insulators, semi-conductors, or conductors based on the magnitude of the forbidden gap. Solids with greater than ~5 eV difference between bands are considered insulators, and in conductors, the bands overlap. Solids with a difference of ~1 eV between bands are known as intrinsic semi-conductors.

It is possible for an electron in the valence band to acquire enough energy to be "excited" to the conduction band, leaving a hole behind in the valence band. The electron and hole together are referred to as an electron-hole pair. If there are electrons in the conduction band, it is possible to cause current flow by applying an

electric field across the solid; any electrons in the conduction band will flow one way, while electrons in the valence band will move to fill the holes, causing hole flow in the opposite direction. The electron-hole pair will eventually recombine (either naturally or with external stimulation), emitting a de-excitation photon in the process, without an applied electric field. Many methods of radiation detection (and all the methods in this study, discussed in the following section) exploit this material attribute, often using added impurities (referred to as doping) to enhance the characteristics of the solid that are conducive to radiation detection.

Basics of dose assessment [49]

Absorbed dose, D, is a fundamental dose quantity that is essentially the average amount of energy absorbed per unit mass in a material at a certain point. The basic procedure of dose assessment is to determine absorbed dose for specified organs and tissues, and to apply appropriate weighting factors to take into account differences of radiations (equivalent dose, H_T) and of organ/tissue sensitivities (effective dose, E). However, protection quantities (equivalent and effective dose) are not directly measurable. Operational quantities can be measured though, and therefore are used to assess effective dose. In routine monitoring, the values of these operational quantities are taken as a sufficiently precise and accurate assessment of effective dose.

For area monitoring the operational quantity for assessing effective dose is the ambient dose equivalent, $H^*(d)$, where d is a specified depth in millimeters. The radiation of concern in this study is strongly penetrating radiation. Therefore, a stationary dose rate meter should be calibrated to the ambient dose equivalent for

penetrating radiation, specifically $H^*(10)$. However, older hand held meters, such as the ones used at the VTH, actually measure exposure rate as opposed to dose rate. Exposure, when referring to the radiation quantity, indicates the ability of electromagnetic radiation to ionize the air it passes through [47]. Hand held meters at the VTH read in milliröntgen per hour (mR h^{-1}). A röntgen is defined for dry air at standard conditions (STP; $T = 273$ K, $P = 101$ kPa, and $\rho_{air} = 1.293 \times 10^{-3}$ g cm^{-3}) [47], and can be converted to absorbed dose [48], although frequently 1 R is taken to equal 1 cGy as a quick, conservative estimate of dose (see following discussion of dosimetric quantities and units.)

Area monitoring measurements are preferably performed free in air, whereas personal dosimeters are worn on the body. Consequently, the response of an area monitor to a radiation field differs from the response of a personal dosimeter in the same field, because the radiation field is strongly influenced by backscatter and absorption of radiation in the body. A different operational quantity is therefore used for individual monitoring, namely the personal dose equivalent, $H_p(d)$. Again, because the radiation of concern is penetrating, the worker's dosimeters were calibrated and read in $H_p(10)$.

The unit of dose is joule per kilogram (J kg^{-1}), and has the special name gray (Gy) when referring to absorbed dose and sievert (Sv) when referring to equivalent or effective dose. Another unit of equivalent dose is the rem, equal to 0.01 Sv [50], which

is still used by many agencies in the United States [51]. Table 2 has a summary of the units associated with radioactivity and radiation dose.

Table 2: Radiation Units

Measure	Unit	Abbreviation	Conversion(s)
Activity (A)	Becquerel	Bq	1 Bq = 1 disintegration per second
			$1\ \text{Bq} = 2.7 \times 10^{-11}$
	Curie	Ci	$1\ \text{Ci} = 3.7 \times 10^{10}$ Bq
Absorbed dose (D)	Gray	Gy	1 Gy = 1 J kg^{-1}
			1 Gy = 100 rad
	Rad	rad	1 rad = 100 erg g^{-1}
			1 rad = 0.01 Gy
Equivalent Dose (H_T) and Effective Dose (E)	Sievert	Sv	1 Sv = 1 J kg^{-1}
			1 Sv = 100 rem
	Rem	rem	1 rem = 0.01 Sv
Exposure (X)	Röntgen	R	$1\ \text{R} = 2.58 \times 10^{-4}$ C kg^{-1} (dry air at STP)
			$1\ \text{R} = 8.76 \times 10^{-3}$ Gy (dry air at STP)
			$1\ \text{R} = 9.5 \times 10^{-3}$ Gy (soft tissue; STP)

Improving Radiation Safety Practices [49]

An additional aim of this study was to provide information to be used in the improvement of VTH radiation safety practices. The basic fundamentals of radiation protection are justification, optimization, and application of dose limits, as defined by the International Commission on Radiological Protection (ICRP) as follows:

> "The Principle of Justification: Any decision that alters the radiation exposure situation should do more good than harm.

> The Principle of Optimisation of Protection: The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.
>
> The Principle of Application of Dose Limits: The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the Commission."

Although this study may support each of the above principles, it ultimately seeks to support the continual process of optimizing radiation protection. The implementation and results of this study aspire to promote radiation safety awareness, ideally improving the radiation safety culture, which is an essential part of a successful radiation safety program [1]. Maintaining an appropriate safety culture, which includes radiation protection, requires commitment from all members of an organization—the veterinarians, technologists, students, etc., all share in the responsibility of promoting and maintaining a safe work environment [1]. The use of real-time dosimetry enables personnel to be aware of their exposures instantaneously; personnel can appropriately adjust their behavior with immediate knowledge of radiation exposure.

MATERIALS

Positron Emission Tomography (PET) [5, 52-53]

A PET scan is a diagnostic nuclear imaging procedure that can help reveal how a patient's tissues and organs are functioning physiologically or metabolically. As such, the applications of PET include disease detection, diagnosis, and staging, surgical and/or radiation treatment planning, and monitoring the effect of treatments such as radiation and chemotherapy (treatment assessment). In human medicine, PET is primarily used for oncologic studies although it can also be used for neurologic and cardiac studies [41].

The PET imaging process involves the detection of radioisotopes that decay by positron emission. Positron decay occurs in isotopes that have a surplus of protons in the nucleus. When these isotopes undergo radioactive decay, a proton is converted to a neutron, positron, and neutrino, and the positron and neutrino are emitted from the nucleus with a certain amount of kinetic energy. The following example is the positron decay of fluorine-18 (F-18) to oxygen-18 (O-18):

$$^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + \beta^{+} + \nu \qquad (1)$$

Neutrinos have no charge and almost no mass. They have extremely low probability of interacting with matter [54], so are considered inconsequential in radiation protection.

The emitted positron will interact with an electron, typically within one to two millimeters of the originating nucleus. In this encounter, the positron and electron annihilate each other. Their masses are converted into energy in the form of two 511 keV photons (gamma rays) that are formed simultaneously and at 180 degrees to each other (Figure 2). It is these coincident photons (not the positrons) that the PET scanner detects.

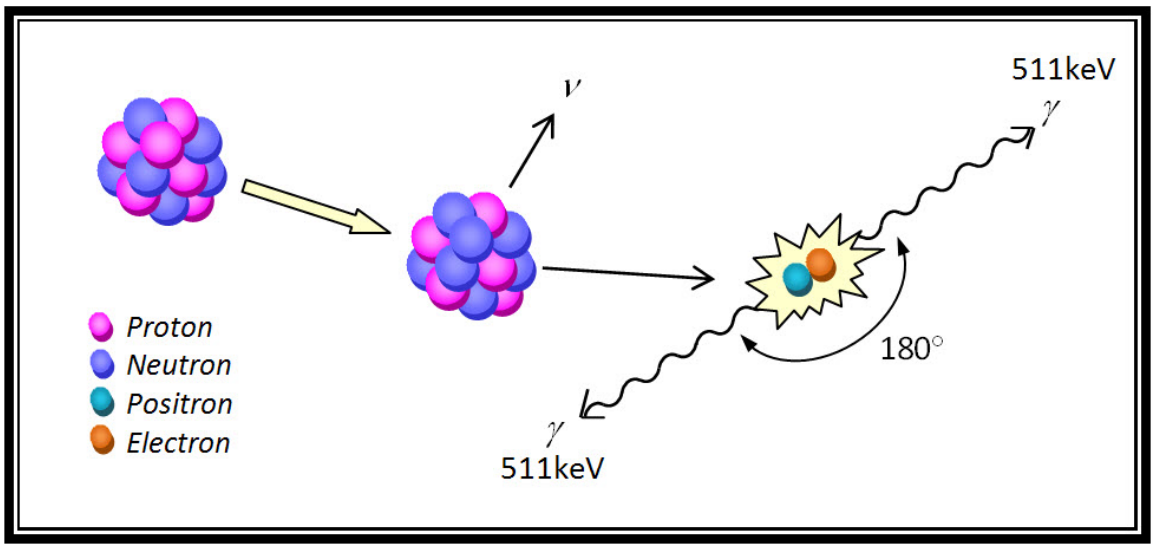


Figure 2: Positron Decay Followed By Electron-Positron Annihilation

To form a radiopharmaceutical, short-lived, positron emitting radionuclides are incorporated into biologically active compounds (known as tracers) like glucose, ammonia, or water. Radionuclides used for PET have a fairly short half life, therefore minimizing dose to the patient. The most common positron emitter used in PET studies is F-18 (half life of 110 minutes). Other radioisotopes used in PET include carbon-11, nitrogen-13, and oxygen-15. The PET radioisotopes involved were in this study were ^{18}F-FDG (2-deoxy-2-[^{18}F]fluoro-D-glucose), and ^{18}F-NaF (F-18 labeled sodium fluoride), both having F-18 as the positron emitter, and are described in the following paragraphs.

Radiopharmaceuticals were supplied by PETNET Solutions, Inc. (a subsidiary of Siemens Medical Solutions USA, Inc.) of Aurora, Colorado.

^{18}F-FDG is the most prevalently used radiopharmaceutical in PET imaging [2]. Twenty-three out of the twenty-five scans conducted in this study utilized ^{18}F-FDG. It is a glucose analog formed by replacing the hydroxide group in position two of the glucose with F-18 [55]. It behaves in the body like another glucose derivative, 2-DG (2-deoxy-D-glucose), which is formed by replacing the aforementioned hydroxide group with hydrogen. Once injected into a patient, ^{18}F-FDG localizes in tissues proportionate to their glycolitic activity. Therefore, ^{18}F-FDG can sensitively detect hypermetabolic tissues including many types of malignant cancer [2], as malignant cancer cells have an increased glucose metabolism (glycolysis) [5]. ^{18}F-FDG enters a cell depending on the glucose concentration difference between the cell and its environment. Once in the cell, ^{18}F-FDG is phosphorylated to FDG-6-phosphate, which is not able to be metabolized further. [53] ^{18}F-FDG is therefore retained in the cell, accumulating in proportion to the amount of glycolysis occurring in the cell, hence providing a record of metabolic activity.[55] Physiologic uptake of ^{18}F-FDG has been characterized in dogs [17, 25] and in cats [19].

Two scans in this study (out of twenty-five) were conducted with ^{18}F-NaF, which is used for bone imaging. Skeletal uptake of ^{18}F-NaF is both rapid and specific. Once injected, it dissociates into sodium and [^{18}F]fluoride ions in the blood [56]. Ion exchange will then occur between the fluoride ion and a hydroxide ion on the bone surface, and the fluoride ion will then be transferred into the bone matrix [57]. ^{18}F-NaF can be used

to image both malignant and benign bone disease because this uptake is proportional to bone blood flow [58]. Although ^{18}F-NaF was approved by the FDA in the 1970s, it has only recently become technologically feasible to use as an imaging agent. Generally, most bone scans are gamma camera imaging or SPECT procedures conducted using radiopharmaceuticals that are labeled with metastable technetium-99 (^{99m}Tc), typically ^{99m}Tc-hydroxymethane diphosphonate (HDP) at the VTH, due to the previous technical and logistical limitations of imaging ^{18}F-NaF [57]. However, ^{18}F-NaF imaging using PET/CT has proven to have higher sensitivity and specificity than traditional bone scans (i.e. higher special resolution and bone to background ratio) [56]. Additionally, because ^{18}F-NaF clears rapidly from the blood image acquisition can be initiated less than an hour after injection of the radiopharmaceutical [57]. Comparatively, ^{99m}Tc-HDP requires two hours for adequate uptake. Animals are sedated, not anesthetized, for gamma camera imaging procedures. Only a two-dimensional image is acquired, and these scans can take up to an hour in a big dog (Great Dane type) to acquire, with personnel holding the sedated dog the entire time. The actual PET acquisition itself is much more rapid, with generally three to five bed positions (depending on the size of the animal) at about five minutes each, and this modality provides highly sensitive three dimensional information. The choice of modality is based on the professional judgment of the clinician, with consideration of cost and availability of the different modalities. However, the intermittent shortage in supply of molybdenum-99, which is used in the production of ^{99m}Tc, may lead to more skeletal studies being conducted using ^{18}F-NaF [59].

In preparation for a PET scan, an appropriate radiopharmaceutical is injected intravenously into a patient and allowed time to distribute throughout the body. The radiopharmaceutical distribution in the body (referred to as uptake) will vary according to the biological properties of the tracer as well as the metabolic activity of the patient. At the VTH, PET scans are always coupled with whole body CT scans; PET/CT provides detailed anatomical information for precise localization of radiopharmaceutical uptake. Additionally, combining CT with PET can be used to estimate (and correct for) attenuation and absorption for processing of PET images.

The scanner at the VTH is a GEMINI TruFlight Big Bore PET/CT from Philips Healthcare [60] (Figure 3), with the PET and CT gantries in separate housings to enable easier patient access.

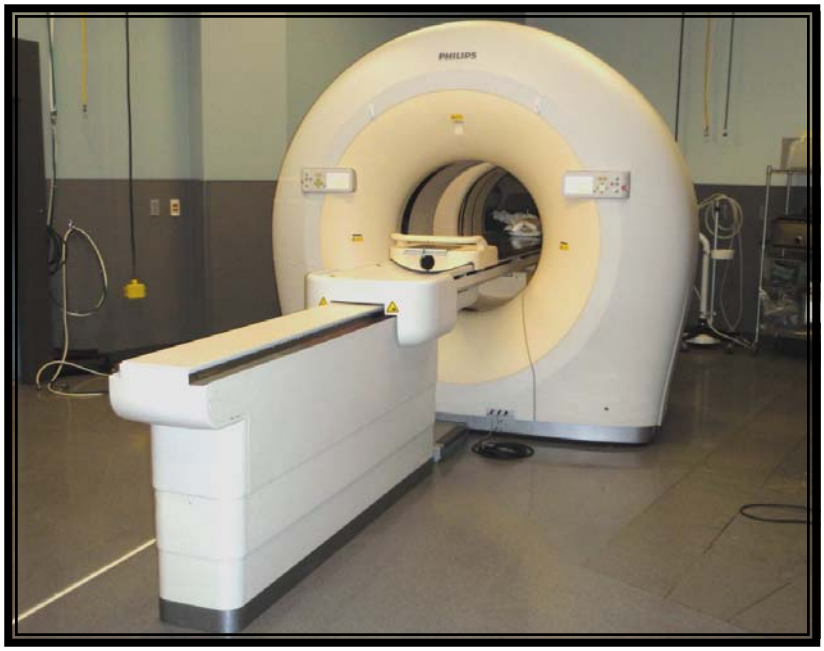


Figure 3: GEMINI TruFlight BigBore PET/CT at CSU VTH

The scanner consists of a ring (made up of 44 individual rings) of scintillation detectors that encircle the patient, covering 18 centimeters of the patient's body at a

time. When one gamma interacts with a detector, there is a certain amount of time (495 ps for the GEMINI TF BigBore [60]) for another gamma to interact in order for the event to be counted. PET is known as a coincidence counting system because it only counts photons that arrive in pairs; non-coincident photons are ignored. In other words, the only photons counted are those photons that result from the annihilation process.

Coincident photons are detected when they interact with the scintillator in the detector. The scintillation material used in the VTH PET/CT is lutetium yttrium oxyorthosilicate (LYSO), and there are 28,336 of these crystals in this particular detector [60]. The photons' energies are absorbed by this scintillator and reemitted as flashes of light. This light is detected by a photomultiplier tube (PMT), which then generates a proportional electrical signal. Figure 4 shows the details of the scintillation process.

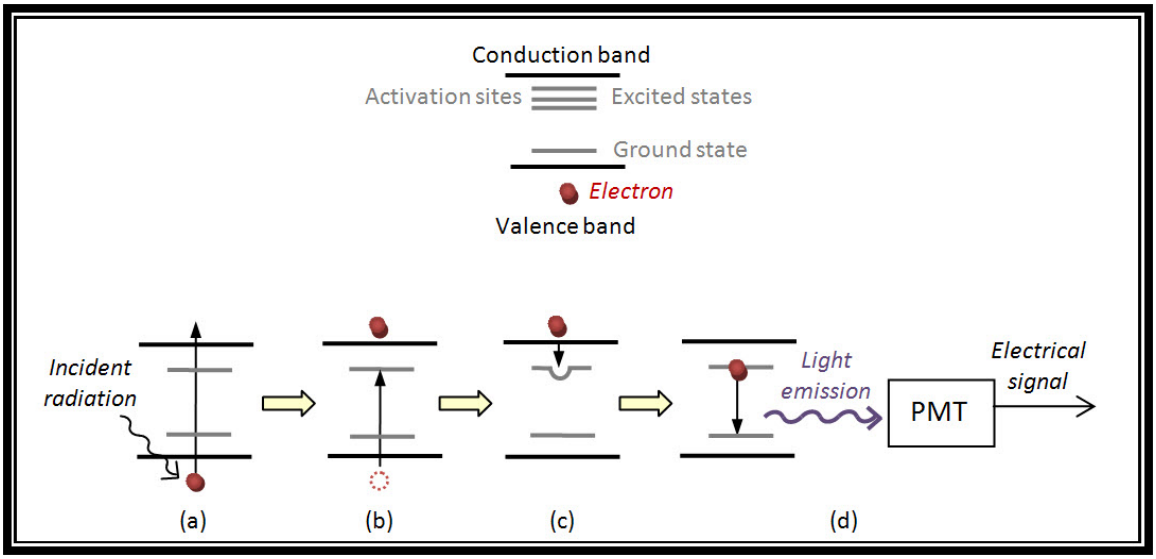


Figure 4: The scintillation process

Incident radiation causes the formation of an electron-hole pair, Figure 4(a). The hole drifts to an activation site and ionizes it, Figure 4(b). The electron "falls into" the ionized activation site, Figure 4(c). The electron relaxes to the activation ground state,

resulting in the emission of visible light, which is converted to an electrical signal by a PMT, Figure 4(d).

This signal is passed through energy level discriminators and on to coincidence circuitry for appropriate processing. The straight line between the two annihilation photons is known as the line of response, and the system utilizes the fact the annihilation event occurred somewhere on that line. Detectors with TruFlight (or time-of-flight) technology, as with the VTH scanner, also measure the time difference between when coincident photons interact with the detector in order to get a more precise determination of where the corresponding annihilation event occurred. There are several methods in constructing an image from the numerous lines of response, but essentially, the statistics collected from all coincidence events can be used to create a three-dimensional map of radioactivity within the body (Figure 5).

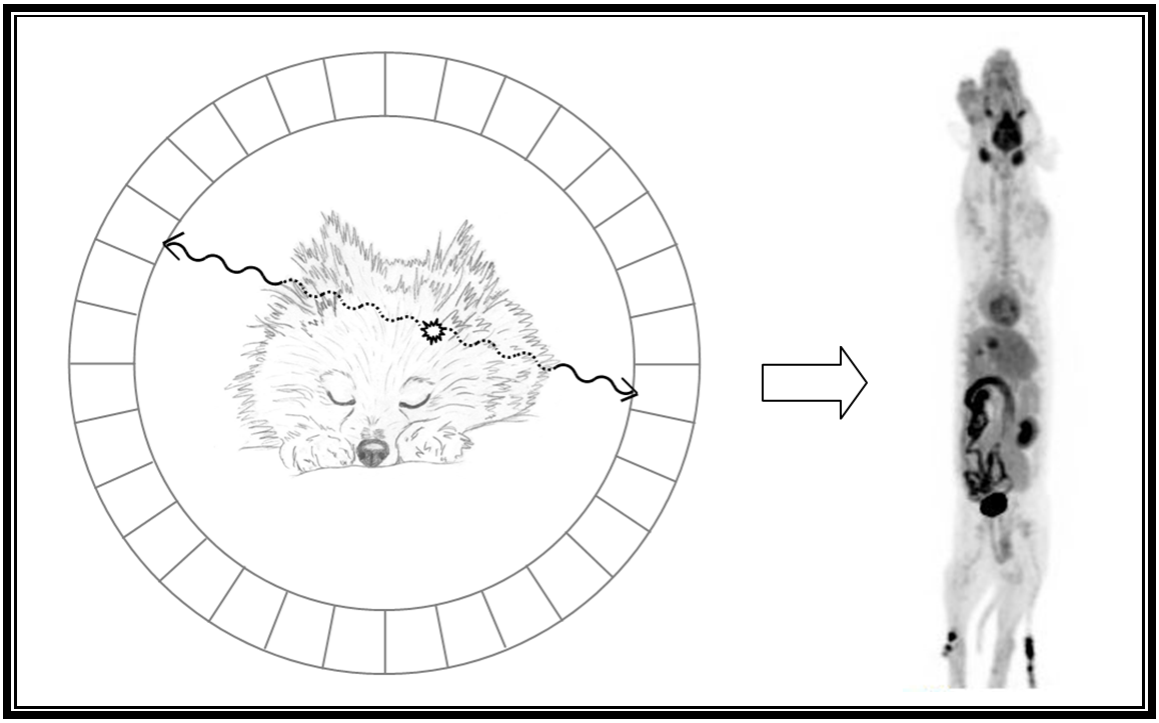


Figure 5: 3D reconstruction of annihilation photon origin

Electronic Pocket Dosimeters (EPD) [48, 61]

The EPDs used in this study utilize a solid state semi-conductor, specifically silicon, detector; electrons in insulators are unable to reach the conduction band at normal temperatures. Silicon is a semi-conductor and has an energy gap of 1.14 eV and, with an appropriate amount of absorbed energy, electrons are able to move to the conduction band at room temperature.

An impurity will often be added to a semi-conductor to increase its conductivity. An impurity with an extra valence electron, referred to as a donor impurity, results in an n-type (negative) semi-conductor. An impurity with one less valence electron, referred to as an acceptor impurity, results in a p-type (positive) semi-conductor. These impurities have energies in the forbidden gap of the intrinsic semi-conductor, just below the conduction band and just above the valence band respectively (Figure 6 [48]).

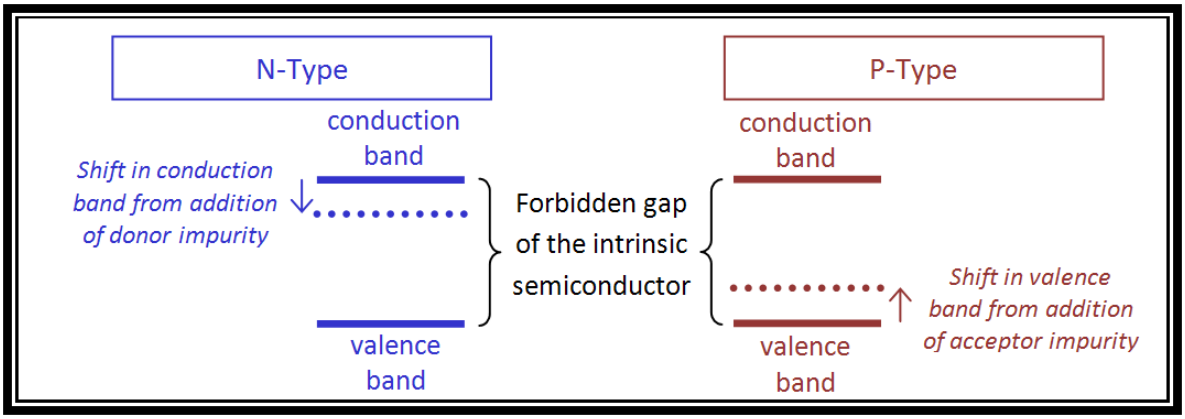


Figure 6: Energy bands of n- and p-type semiconductors

Joining n- and p-type semiconductors results in certain properties that make an effective radiation detector. Due to the nature of the impurities, the conduction and

valence energy bands deform across what is referred to as the junction region (also known as the depletion region or active volume), as represented in Figure 7 [48].

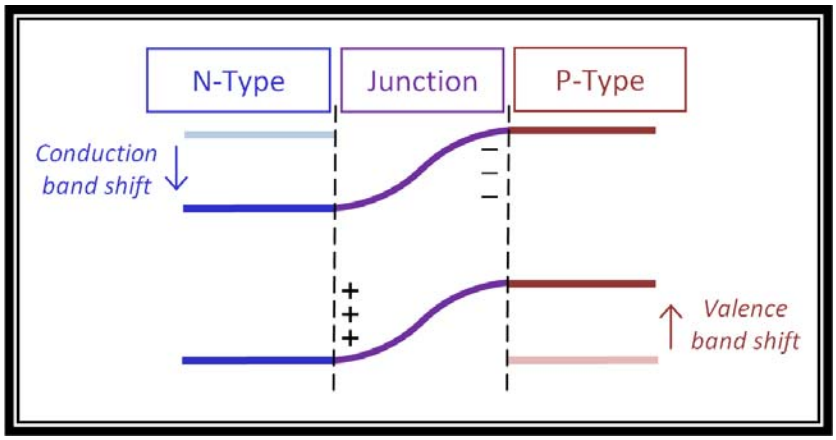


Figure 7: Energy level representation of n- and p-type junction

Incident radiation will interact in this region, forming a proportional amount of electron-hole pairs, which serve the same basic purpose in this type of detector as ion pairs in gas filled detectors. Due to the charge imbalance across the junction region, any electron-hole pairs produced in the region will migrate out, causing a current flow that can be related to absorbed energy. As this current flow is an immediate consequence of the incident radiation, it can provide a real-time indication of radiation dose. A digital display is used by EPDs to indicate dose (Figure 8).

Figure 8: EPD digital display

To further improve performance of these devices, electronic personal dosimeters utilize a reverse bias voltage. Because the resistivity of the junction region is much

larger than either the n- or p- type, applying a reverse bias voltage increases the potential difference across the junction. Consequently, the junction region is extended, meaning that there is more volume for radiation-created electron-hole pairs to be collected.

The electronic personal dosimeters used (Figure 9) were DMC 2000S by MGP Instruments of Mirion Technologies (Smyrna, Georgia) [62].

Figure 9: DMC 2000S EPD by MGP Instruments

They consist of a single silicon diode solid state semi-conductor detector. The DMC 2000S is compliant to IEC 1283 and ANSI 4220A, and measures (and instantaneously displays digitally) radiation dose from 1 µSv to 10 Sv or dose rates from 0.01 mSv/h to 10 Sv/h within the x-ray and gamma energy range of 50 keV to 6 MeV [62]. The accuracy of these EPDs is within ±10%. They were calibrated 01 January 2011 at Palo Verde Power Generating Station (Peoria, Arizona). These EPDs were operated in autonomous mode, with doses being manually read and recorded in units of millirem

(mrem) from the digital display after each PET scan[1]. EPDs (with semiconductor detectors) were selected for this study as the dominant dosimetry for their convenience, sensitivity, and ability to instantaneously display dose information.

Optically Stimulated Luminescence (OSL) Dosimeters [63-64]

The basic operation of TLDs (thermoluminescent dosimeters), which were used in several similar human studies [31, 34-36, 38-39, 41-43], and OSL (optically stimulated luminescent) dosimeters is essentially the same. Exposure of either type of dosimeter to ionizing radiation results in the creation of electron-hole pairs. The electrons can become trapped in the forbidden gap due to the specific arrangement of atoms within the lattice structure of the detector crystal (Figure 10(a) and 10(b)). With external stimulation, the electrons will be freed from the traps and recombine with a hole (called a "luminescence center") in the valence band (Figure 10(c)).

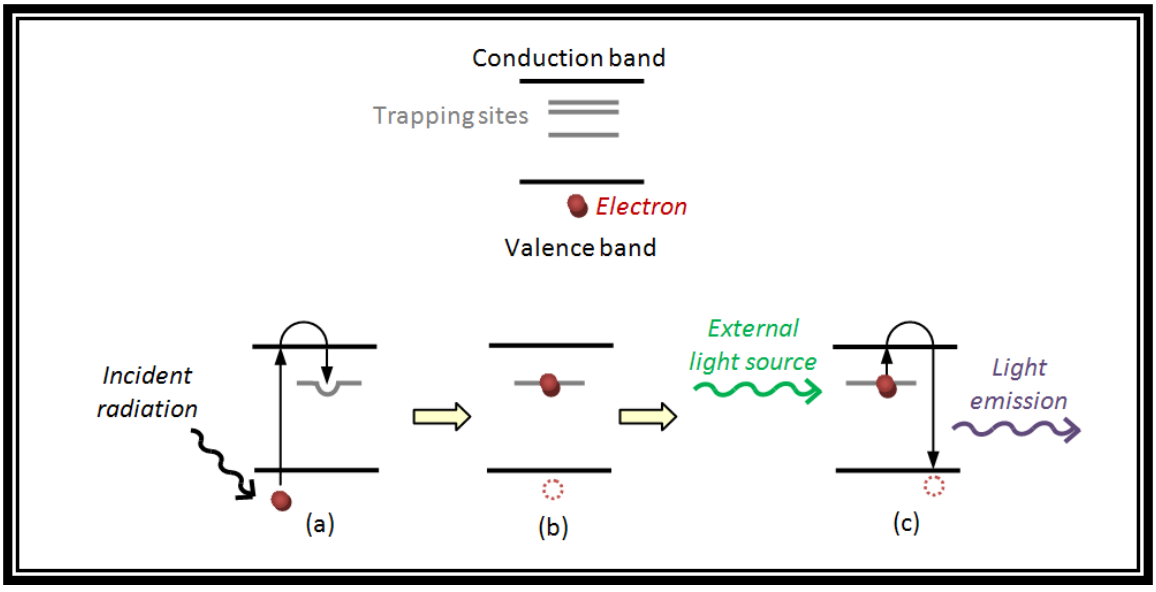


Figure 10: Basic OSL process

[1] With few exceptions, see Results section

The resultant deexcitation photon signal is in the visible range of light, but is a different wavelength from the stimulating light. The signal light is detected and amplified by a photomultiplier tube (PMT); the amount of signal light emitted (luminescence) is proportional to the amount of radiation dose. Whereas a TLD is heated to release the trapped electrons, an OSL dosimeter is exposed to light stimulation of a specific wavelength, typically a laser (Figure 10(c)).

The supplemental optically stimulated luminescence dosimeters used in this study (Figure 11) were the Luxel+ Dosimeter for X, Gamma, Beta, and Neutron Radiation by Landauer (Glenwood, Illinois).

Figure 11: Luxel+ OSL Dosimeter by Landauer

The Luxel+ dosimeter measures radiation dose from 10 μSv to 10 Sv within the x-ray and gamma energy range of 5 keV to in excess of 40 MeV. The accuracy of these dosimeters (for photons >20 keV) is within ±15% for $H_p(10)$ with 95% confidence [65].

Currently, Landauer is the only manufacturer that offers OSL dosimeters for commercial use. The Luxel+ personal dosimeter is a carbon-doped aluminum oxide crystal sandwiched in a three element filter pack which is sealed in a light-tight

wrapping. This assembly is then radiofrequency sealed inside a plastic blister pack which makes the dosimeter unaffected by heat, moisture, and pressure as long as the blister pack is uncompromised [65]. When OSL dosimeters are read, a dose algorithm is employed that utilizes the measured luminescence and corresponding response ratios between the filter positions to distinguish between beta and photon radiation [47].

Continuous wave OSL (CW-OSL) is the traditional technique used to read OSL dosimeters. The crystal is illuminated with a constant intensity source, and filters are used to discriminate between the excitation light and the emission light. Another method for reading OSL is pulsed OSL (POSL) where the stimulation laser is pulsed at a particular frequency. The luminescence is only measured between pulses to discriminate between the excitation light and the emission signal light, which means that less optical filtration is necessary with POSL than with CW-OSL. Landauer employs POSL in reading their personal dosimeters [63].

Originally used for archeological dating in the 1980s [61], OSL has since found application in three areas of radiation dosimetry: retrospective dosimetry, personal dosimetry, and environmental dosimetry. Advantages of OSL dosimeters include high sensitivity, ability to be re-read, and that sample temperature is not elevated significantly, so heat-tolerant materials are not needed for OSL which are required for standard TLDs [61]. The disadvantage of OSL for this study is that OSL dosimeters are difficult to read; POSL requires precise timing [66]. Due to the difficult nature of reading OSL badges, they have to be sent back to the manufacturer to be read. As such,

Landauer calibrated and processed these dosimeters. Consequently, a per patient dose reading is not physically or financially feasible, and an immediate reading is not possible.

METHODS

This study was approved as a minimal risk study by the CSU Institutional Review Board for the protection of human subjects in research on 28 October 2010, protocol number 10-2188H; Appendix G contains sample consent and participant information forms. Starting 20 January 2011, veterinary staff members were monitored with EPDs (through 09 June 2011) and OSL dosimeters (through 01 June 2011 to allow for processing) at the VTH. Nuclear medicine technologists were given his/her own dosimeters specifically for this study. Anesthesia personnel rotate for PET procedures, so a single EPD was designated as the anesthesiology dosimeter, although the actual person in that position changed. Therefore, the anesthesia EPD was task versus person specific, where as all others were assigned to specific persons. A control EPD was kept in a storage location (ACC 148) to monitor background.

Dosimeters

Both EPD and OSL dosimeters (referred to as "badges") were labeled as NUCMED 1, NUCMED 2, NUCMED 3, VET 1, and OBSERVER 1. Persons routinely involved with PET received corresponding OSL and EPD badges. Participants were instructed to wear their study badges where they wear their regular dosimetry for minimal intrusion into their normal operating conditions. For NUCMED 3, this was on her lanyard, which put her badges in the middle of her chest (Figure 12).

Figure 12: Dosimeter worn at chest

NUCMED 2 and VET 1 both wore theirs on their belts like a pager (Figure 13).

Figure 13: Dosimeter worn at waist

The majority of the anesthesia staff wore their badge in their left front shirt pocket, but occasionally the EPD was placed in the pants pocket. This is an inconsistency, but in the interest of not interfering with typical work habits, considered acceptable.

Table 3: Job positions corresponding to dosimeter labels

Badge label	Job Title	Duties	Years Experience	Badge location
NUCMED 1	Research Associate in computed tomography (CT) and magnetic resonance (MR) imaging (Tech 1)	Primary PET/CT technologist. Performs, supervises, oversees safety, and provides clinical instruction in CT, PET/CT, and MRI studies	22 years	Chest
NUCMED 2	Research Associate in computed tomography (CT) and magnetic resonance (MR) imaging (Tech 2)	Primarily the MRI Technologist. Assist and cover for CT, conduct and assist with all aspects of PET/CT studies	15 years in the field, with 2.5 in current position	Waist
NUCMED 3	This replacement badge was worn by NUCMED 1 after the original badges were accidentally pulled off by a patient and run through the CT (Tech 1)			
VET 1	Nuclear medicine/radiology technologist (Tech 3)	Primarily the nuclear medicine technologist and an x-ray technologist. When needed, assists in PET/CT studies	1.5 years	Waist
ANESTHESIA	Anesthetist	Anesthetize patients, to include catheterization, intubation/extubation, general monitoring, and recovering of animals. Section staff rotate for PET/CT procedures.	Varies	Chest, on average
OBSERVER 1	Student	Observation	2 years	Waist

Procedure Summary

The radiopharmaceutical dose is received the morning of the corresponding PET scan. It is provided in a unit-dose syringe, housed in a lead container (called a “pig”) within an appropriate transportation package (Figures 14 - 16 below).

Figure 14: Dose transportation package

Figure 15: Lead "pig" containing dose

Figure 16: Unit dose syringe

Once the animal arrives at the clinic, it is anesthetized in the anesthesia suite. Urinary and intravenous (IV) catheters are placed at this time. The animal is then taken to the PET/CT suite, where it positioned on the table for the scan (Figures 17 and 18).

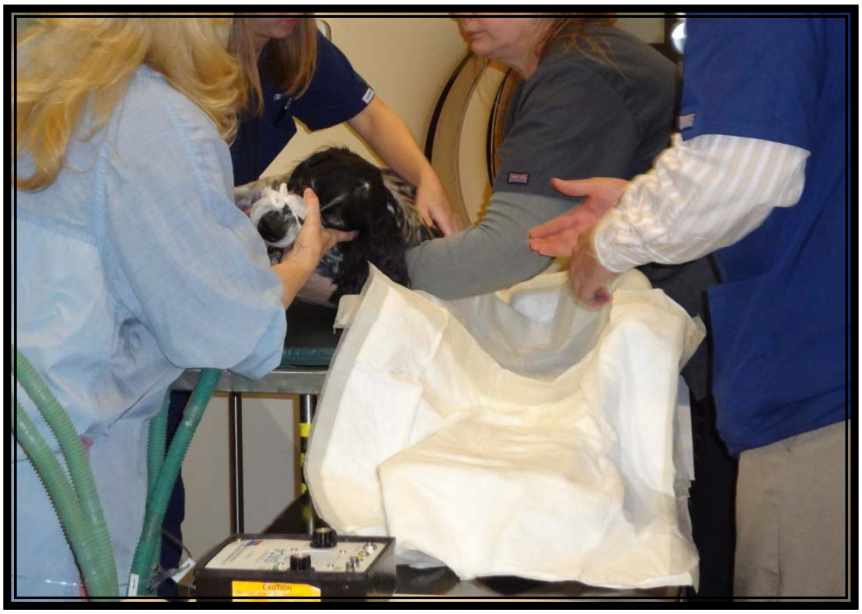


Figure 17: Moving patient from transport cart to scanner bed

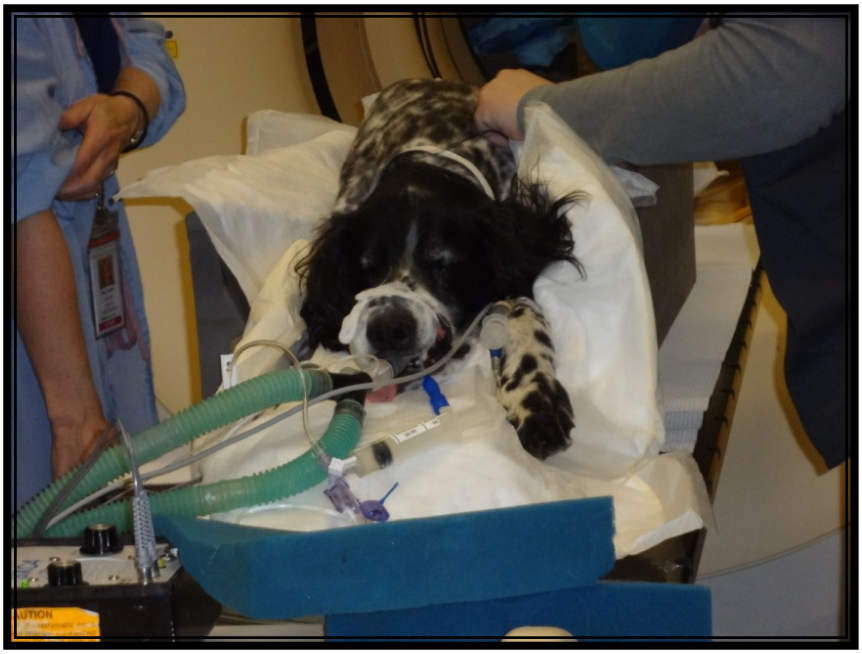


Figure 18: Positioning patient on scanner bed

This typically includes adjusting leads and possibly covering the animal to keep it warm (Figure 19).

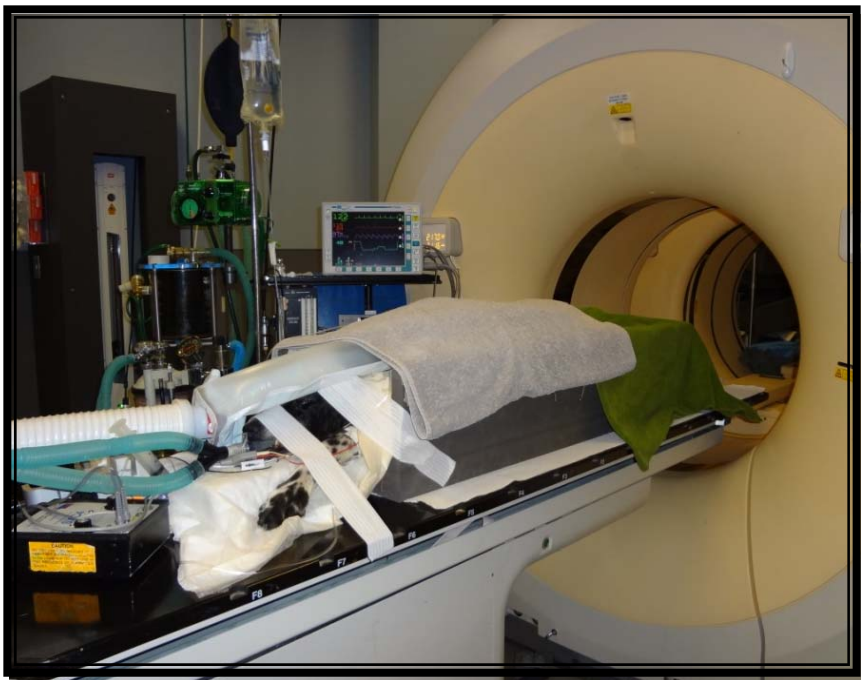


Figure 19: Final patient preparation for PET/CT scan

The animal's urinary catheter bag is placed in a lead pig at the rear of the scanner (Figure 20).

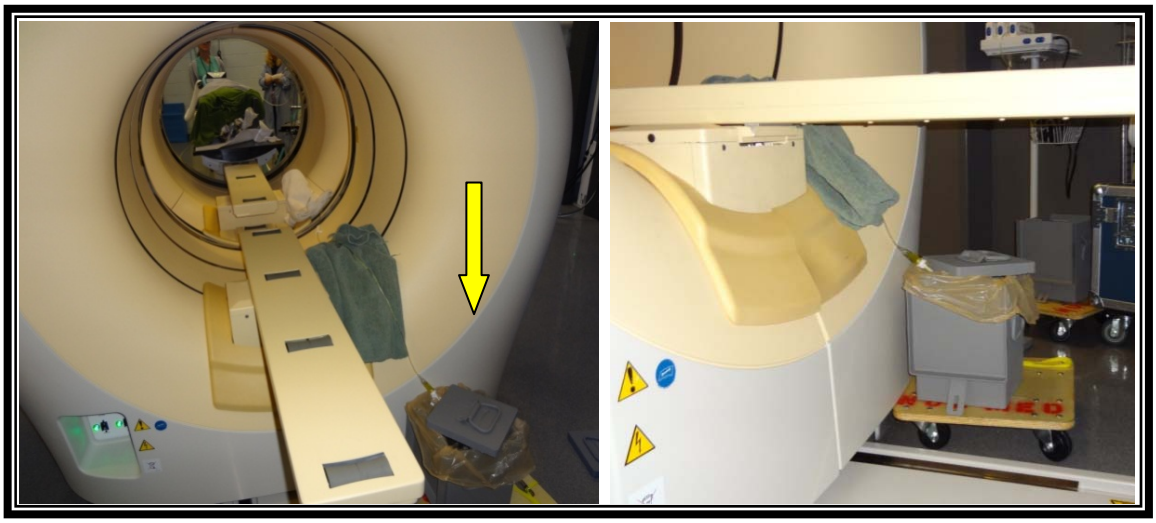


Figure 20: Lead pig with patient catheter bag

Once the patient is ready for the scan, the dose is assayed (using the AtomLab 500 Dose Calibrator, Biodex, Shirley, New York) (Figure 21), placed in a lead carrier (Figure 22), and then wheeled on a transport cart to the PET/CT suite (Figure 23) where it is injected into the patient via an indwelling venous catheter (Figure 24).

Figure 21: Dose calibration

Figure 22: Lead-lined carrier

Figure 23: Dose transport

Figure 24: Injection of radiopharmaceutical

The residual dose is transported back to the dose locker and assayed to determine the net injected dose. About an hour is allotted for uptake of the radiopharmaceutical, and in that time, pre- and post-contrast CTs are performed. The length of the PET scan is dependent on the number of bed positions; each bed position covers 18 cm of the patient's body.

Once the PET scan is completed, the patient's catheters are removed (Figure 25) and placed in decay-in-storage in the PET/CT suite, along with the catheter bag.

Figure 25: Catheter removal

The patient is then prepared for transport, including being moved from the table to a cart (Figure 26). The patient is then relocated (Figure 27) to the designated recovery area, ACC 162 (Figure 28).

Figure 26: Moving patient from scanner bed to transport cart

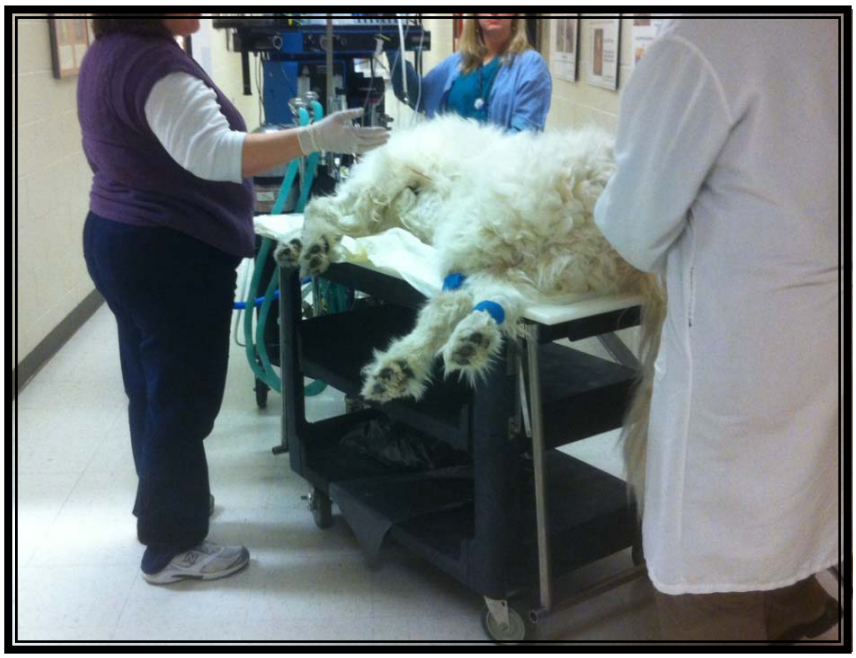


Figure 27: Patient transport

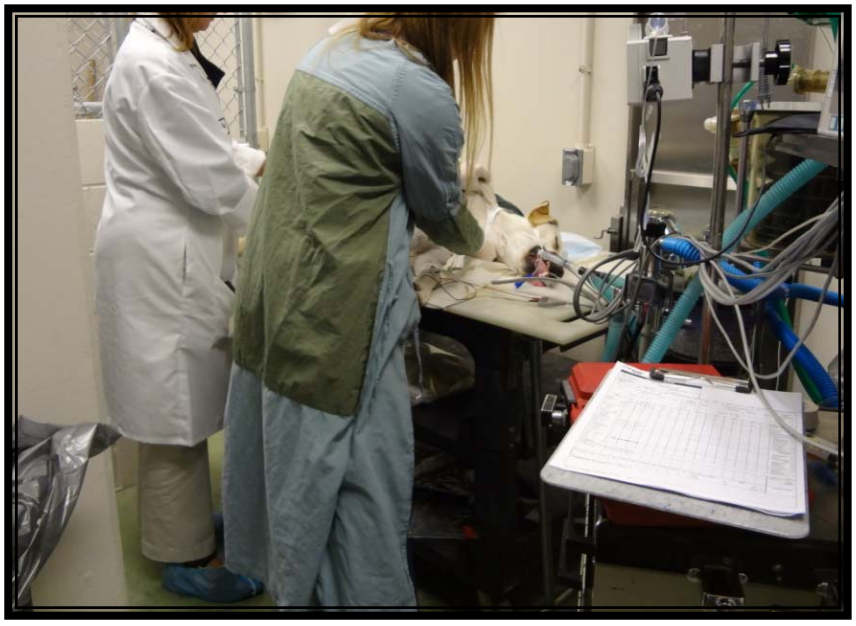


Figure 28: PET Recovery

The transport path along with areas of the VTH involved in the process discussed above is shown in Appendix B. The patient is recovered in the CT suite or ACC 162 at the discretion of the anesthesia technologist. The patient may be released once exposure

readings at the skin are less than 2 mR/h. Until then, the patient will remain in ACC 162. The patient will be monitored and walked for bathroom breaks in a designated area if necessary. Details of the scan were recorded on an activity record sheet. Appendix A provides a comprehensive protocol for PET/CT procedures, Appendix E provides details of each scan in this study, and Appendix H provides sample log sheets used in this study. From the above, potential for radiation exposure exists in the following:

- dose check in,
- dose assay/transport/residual assay,
- injection,
- room entry (vitals, leads, etc) to check on patient,
- moving patient from the gantry to the transport cart,
- transport to recovery,
- recovering the patient, moving patient from cart to kennel
- removing IVs etc, ,
- walking patient,
- caring for patient post-recovery and pre-release.

RESULTS

Patient information summary

From 20 January 2011 to 06 June 2011, twenty-five PET/CT scans were conducted at the VTH, including six different cats, thirteen different dogs, and a sheep (with two cats and three dogs receiving repeat scans). Twenty-three of the scans were conducted with ^{18}F-FDG and the remaining two with ^{18}F-NaF. Patient information is listed in Table 4 and summarized in Table 5, color coded for species and the particular isotope injected. The color code is maintained in subsequent tables.

Table 4: Patient List

All | Cats | All Dogs | FDG Dogs | NaF Dogs | Sheep

Scan #	Date	Patient	Species	Breed	Mass (kg)	Inj activity (MBq)	Isotope
1	1/20/2011	C1	Feline	Domestic Shorthair	4.2	25.2	^{18}F-FDG
2	1/21/2011	D1	Canine	Bernese Mountain Dog	47	41.8	^{18}F-NaF
3	2/8/2011	C2	Feline	Domestic Shorthair	4.8	30.1	^{18}F-FDG
4	2/9/2011	C3	Feline	Domestic Shorthair	3.5	20.2	^{18}F-FDG
5	2/10/2011	D2	Canine	Great Pyrenees	58	384.4	^{18}F-FDG
6	2/23/2011	C4	Feline	Domestic Shorthair	5.05	27.5	^{18}F-FDG
7	2/24/2011	D2	Canine	Great Pyrenees	55	367.0	^{18}F-FDG
8	2/25/2011	D3	Canine	Rottweiler	62	399.6	^{18}F-FDG
9	3/8/2011	C5	Feline	Domestic Shorthair	2.77	24.8	^{18}F-FDG
10	3/10/2011	D3	Canine	Rottweiler	61	378.8	^{18}F-FDG
11	3/25/2011	D4	Canine	Greyhound	25.5	154.8	^{18}F-FDG
12	3/29/2011	D5	Canine	Great Pyrenees	55	142.8	^{18}F-NaF
13	3/30/2011	C4	Feline	Domestic Shorthair	4.7	35.3	^{18}F-FDG
14	4/5/2011	C6	Feline	Domestic Shorthair	4.26	34.2	^{18}F-FDG
15	4/7/2011	D4	Canine	Greyhound	25.5	153.7	^{18}F-FDG
16	4/14/2011	D6	Canine	Walker Hound	26.5	139.5	^{18}F-FDG
17	4/15/2011	D7	Canine	Walker Hound	25	133.6	^{18}F-FDG
18	4/26/2011	D8	Canine	Walker Hound	28.5	147.3	^{18}F-FDG

19	4/27/2011	D9	Canine	Shih-Tzu	4	24.1	^{18}F-FDG
20	5/4/2011	D10	Canine	Mixed Breed	53.3	246.1	^{18}F-FDG
21	5/5/2011	C6	Feline	Domestic Shorthair	4.08	27.3	^{18}F-FDG
22	5/5/2011	S1	Ovine	N/A	76.4	416.6	^{18}F-FDG
23	5/31/2011	D11	Canine	English Setter	25	196.1	^{18}F-FDG
24	6/8/2011	D12	Canine	Yellow Lab	26.4	119.9	^{18}F-FDG
25	6/9/2011	D13	Canine	Rottweiler	35.9	225.7	^{18}F-FDG

Table 5: Patient Summary

Animal (#)		Mass (kg)	Inj Act (MBq)
All (25)	Mean ± SD	28.9 ± 23.4	155.8 ± 137.2
	Range	2.8 to 76.4	20.2 to 416.6
Cat (8)	Mean ± SD	4.2 ± 0.7	28.1 ± 5.0
	Range	2.8 to 5.1	20.2 to 35.3
Dog (16)	Mean ± SD	38.4 ± 17.4	203.4 ± 120.3
	Range	4.0 to 62.0	24.1 to 399.6
FDG Dog (14)	Mean ± SD	36.5 ± 17.9	219.3 ± 118.9
	Range	4.0 to 62.0	24.1 to 399.6
NaF Dog (2)	Mean ± SD	51.0 ± 5.7	92.3 ± 71.4
	Range	47.0 to 55.0	41.8 to 142.8
Sheep (1)		76.4	416.6

Detailed patient data can be found in the Appendix E. Figures 29 - 32 show examples of the wide variety of PET/CT recipients.

Figure 29: 4 kg Shih-Tzu; smallest PET/CT dog in the study

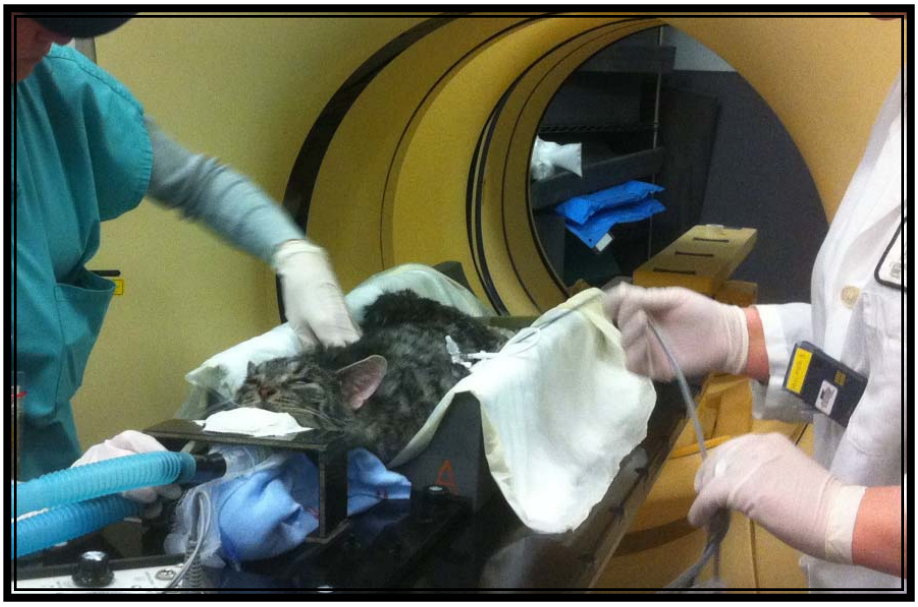


Figure 30: 4.8 kg Domestic Shorthair

Figure 31: 36 kg Rottweiler

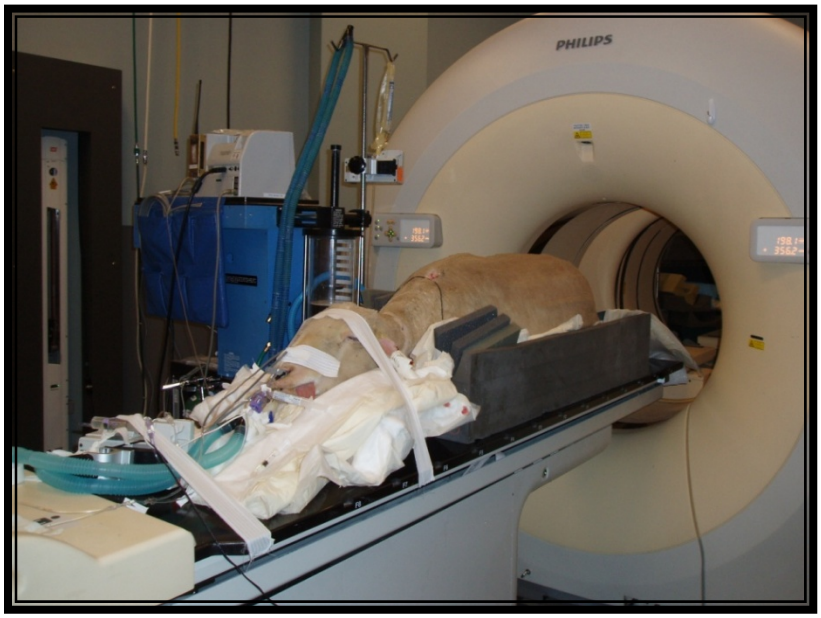


Figure 32: 72 kg sheep; largest PET/CT recipient in the study

The amount of administered (injected) activity for ^{18}F-FDG patients is consistent on a per mass basis at about 6 MBq/kg (Figure 33).

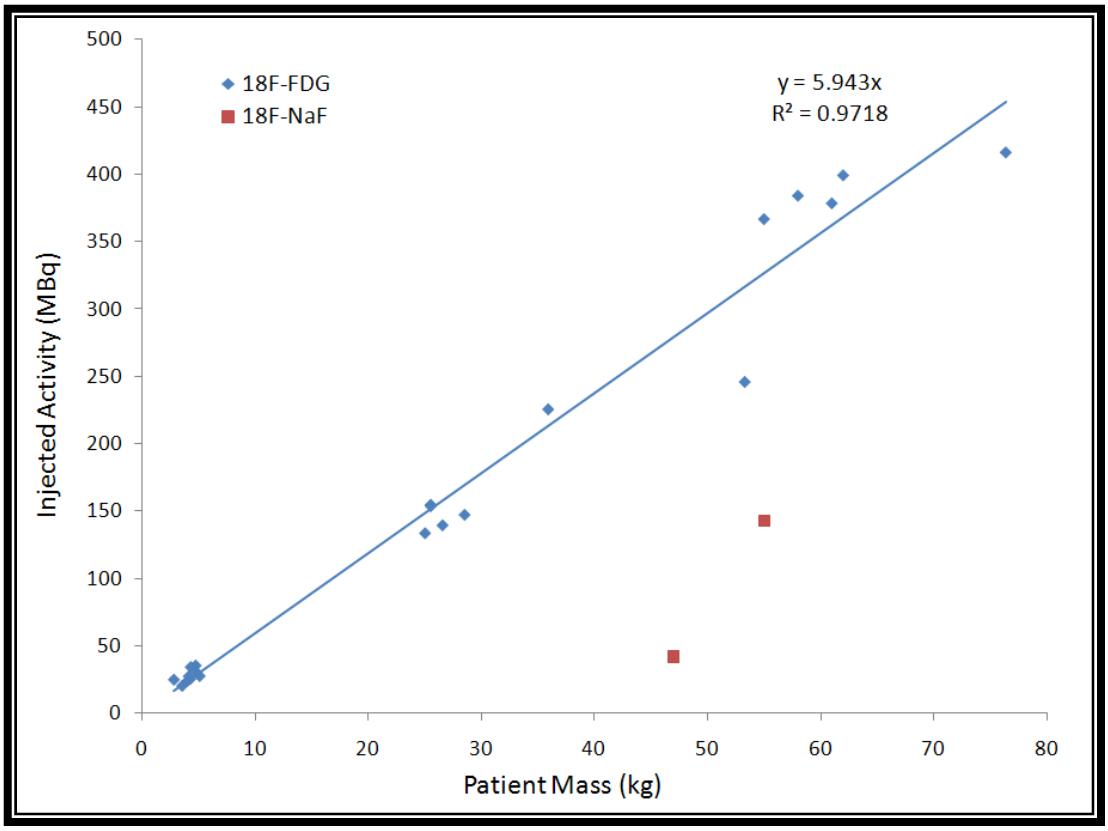


Figure 33: Patient Mass vs Injected Activity

Therefore, the injected activity is considered as a variable in analyzing radiation dose variability, but not mass. The administered dose of ^{18}F-NaF, however, is not consistent with ^{18}F-FDG doses or even between the two patients. Less activity of ^{18}F-NaF than ^{18}F-FDG is needed to obtain the same quality of image. Also, the injected activity per kilogram of ^{18}F-NaF is inconsistent between patients because the dose received for one of the patients was much less than the amount ordered (see Discussion section). Consequently ^{18}F-NaF patients are not included in the analyzed data set.

EPD and OSL comparison

The cumulative EPD and OSL (deep dose) dose comparison data is summarized in Table 6.

Table 6: OSL and EPD comparison

Dosimeter	Dose read (μSv)				
	NUCMED 1	NUCMED 2	NUCMED 3	VET 1	OBSERVER 1
EPD	Not recorded	127	219	39	1
OSL	*M*	100	190	100	20
M: minimum reporting					

Before being issued, EPDs and OSL dosimeters were kept with the control dosimeters in ACC 148. The only scans included in Table 6 are those where both the EPD and OSL dosimeter were worn (for NUCMED 1, only 20 January 2011; for NUCMED 3, 21 January 2011 through 31 May 2011; for NUCMED 2 and OBSERVER 1 20 January 2011 through 31 May 2011; and for VET 1, 28 February 2011 through 31 May 2011).

There were four OSL dosimeters that ended up not being used in this study, and consequently do not have a corresponding EPD. They were kept in ACC 148, and the readings for these spare dosimeters are provided in Table 7.

Table 7: OSL readings for badges not used

Dosimeter	Dose read (μSv)			
	CONTROL	ANESTHESIA	VET 2	OBSERVER 2
OSL	*M*[2]	*M*	*M*	*M*
M: minimum reporting				

Doses were read in mrem for both OSL and EPD, but are converted to μSv for presentation. The minimum reporting service for the OSL dosimeters was 1 mrem (10 μSv). There is a certain level of unexpected variation between the OSL and EPD readings. The OSL readings are suspect; the NUCMED 1 OSL dosimeter was "lost" in the PET/CT suite for about 24 hours, so it is highly unlikely that this reading would be below background. This badge was pulled off the technologist while moving a large patient, along with the EPD. The EPD was found quickly because it began alarming, another indicator that the OSL reading should be above background. The NUCMED 2 OSL readings would be expected to be higher than the EPD cumulative reading, because three scans (scans 6, 7, and 8) were omitted for the EPD reading presented, due to the amount of uncertainty for those particular scans (see the following section). The VET 1 and OBSERVER 1 OSL dosimeters are significantly different as well, although in the opposite direction; i.e. the OSL readings are higher than the EPD readings. The suspect

[2] Control OSL actually read 630 μSv; see following discussion

OSL readings prompted contacting Landauer technical customer service. Through this personal communication, it was discovered that this batch of OSL dosimeters was exposed to measurable radiation independent of this study, as the actual readings varied between 630 and 890 μSv (see Appendix D). These badges had an issue period of 157 days; at 3 μSv per day expected background (see Appendix C), the control should have been 471 μSv, approximately 160 μSv less than the actual control reading. As such, the readings, although technically above background for the batch of dosimeters, were deemed unreliable because the nature of the additional radiation exposure is unknown.

Radiation dose summary - EPDs

For the purpose of data analysis, badge labels are equated with more convenient job position descriptions: NUCMED 1 and NUCMED 3 correspond to Tech 1, NUCMED 2 corresponds to Tech 2, and VET 1 corresponds to Tech 3. Three scans were conducted the week of 21 February 2011 (scans 6, 7, and 8; see Table 4). The total radiation dose received by Tech 2 for the three scans combined is known (25 μSv for the week if background radiation is estimated at 3 μSv per day; see Appendix C for VTH background information), but the distribution between the scans, i.e. scan per procedure, is not known with certainty. Therefore, these scans are used in the consideration of patient data, but are omitted from the dose summary in Table 8 (where dose is in μSv and dose per injected activity is in nSv mBq^{-1}.)

Table 8: VTH Personnel Per Patient Radiation Dose Summary

			Tech 1	Tech 2	Tech 3	Anesthesia	Observer
All (*22*)	Dose	Mean ± SD	11.5 ± 8.0	7.6 ± 6.0	4.4 ± 3.1	8.3 ± 6.4	0.4 ± 0.7
		Range	2 to 30	1 to 22	0 to 10	1 to 22	0 to 2
	Dose per injected activity	Mean ± SD	117.0 ± 76.9	72.2 ± 46.5	32.0 ± 23.1	101.1 ± 117.2	2.0 ± 3.6
		Range	35.0 to 357.2	14.0 to 198.1	0.0 to 71.7	25.0 to 404.0	0.0 to 8.9
	Number scans		*22*	*19*	*9*	*19*	*11*
Cat (*7*)	Dose	Mean ± SD	5.3 ± 2.6	3.0 ± 2.2	2.0	5.8 ± 4.4	0.0
		Range	2 to 9	1 to 7	2.0	1 to 11	0.0
	Dose per injected activity	Mean ± SD	188.5 ± 96.6	103.8 ± 59.1	58.6	211.3 ± 179.5	0.0 ± 0.0
		Range	87.8 to 357.2	39.7 to 198.1	58.6	28.3 to 404.0	0.0
	Number scans		*7*	*6*	*1*	*5*	*2*
Dog (*14*)	Dose	Mean ± SD	14.1 ± 8.1	10 ± 6.2	4.8 ± 3.2	8.3 ± 6.3	0.5 ± 0.8
		Range	3 to 30	1 to 22	0 to 10	2 to 22	0 to 2
	Dose per injected activity	Mean ± SD	86.2 ± 33.5	61.1 ± 31.5	28.7 ± 22.2	62.6 ± 54.4	2.8 ± 4.0
		Range	35.0 to 153.0	14.0 to 107.5	0.0 to 71.7	25.0 to 207.9	0.0 to 8.9
	Number scans		*14*	*12*	*8*	*13*	*8*
FDG Dog (*12*)	Dose	Mean ± SD	15.6 ± 7.7	11.6 ± 5.5	4.6 ± 3.4	9.3 ± 6.3	0.7 ± 0.8
		Range	3 to 30	1 to 22	0 to 10	3 to 22	0 to 2
	Dose per injected activity	Mean ± SD	87.7 ± 31.4	67.1 ± 30.2	26.8 ± 23.3	67.0 ± 58.2	3.7 ± 4.3
		Range	50.1 to 153.0	26.0 to 107.5	0.0 to 71.7	25.0 to 207.9	0.0 to 8.9
	Number scans		*12*	*10*	*7*	*11*	*6*
NaF Dog (*2*)	Dose	Mean ± SD	5.0 ± 0.0	2.0 ± 0.0	6.0	3.0 ± 1.4	0.0 ± 0.0
		Range	5.0	2.0	6.0	2 to 4	0.0
	Dose per injected activity	Mean ± SD	77.2 ± 59.7	30.9 ± 23.9	42.0	37.9 ± 14.0	0.0 ± 0.0
		Range	35.0 to 119.5	14.0 to 47.8	42.0	28.0 to 47.8	0.0
	Number scans		*2*	*2*	*1*	*2*	*2*
Sheep (*1*)	Dose		20.0	7.0	----	21.0	0.0
	Dose per injected activity		48.0	16.8	----	50.4	0.0
	Number scans		*1*	*1*	*0*	*1*	*1*
Cumulative Dose (µSv)			254	157	40	158	4

Data analysis - EPDs

Data analyss was conducted to provide indication of what factors most contribute to radiation dose, and consequently determine how well dose can be predicted given those factors. The statistical software Minitab was used (release 14, Minitab, Inc., State College, Pennsylvania). At the beginning of a PET scan, the only known information is mass of the patient, species of the patient, amount of injected activity, who performed the injection, where dosimeters are worn, and personnel job positions. The specifics of behavior that follow are highly variable. Consequently, the above listed variables (except mass, as discussed above) are the only ones considered in the data analysis, where mass of the patient is in kilograms, species is given by 0 (cat) or 1 (dog), the amount of injected activity is in megabecquerels, who injected the patient is indicated by 0 (yes) or 1 (no), dosimeter position is given by 0 (waist) or 1 (chest), and job position is given by 1 (Tech 1), 2 (Tech 2), 3 (Tech 3), 4 (Anesthesia), and 5 (Observer). The resulting prediction of radiation dose covers a wide range of behaviors, although behaviors not observed may not be accounted for.

Data analysis – Omitted data points

The data was split into two sets for analysis – dogs and cats. As there was only one sheep, that data point was omitted. As discussed above, ^{18}F-NaF studies (scans 2 and 12) along with scans 6, 7, and 8 were also omitted. Two patients (C6 and D4) in the remaining data set had repeat scans (scan numbers 21 and 15 respectively), which were the final scans to be omitted from analysis.

Data analysis – Cats

Linear regression was conducted for the cat data $(6\text{ cats}, n=18)$, with dosimeter (badge) location being the only significant indicator of radiation dose (in μSv), with the following relationship ($p=0.013$):

$$\text{radiation dose} = 1.89 + 3.33(\text{badge loc}) \quad (2)$$

Which means that for cats, wearing the dosimeter at the chest will result in a higher radiation dose than wearing it at the waist. It should be noted that where the dosimeter is worn does not affect the actual amount of radiation dose a person receives; it only will change the accuracy of dose measurement. Also, it is likely that injected activity is not significant in this model because most of the patients are very similar in size, and thus received similar radiopharmaceutical doses. With small variation in injected activity between patients, it follows that it would not significantly contribute to predicting the varied radiation doses. This data set is fairly small as well, with only 6 cats and 18 data points to consider.

Data analysis – Dogs

Linear regression was conducted for the dog data $(11\text{ dogs}, n=41)$, with job position $(p=0.000)$, injected activity $(p=0.000)$, and badge location $(p=0.039)$ as significant indicators of radiation dose (in μSv), with the following relationship:

$$\text{radiation dose} = 8.62 - 2.64(\text{job position}) + 0.0337(\text{inj activity}) + 3.59(\text{badge loc}) \quad (3)$$

All things held the same, radiation dose is expected to be higher for dosimeters worn on the chest versus waist, as it was for cats above. Radiation dose is also expected to

increase with increasing amount of injected activity. Finally, radiation dose is expected to be lower for the "increasing" job positions. This is also logical as indentifiers were assigned based on a general expectation of how long the job position would be in contact with the patient and/or radiopharmaceutical dose.

Although there is not enough data in this study to confirm statistically, it appears that there is in general a larger proportionate radiation dose received at smaller amounts of injected activity, possibly due to less self-attenuation by smaller patient bodies. Ultimately, a longer study should be done for improved statistics and a more thorough picture of the what factors most influence radiation doses received from the PET imaging process.

Dose analysis – comparison to human studies

Table 9 below provides a concise summary of various studies from the human literature that are similar to this study.

Table 9: Radiation dose from ^{18}F-FDG PET in the human literature[3]

Lead Author	Dose per scan (μSv)	Dose per MBq injected (nSv MBq^{-1})	Dosimeter(s) used
Benatar[30]	---	18	EPD
Biran [31]	7.2	19.5	TLD and EPD
Carson [32]	5.1	13.6	EPD
Chiesa [33]	5.9	11.8	Geiger Muller PD
Dalianis [34]	3.3	8.6	TLD and EPD
Demir [35]	6.3	12.2	TLD (some EPD)
Guillet [36]	3.2	9.4	TLD and EPD
Leide-Svegborn [38]	4.5	15	TLD

[3] Values are selected study averages

McCormick [39]	14.0	---	TLD
McElroy [40]	10.0	18.6	EPD
Roberts [41]	4.5	15	TLD
Robinson[42]	4.1	11.0	TLD
Seierstad [43]	8.8	25.0	EPD and TLD

The average of the above doses per scan from the human literature is 6.4 μSv. The 95% confidence interval for this mean is (4.4 μSv, 8.4 μSv).

If we consider our dog model (equation (2) above), using the typical activity administered to a human patient (370 MBq), the expected per patient doses to veterinary personnel are as follows in Table 10:

Table 10: Predicted doses (μSv) from human patients using the dog model

Job	Badge Location	
	Chest	Waist
1	22.1	18.5
2	19.4	15.8
3	16.8	13.2
4	14.1	10.5
5	11.5	7.9

Only one out of ten of the doses is within the 95% confidence interval for the mean dose per scan from the human literature. All the other doses are outside the confidence interval on the high side. This would imply that the occupational radiation doses (per

patient) to veterinary personnel are in general higher than the doses to personnel working in a human hospital, for the same amount of injected activity.

Additionally, we consider the expected doses to veterinary personnel using the average injected activity for the patients in this study (155.8 MBq), shown in Table 11.

Table 11: Average expected per patient veterinary doses (μSv) from canine patients

Job	Badge Location	
	Chest	Waist
1	14.8	11.2
2	12.2	8.6
3	9.5	6.0
4	6.9	3.3
5	4.3	0.7

Although the doses are lower than those presented in Table 10, half of these doses are still outside the 95% confidence interval for human patient doses. This would imply that on average, veterinary personnel doses per canine PET scan are slightly higher than the average doses to personnel working with human patients.

If we consider the cat model, expected doses (per patient) to veterinary personnel are 1.89 μSv (if the dosimeter is worn on the waist) or 5.22 μSv (if the dosimeter is worn on the chest). The former is below the 95% confidence interval for conventional doses, and the latter within the confidence interval. Therefore, for veterinary personnel working with feline PET patients, the per scan doses will be equal to or slightly less than personnel working with human patients.

Table 9 contains radiation doses to personnel directly involved with the PET procedure. However, there will also be occupational radiation exposure to nursing staff who care for a patient (should they require it) post-PET scan. Although animal patients do not require as much nursing attention as humans, this is an interesting dose comparison due to the close proximity nurses have to patients. The dose received will depend on the time after injection the nurse first encounters the patient. Assuming contact at various times post-injection, expected nursing staff doses (time averaged over an 8 hour shift) have been estimated as those listed in Table 12 [67]. The earliest post-injection contact time is considered to be 2 hours, allotting for the length of the PET procedure.

Table 12: Radiation Dose (μSv) to Nursing Staff per PET patient

Patient Type	Time elapsed post-injection prior to contact			
	2 h	3 h	4 h	5 h
Helpless	112	77	53	36
Partially Helpless	57	39	27	18
Chairfast/Bedfast	30	20	14	10
Semiambulant	7	5	3	2

If we compare the above doses to the range of doses in Table 10 (7.9 to 22.1 μSv), we see that nursing staff doses from bedfast and semi-ambulant patients are reasonably comparable to veterinary staff doses (for about the same amount of injected activity), especially if there is delay in care. Consequently, we see that VTH technologists receive radiation doses more in line with nursing staff handling PET patients than with their

human nuclear medicine technologist counterparts. However, it should be noted that this comparison is made to only one study for nursing staff; additional studies need to conducted and compared to draw a more concrete conclusion.

Data analysis – comparison to other veterinary protocol

Since no other occupational radiation exposure studies have been conducted in veterinary PET, a simple model was developed to estimate radiation dose received by personnel from PET procedures. This model is subsequently used to compare different protocols.

Although ^{18}F-FDG uptake will never be exactly the same between animals, there are certain organs that preferentially take up ^{18}F-FDG, due to the physiologic properties of the radiopharmaceutical (i.e. accumulation in hypermetabolic areas as well as biological elimination). Generally, there will be uptake to the brain, heart, bladder, and kidneys, although within the thorax and abdomen, the uptake is fairly unpredictable due to variations in heart and gastrointestinal uptake. Also, as the majority of dogs undergoing PET procedures are tumor bearing, there will often be intense uptake to the tumor site as well. ^{18}F-FDG uptake is not uniform (a line source model is likely not the best model) nor is it contained within one point of the patient (a single point source model is also likely not the best model). Therefore, we consider a model with three point sources, equally spaced within a soft tissue cylinder (Figure 34).

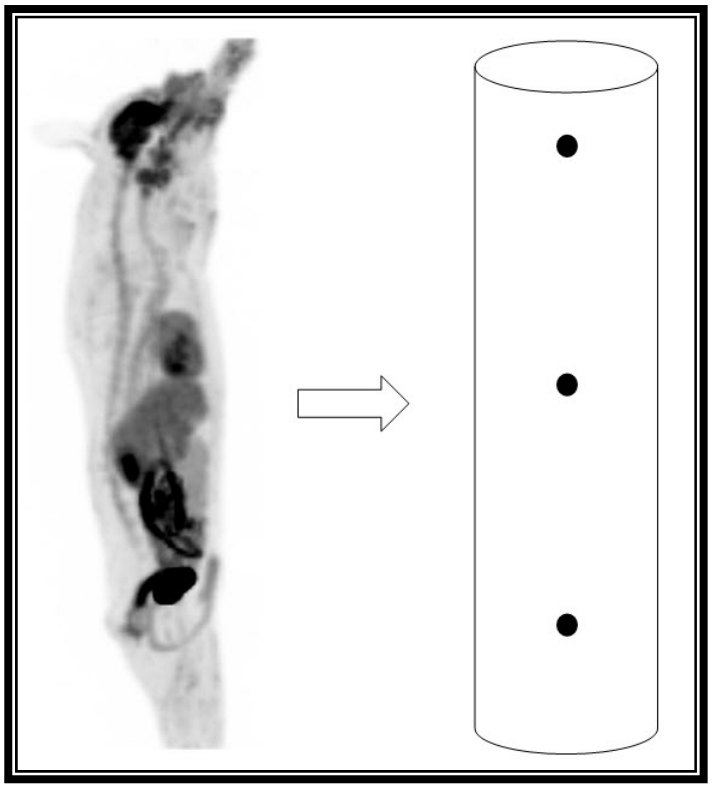


Figure 34: Three point source uptake model for a dog

As ^{18}F-NaF provides indication of bone metabolism, the uptake for ^{18}F-NaF will be different than that of ^{18}F-FDG (Figure 35 shows an example of ^{18}F-NaF uptake), and in fact, a modified line source model may be the best model for ^{18}F-NaF.

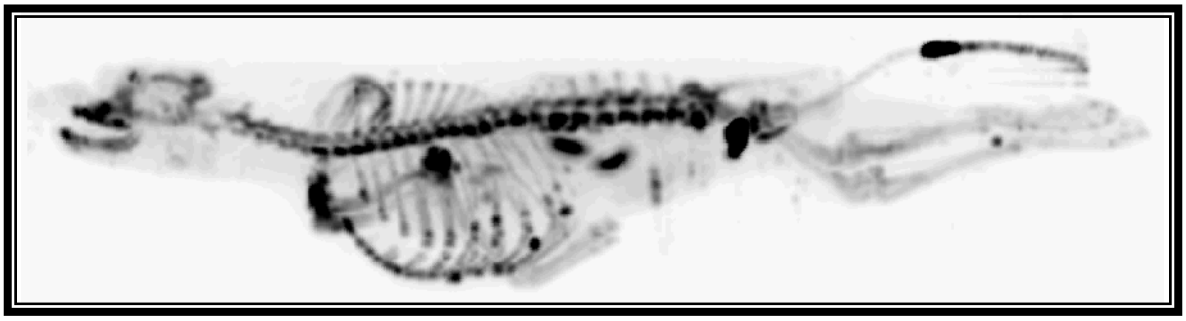


Figure 35: Example 18F-NaF Uptake

However, since there is limited dose information for this particular radiopharmaceutical, we only develop a dose estimate model for ^{18}F-FDG. In this ^{18}F-

FDG model, the assumption is also made that a technologist will stand either at one end of the patient, or at the side of the patient at the midway point (Figure 36).

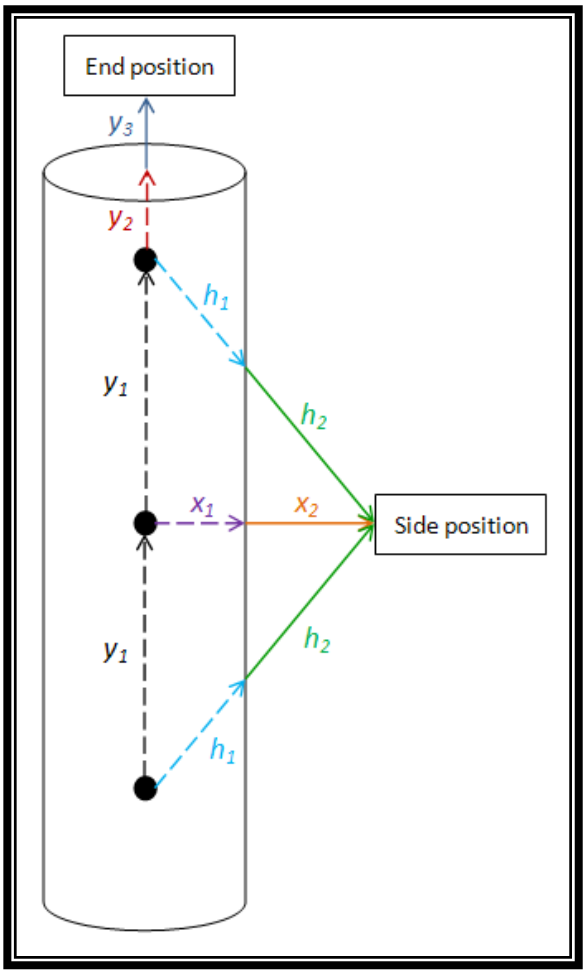


Figure 36: Three point source model – positions

To calculate the dose to a person using this model, we first need the distances between the source and the surface of the patient (in the direction of the technologist), and the distances between the technologist and the patient. In this estimate, we take y_1 (distance between point sources) as well as x_1 and y_2 (perpendicular distances to the surface of the dog) to be known and constant. To estimate dose, x_2 and y_3 (distance of

technologist from the patient) will be known, but variable, depending on the position of the technologist.

We need h_1 and h_2 to complete the dose estimate, but each can be calculated from y_1, x_1, and x_2 (utilizing Figure 37) as follows:

$$h_1 + h_2 = \sqrt{\left(x_1 + x_2\right)^2 + y_1^{\,2}} \tag{4}$$

$$\sin\theta = \frac{x_1 + x_2}{h_1 + h_2} = \frac{x_2}{h_2} \tag{5}$$

$$\Rightarrow h_2 = \frac{x_2\left(h_1 + h_2\right)}{x_1 + x_2} = \frac{x_2\sqrt{\left(x_1 + x_2\right)^2 + y_1^{\,2}}}{x_1 + x_2} \tag{6}$$

$$\Rightarrow h_1 = -h_2 + \sqrt{\left(x_1 + x_2\right)^2 + y_1^{\,2}} \tag{7}$$

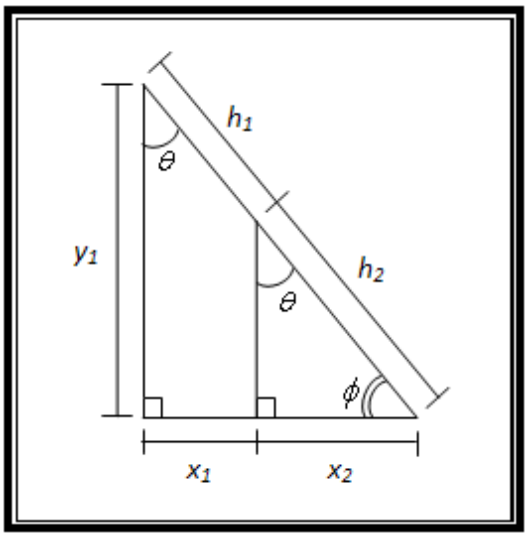


Figure 37: Angles and distances for the side position

Because the body of the animal will both attenuate and scatter the radiation, we use equation (8) [48] to calculate the dose rate at the surface of the animal, where *B* is the

build-up factor, μ is the linear attenuation coefficient, and x is the distance from the source to the surface of the dog, in the direction of the person exposed (x_1, y_2, or h_1):

$$\dot{H}_{\text{surface}} = B\dot{H}_0 e^{-\mu x} \tag{8}$$

For our calculations, we assume that soft tissue is equivalent to water (ρ = 1 g cm^{-3}). The linear attenuation coefficient for 511 keV photons in water is 0.097 cm^{-1}. The buildup factor *B* depends on the number of relaxation lengths, or μ*x*, and is determined from Figure 38 [48].

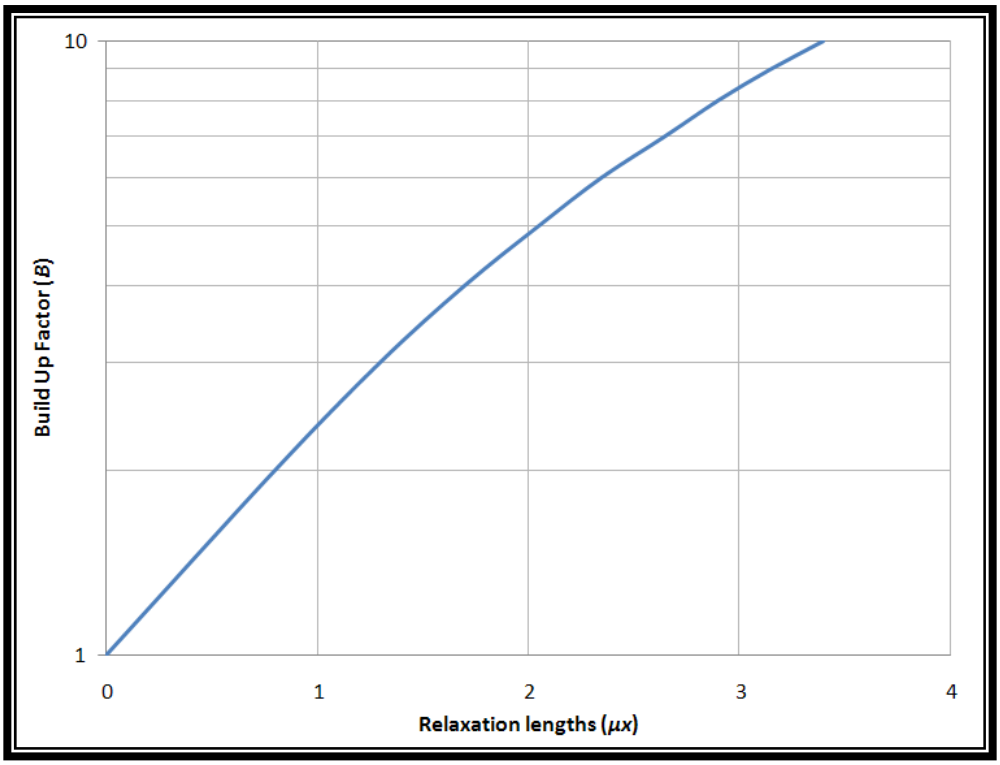


Figure 38: Buildup factors for 0.5 MeV photons in water

Buildup factors for $\mu x > 3.3$ were extrapolated, using the best fit curve for Figure 37:

$$B = 0.527(\mu x)^2 + 0.8718(\mu x) + 1 \text{ with } R^2 = 0.9999 \tag{9}$$

$\dot{H}_0$ above is the dose rate at the surface of the dog with no shielding, and we calculate it using equation (10) [47], where Γ is the gamma ray constant for F-18 and *A* is the activity, of the source:

$$\dot{H}_0 = \frac{\Gamma A}{x^2} \tag{10}$$

Once we have the dose rate at the surface of the animal, we need to calculate the dose rate at the particular distance of the technologist. To do so, we use the inverse square law [47], where *r* is the distance between the technologist and the source:

$$\dot{H} = \frac{\dot{H}_{\text{surface}} x^2}{r^2} \tag{11}$$

Combining equations (8), (10), and (11), we have the following:

$$\dot{H} = \frac{\Gamma A B}{r^2 e^{\mu x}} \tag{12}$$

Build-up and attenuation of the air (equation (8)), can be neglected because $B_{\text{air}} = 1$ and $\mu_{\text{air}} = 1.12 \times 10^{-4}$ cm [47] (i.e. $Be^{-\mu x_2} = 1$). Once we have the initial dose rate, we need to calculate the actual dose, accounting for the decay of the radioisotope:

$$H = \int_0^t \dot{H} e^{-\lambda t} dt \text{ where } \lambda = \frac{\ln 2}{t_{1/2}} \tag{13}$$

$$\Rightarrow H = \dot{H}\left[-\frac{1}{\lambda} e^{-\lambda t} \Big|_0^t \right] \tag{14}$$

$$\Rightarrow H = \dot{H}\left(-\frac{1}{\lambda} e^{-\lambda t} + \frac{1}{\lambda} \right) \tag{15}$$

$$\Rightarrow H = \frac{\Gamma A B}{\lambda r^2 e^{\mu x}} \left(1 - e^{-\lambda t} \right) \tag{16}$$

Injection will be the only action that is considered a single point source with essentially no shielding. Therefore, for injection, the above equation simplifies to:

$$H = \frac{\Gamma A}{\lambda r^2}\left(1 - e^{-\lambda t}\right) \tag{17}$$

For simplicity's sake, we will assume the average amount injected activity, or 155.8 MBq, and a 26 kg dog. The gamma ray constant, Γ, is 1.84×10^{-4} mSv m^2 MBq^{-1} h^{-1} for F-18 [68], and the half life of F-18 is 109.77 minutes.

To start, we assume, for comparison, the average amount of injected activity in this study, 155.8 MBq, which corresponds to a dog of about 26 kg. From there, we take the distance between the point sources to be about 35 cm, and the perpendicular distance from the point source to the surface of the dog as 10 cm (from the side, x_1, and from the end, y_2). Additional details of the calculations discussed below are provided in Appendix I.

Not including dose assay, the initiation of the PET procedure is injection of the radiopharmaceutical. For the protocol at CSU, anesthesia and positioning is done prior to injection. As mentioned above, we treat injection as a single point source. If we assume that injection takes about one minute, and the syringe is held away from the body 0.25 m, then the dose received from injecting the patient is $H = 7.63$ μSv.

Post-injection, there is about an hour uptake time allotted, followed by the PET scan which takes approximately 30 minutes. In this time, there is generally little to no contact with the patient if everything is going well. Activity is decay corrected using equation (17) and divided equally between the three point sources.

$$A = A_0 e^{-\lambda t} \tag{18}$$

Activity is also adjusted between each action. The time and distance of each action are estimates, and dose estimates are done for the primary nuclear medicine technologist and anesthetist only. Tables 13 and 14 contain the per patient dose estimates based on the model described above.

Table 13: Dose estimate for primary technologist, CSU protocol

Action	Position	Distance (m)	Time (min)	Dose (μSv)
Injection	N/A	0.25	1	7.6
Catheter removal	End	0.25	7	4.7
Additional prep for transport	Side	0.5	8	4.1
Moving patient	Side	0.1	0.5	1.2
Final prep for transport	Side	1	5	0.8
Transport	Side	1	3	0.5
Recovery	Side	0.5	5	2.3
Observation and assessment	End	1	3	0.6
			Total dose:	21.8

Table 14: Dose estimate for anesthetist, CSU protocol

Action	Position	Distance (m)	Time (min)	Dose (μSv)
Injection	N/A	N/A	N/A	0.0
Catheter removal	N/A	N/A	7	0.0
Additional prep for transport	Side	0.5	8	4.1
Moving patient	Side	0.1	0.5	1.2
Final prep for transport	Side	1	5	0.8
Transport	Side	1	3	0.5

Recovery	Side	0.5	5	2.3
Observation and assessment	End	1	5	0.9
			Total dose:	9.8

Comparing the results in Tables 13 and 14 to the expected doses determined by our dog model (equation (3)) for the same injected activity (Table 11), the above estimated doses are 40% greater than expected (for badges worn chest level). However, the doses are still well within the range of doses received in this study, and this dose estimate model is designed to provide the highest magnitude dose estimate. Therefore, the above described model is considered acceptable.

Some PET veterinary studies use an alternate protocol [19, 22, 24-26], where the patient is injected prior to the induction of anesthesia. In this case, the radiopharmaceutical is injected, and the animal kept in a quiet place for the uptake period. Anesthesia is then induced and the patient positioned on the scanner bed. These alternate protocols are not exactly the same, so a general protocol is considered, with injection performed before anesthesia (assuming a 26 kg dog) for comparison's sake. Per patient dose estimates are summarized in Tables 15 and 16.

Table 15: Dose estimate for primary technologist, alternate protocol

Action	Position	Distance (m)	Time (min)	Dose (µSv)
Injection	N/A	0.25	1	7.6
Induce anesthesia	Side	0.5	20	12.3
Patient positioning	Side	0.25	10	12.9
Catheter removal	End	0.25	7	3.9

Additional prep for transport	Side	0.5	8	3.4
Moving patient	Side	0.1	0.5	1.0
Final prep for transport	Side	1	5	0.7
Transport	Side	1	3	0.4
Recovery	Side	0.5	5	1.9
Observation and assessment	End	1	3	0.5
			Total dose:	44.6

Table 16: Dose estimate for anesthetist, alternate protocol

Action	Position	Distance (m)	Time (min)	Dose (µSv)
Injection	N/A	N/A	N/A	0.0
Induce anesthesia	Side	0.5	20	12.3
Patient positioning	Side	0.25	10	12.9
Catheter removal	End	N/A	7	0.0
Additional prep for transport	Side	0.5	8	3.4
Moving patient	Side	0.1	0.5	1.0
Final prep for transport	Side	1	5	0.7
Transport	Side	1	3	0.4
Recovery	Side	0.5	5	1.9
Observation and assessment	End	1	5	0.8
			Total dose:	33.4

Therefore, considering a 26 kg dog injected with 155.8 MBq of ^{18}F-FDG, and utilizing a three-point source dose estimate model, injecting the radiopharmaceutical before inducing anesthesia is expected to result in an increased radiation dose (per patient) compared to injecting after anesthesia, as summarized in Table 17.

Table 17: Dose (μSv) estimate comparison for different protocols

Job Position	Protocol	
	CSU	Alternate
Primary Nuclear Medicine Technologist	21.8	44.6
Anesthetist	9.8	33.4

DISCUSSION

Variability – Anesthesia Considerations

Anesthesia technologists rotate through providing anesthesia services for PET/CT patients. Eight different technologists were involved in this study, performing essentially the same tasks. The anesthesia portion of the PET scan is very dynamic and varies between technologists, between patients, and even between the same patient having a repeat scan. This variability extends to the other non-anesthesia technologists as they assist in patient positioning, set up, and recovery. The main opportunities for exposure to the anesthetist arise from room entries post radiopharmaceutical injection, and also unhooking, transporting, and recovering the patient. Remote monitors (circled in Figure 39) are available with a zooming video camera, but sometimes fluid levels and the CO_2 monitor are difficult to see, especially on the smaller carts.

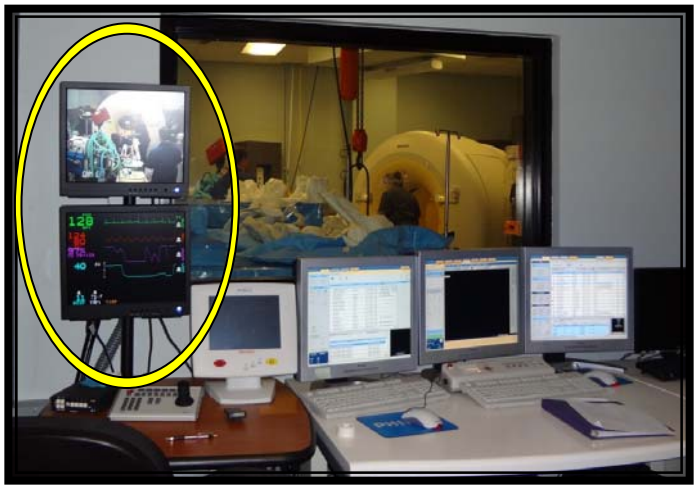


Figure 39: PET/CT workstation with patient monitors

Additionally, the anesthetist may have to administer medication (gas or injectible), depending on the patient's condition. Frequency of room entry is patient dependent and also a judgment call. Where a patient is recovered from anesthesia depends on a few factors, including whether or not the animal responds well to anesthesia and also the animals propensity to escape. Recovery has the potential for increased occupational exposures, due to the time spent in close proximity to the patient. It is difficult to predict how an animal will recover from anesthesia; sometimes the animal will wake up too quickly, wake up "rough," or have trouble breathing on their own. A Rottweiler who came in for a repeat scan on 10 March 2011 had no difficulties while under anesthesia, but was very difficult to recover; it took much longer than normal for the dog to breathe on his own. Consequently, the anesthesia technologist spent more time than usual in close proximity to the patient.

In addition to patient variability, there is also variability between technologist behaviors. Through observation, and despite continued instructions from the PET/CT technologists, some personnel make a concerted effort to keep distance between themselves and the patient, others take no special precautions. One anesthesia technologist (who was the PET technologist twice), in empathy for a cat who was "cold" laid her upper body across the cat, actually touching the cat with her chest. During this scan she was not wearing an EPD because she declined to do so. The same technologist, on a different scan, picked a cat up from the transport table and carried it inside to the recovery kennel, rather than wheel the cart inside ACC 162. She did wear an EPD for this patient, and the dose received was 11 µSv. It should be noted, however, that these

behaviors are not compliant with VTH radiation safety policies and are expressly contrary to specific safety instructions from the nuclear medicine technologists.

Variability – cats

At the time of this study, a simultaneous research study focusing on cats with squamous cell carcinoma (SCC) was also underway. The cats used in the concurrent study were generally geriatric and in poor health. Consequently, these cats responded poorly to anesthesia, resulting in the need for additional care from the anesthesia technologist. Also, occasionally cats in the SCC research study would have lymph node aspirations post-PET scan and prior to recovery, which usually involved (in addition to the technologists) two veterinarians, neither of whom wore an EPD (due to lack of availability). Consequently, the time of radiation exposure was longer and the number of people exposed higher than other scans where additional patient care was not needed.

Generally cats are recovered in the PET/CT suite and dogs in ACC 162. Cats are easier to restrain (i.e. less likely to escape en route to recovery) and also generally recover faster and easier than dogs.

Variability – dogs

The activity of the radiopharmaceutical dose received (1.16 mCi, or 42.9 MBq) for the first ^{18}F-NaF patient in this study (patient D1) was much less than the dose ordered (6.58 mCi, or 243.5 MBq). The patient was already under anesthesia when the dose was assayed, so the PET procedure was performed as scheduled. Despite the administered dose being less than the recommended dose, a diagnostic quality scan was produced

that was clinically useful. The exposure rate at the dog's skin was 2.6 mR h^{-1} at the conclusion of the PET scan, and by the time he was unhooked and prepared for transport, he was able to be recovered in regular anesthesia rather than in the special PET housing, which is much easier for the staff. Because the radioisotope activity was so much less than usual, we would expect doses to staff to consequently be lower than they would have been, assuming unchanged behavior.

In another unusual situation, patient D4 did not void any urine during the entire PET/CT procedure (a repeat scan). Upon entry into ACC 162 recovery, it became a concern that her bladder may have ruptured. Performing an ultrasound became a possibility, but only a radiation worker would be able to perform it. Fortunately, the CT showed an intact bladder. However, as the dog was housebroken, it was also a concern that she might be in pain from "holding it." She was taken outside immediately – a towel was used to help her walk (Figure 40).

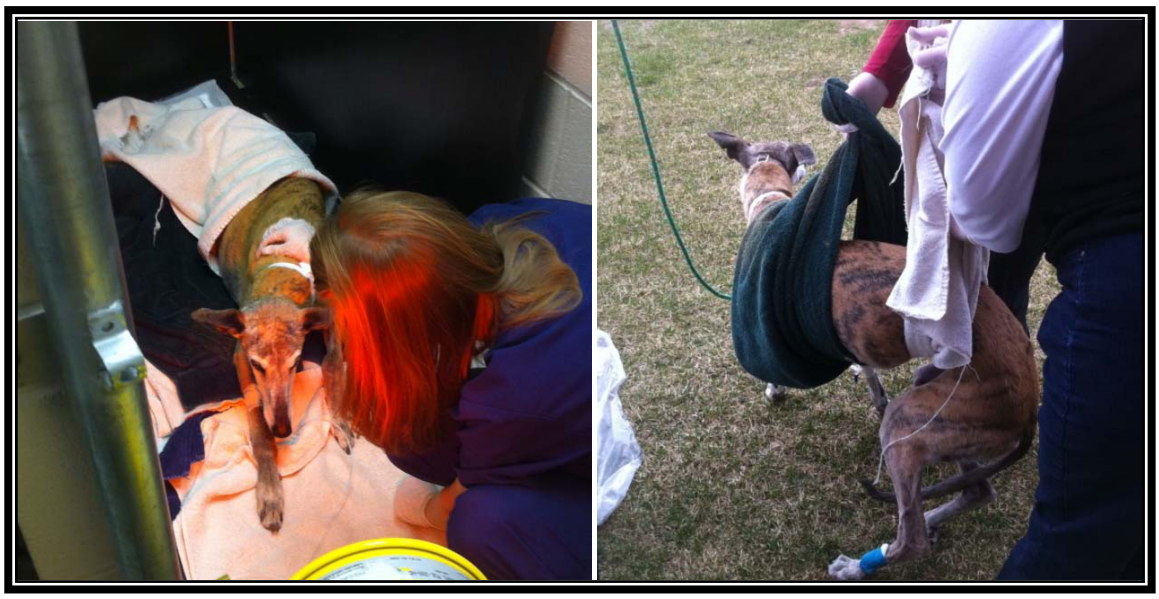


Figure 40: Patient D4

All the nuclear medicine technologists plus the anesthesia technologist were involved. Eventually the dog gained her footing and loped around, and found a place to urinate. Everyone made efforts to comfort and soothe the dog, insomuch spending more time and in closer proximity than typical.

Typically, the IV injection catheter will be flushed (tested) with saline immediately prior to injection to make sure it has not become blocked. However, for patient D11, the catheter was not tested; when it came time to inject the ^{18}F-FDG dose, it would not pass through the catheter. Consequently, the catheter had to be repositioned (Figure 41) and much more time was spent on injecting the dose than usual, resulting in a higher radiation dose to the technologist.

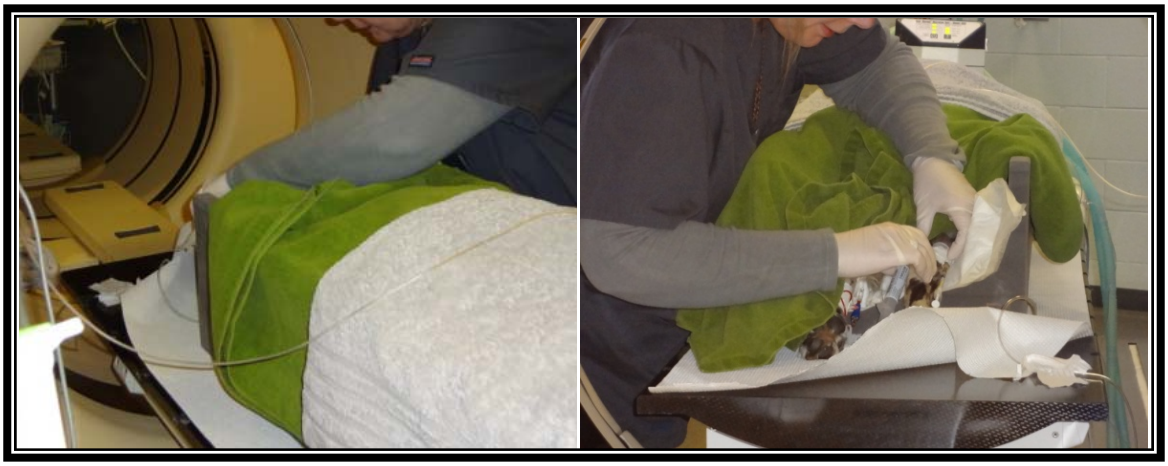


Figure 41: Injection difficulties

Patient D12 received a CT guided biopsy and node aspiration post-PET scan, involving active participation by two veterinarians, neither of whom had an EPD. The biopsy was done after the PET scan, because it is preferable to do a biopsy under anesthesia, and there is concern that conducting a biopsy before radiopharmaceutical injection may change the site uptake (resultant bleeding, etc.) A third veternarian came

in at the end of the biopsy to help the technologists with clean up and patient recovery. The post-PET procedure included shaving and cleaning the biopsy location (Figure 42), positioning the patient, the actual biopsy (Figure 43), and the final clean-up, all of which involve being very close to the patient.

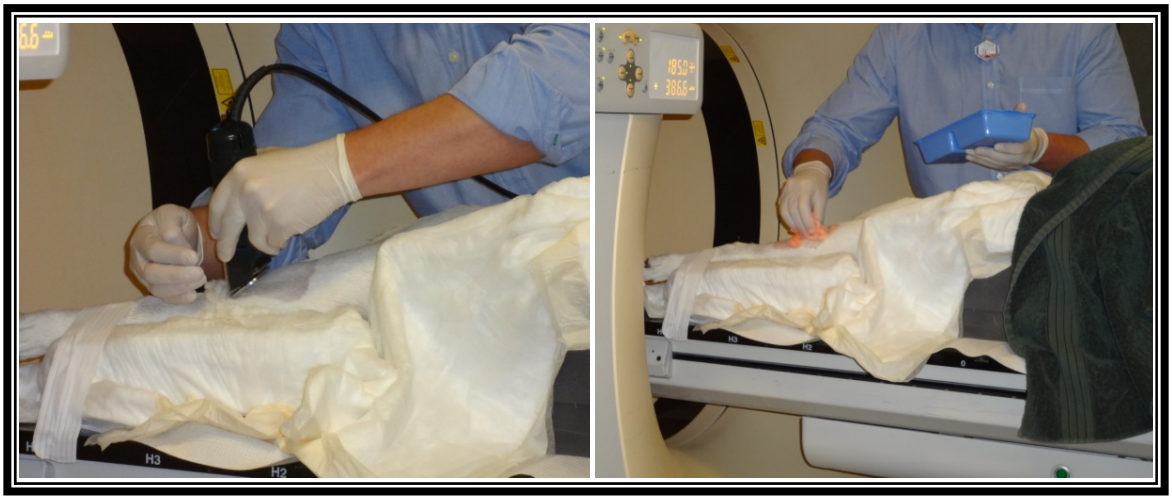


Figure 42: Shaving and cleaning biopsy site

Figure 43: Performing aspiration

Radiation doses are expected to be higher for any additional patient care performed post-injection, such as this biopsy.

Three of the animals in this study were purpose-bred dogs involved in a brain scan research project. The procedure for these dogs was different than for the other animals as each dog received an MR scan in addition to the typical full-body PET/CT. The dogs were anesthetized in the Bioinstrumentation Lab (Figure 44) and the radiopharmaceutical was injected in the Magnetic Resonance Suite (see Appendix B for locations in the VTH). After an MR brain scan, the dog was transported to the CT suite for the PET/CT. The procedure post PET/CT was the same as for other patients.

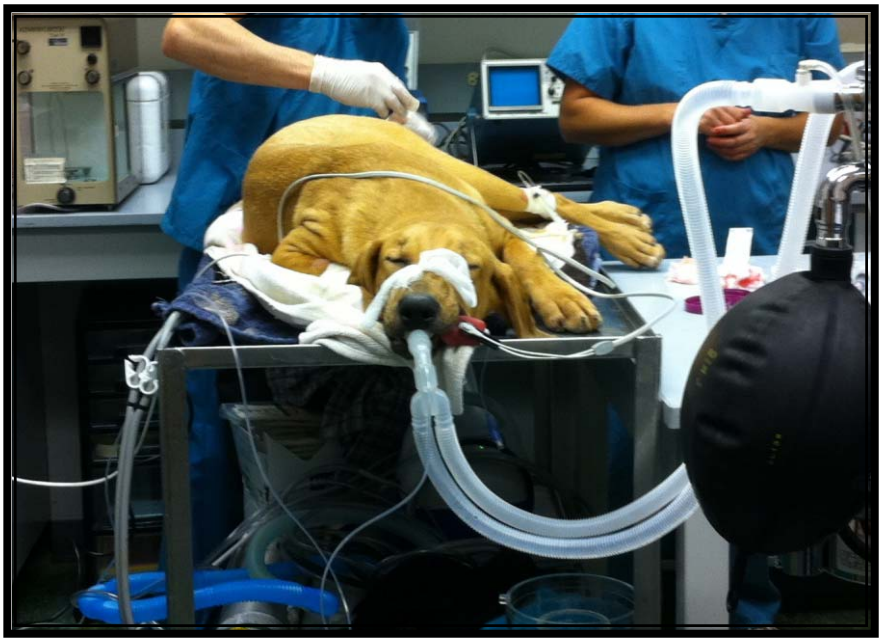


Figure 44: One of three research dogs

Variability – sheep

The first live sheep PET/CT at CSU was performed on 05 May 2011. She was a research animal retained by CSU because of the propensity of other sheep to follow her. She developed significant lung disease and had to be humanely euthanized; it was decided, however, that she would receive a PET/CT for educational purposes prior to euthanasia (Figure 45).

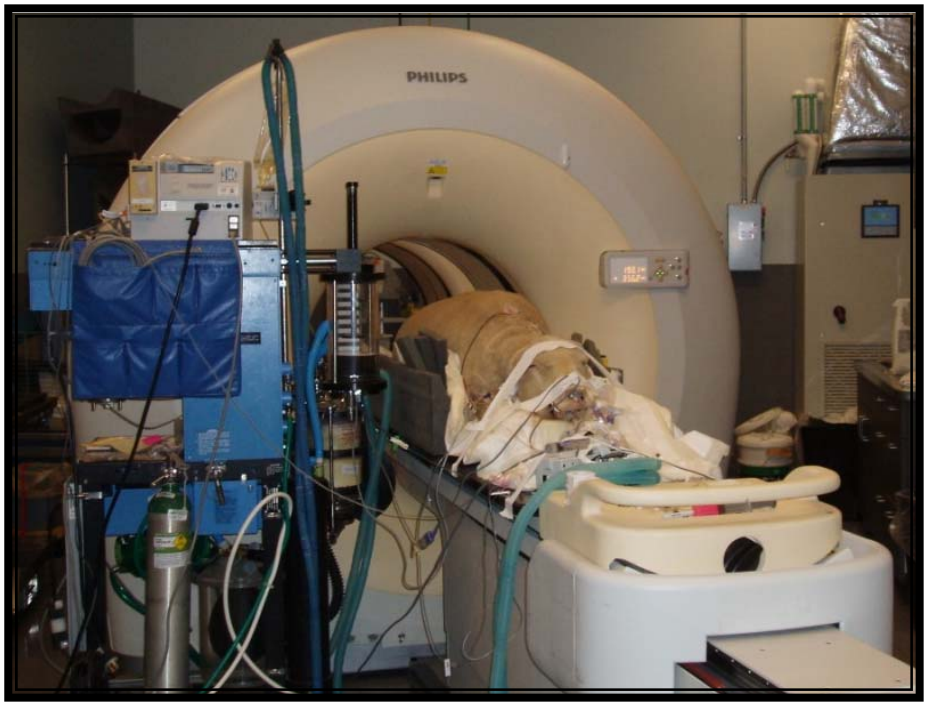


Figure 45: Sheep PET/CT

In this instance, since the patient was euthanized post-PET scan, she did not have to be recovered. Instead, she was simply transported to the necropsy locker. The only dose received after transport would be to the person checking the exposure rate at the sheep's skin to determine when a necropsy could be performed. If other sheep studies are conducted, we would expect potential radiation doses to be higher to VTH personnel when recovery is included as part of the study

Dose comparison and risk assessment

Although the doses received in this study (maximum of 30 μSv, or 3×10^{-5} Sv) are well below the levels needed for deterministic effects to occur (about 1 to 2 Gy, or 1 to 2 Sv gamma radiation) [46], there is still an increased risk for the occurrence of stochastic effects. It is widely held that there is risk associated with any level of ionizing radiation exposure; according to the most recent BEIR report [69],

> "the current scientific evidence is consistent with the hypothesis that there is a linear, no-threshold dose-response relationship between exposure to ionizing radiation and the development of cancer in humans."

While there is risk associate with exposure, it is worthwhile to consider the magnitude of that risk. On average, out of 100 people (represented in Figure 46 [69]), 42 are expected to develop cancer from non-radiation induced causes (pink squares). An additional incidence of cancer (green star) will be expected as a consequence of receiving a single effective dose of 0.1 Sv (above background) [69].

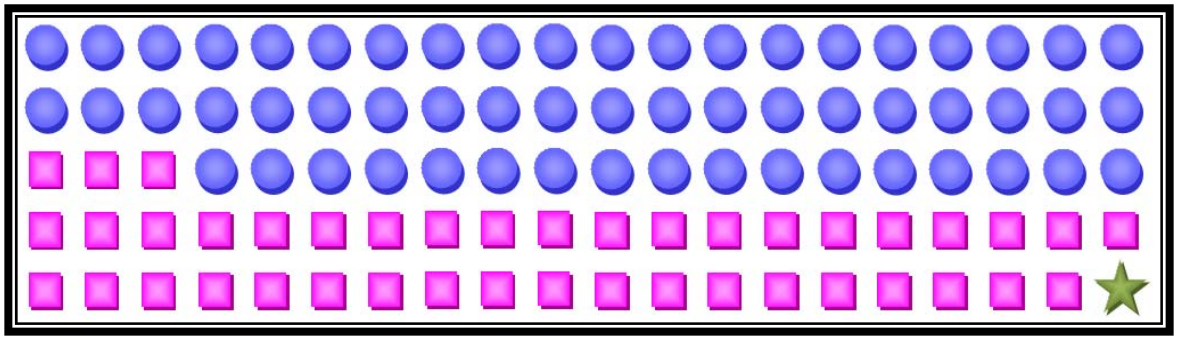


Figure 46: Representation of cancer risk

For a more detailed example, suppose 100,000 people (male or female population) were each exposed to 0.1 Gy (or 0.1 Sv gamma radiation). The corresponding lifetime risk of cancer incidence and mortality for both the exposed and an unexposed equivalent population is provided in Table 18 [69].

Table 18: BEIR committee's preferred lifetime attributable risk estimates

	All Solid Cancers		Leukemia	
	Males	Females	Males	Females
Excess cases from exposure to 0.1 Gy	800	1300	100	70
Number of cases in the absence of exposure	45500	36900	830	590
Excess deaths from exposure to 0.1 Gy	410	610	70	50
Number of deaths in the absence of exposure	22100	17500	710	530

The maximum cumulative exposure from this study is 254 μSv, which corresponds to an absorbed dose of 2.54×10^{-4} Gy, meaning that the risk of stochastic effects from radiation exposure received during this study is extremely low (about 0.003%.) Even if this exposure was received every four months for 30 years, the absorbed dose would be < 0.02 Gy, which corresponds to a risk of 0.23%.

To gain additional perspective of the doses received in this study, they should also be considered against background radiation exposure. The most recent information concerning background radiation exposure, not including occupational exposure, is shown in Table 19.

Table 19: Average Annual Background Radiation Dose

Source	National [70]	Worldwide [71]
Natural	3.1 mSv	2.4 mSv
Artificial	3.1 mSv	0.6 mSv

The average cumulative exposure for this study is 128 μSv (the maximum is 254 μSv). If this average exposure was received by a worker (every four months) for a year, then the average annual exposure would be 384 μSv, or 0.384 mSv (for the maximum, it would be 0.762 mSv), which is about 12% of the national natural background exposure, or 6% of the total national background exposure. The distribution of public radiation exposure, including occupational, is shown in Figure 47 [70-73].

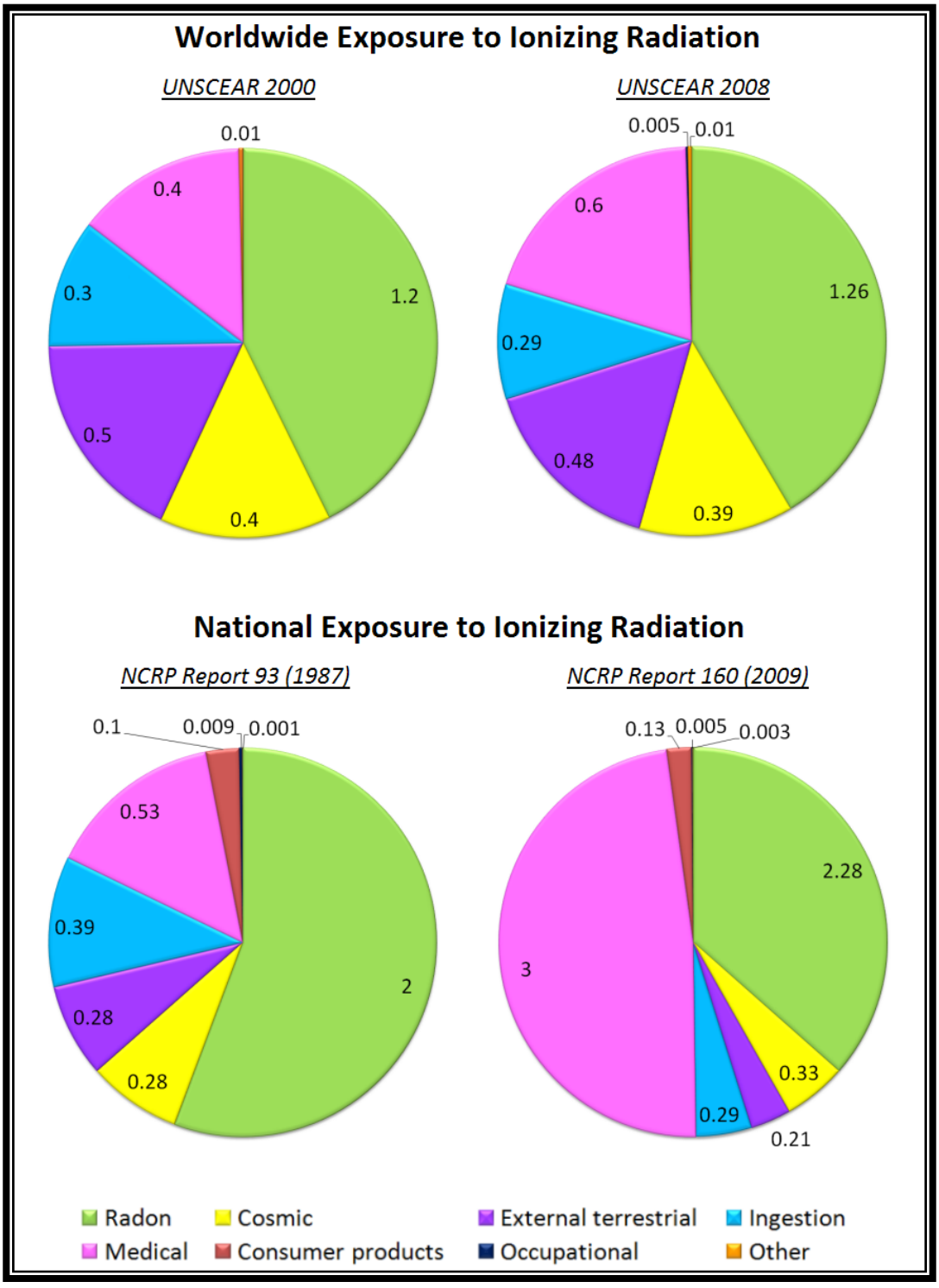


Figure 47: Worldwide and National Exposure to Ionizing Radiation (mSv)

Worldwide exposures have remained generally unchanged, with just a slight increase in medical exposure. National exposures, however, have seen a dramatic increase in the

medical component, due in large part to the increase in CT and nuclear medicine studies [70].

As discussed in the Introduction of this paper, the increase in use of technology in the human medical community will eventually be incorporated into veterinary practice. The most recent compilation of veterinary occupational exposure to ionizing radiation indicates that worldwide, the average annual effective dose is 0.15 mSv (0.59 mSv for measurably exposed workers), the majority of which is received through diagnostic radiology [71]. With the advent of veterinary PET/CT, it is likely that this figure will change in the coming years, with more exposure resulting from PET/CT.

Finally, the doses received in this study are compared to the annual whole body dose limits. The national dose limits are set by the United States Nuclear Regulatory Commission (US NRC) in Title 10 of the Code of Federal Regulations (CFR) [74-75]. However, the most recent dose limit recommendations of the ICRP are less than the national limits, so both shown in Table 20.

Table 20: Annual Dose Limits for Workers and Members of the Public

	ICRP 103 [49]	US NRC [74-75]
Occupational	20 mSv	50 mSv
Public	1 mSv	1 mSv

As mentioned earlier, the maximum cumulative radiation dose received in this four month study was 0.254 mSv. If this dose was extrapolated from four to twelve months, the total annual dose would be 0.762 mSv, which is less than the public dose limit. The maximum dose received per patient was 30 mSv, which means that, conservatively, a

veterinary PET/CT technologist would need to handle 667 patients in one year to receive an annual dose equal to the international dose limit recommendation (or 1,667 patients to reach the legal dose limits of the United States.) Comparatively, if we consider the alternate protocol dose estimate (Table 17), a veterinary PET/CT technologist could handle 444 patients in a year before reaching international dose limits (1,111 patients for national dose limits.)

CONCLUSIONS

How veterinary personnel radiation doses compare to personnel working with human patients depends on the type of patient. On a per scan basis, the predicted doses to veterinary PET/CT technologists from feline patients will be less than or equal to doses from human patients. For canine patients the predicted doses will be equal to or slightly higher than human patient doses. The doses to veterinary PET/CT technologists from canine patients are more in line with nursing staff caring for chairfast or semiambulatory human patients post-PET procedure. In future studies of this nature (with additional data acquisition) it may be worthwhile to consider animal size versus species in creating predictive models.

CSU currently employs a PET protocol that minimizes radiation exposure to VTH personnel. Although a dose estimate model indicates that that an alternate protocol of anesthetizing animal patients after they have received their radiopharmaceutical dose will result in higher per patient radiation doses, these doses are still much lower than the legal dose limits. Considering both radiation exposure and patient care needs, there are advantages and disadvantages of each protocol. The presented dose estimate model presented needs further refinement and validation to more accurately predict potential radiation dose from different protocols. This model can then be used in

conjunction with patient care considerations to make a well-informed determination of optimal protocol.

Considerations

In additional to the physical variability, the PET imaging process is often emotional, in a different way than with human patients. Human patients are aware of their disease and make the choice to have a PET/CT – informed consent is required in the medical field. It is possible to get informed consent from pet owners, but not from the animals themselves. Animals often come in scared, and can become dysphoric during recovery. During or shortly after recovery, personnel generally try to comfort the animal by sitting next to or petting it. For example, patient D10 became excessively dysphoric after his initial recovery. The staff attempted to reverse his medications, but still had to spend an extra amount of time with him, as there was concern he could injure himself. Tech 1 received 17 μSv up to the patient's initial recovery. In the supplementary time spent with the patient, the technologist received an additional 4 μSv.

Due to patient care needs, veterinary patient interactions are generally more physical and more demanding than human patient interactions. Even so, the radiation doses received from veterinary PET procedures are low, and at the VTH's current caseload, well below the legal dose limits. In human nuclear medicine studies, the ICRP recommends that radiation protection strategies be designed and implemented so that a patient's sense of isolation is minimized [76]. Although animals are not the same as people, we recommend that the optimization of radiation protection in the veterinary

setting should continue to include reasonable consideration of the animal's overall health and comfort.

Radiation safety practices and recommendations

This study is not the first time EPDs have been used at the VTH, but to date, the only EPDs in use at the VTH were specifically for persons touring the radiology or nuclear medicine departments; there were only two EPDs available for use, and they are both cumbersome and well worn (Figure 48).

Figure 48: EPD Comparison

Additionally, they can only be read manually, whereas the MGP DMC 2000S has the capacity to operate in satellite mode, recording doses to a computer network automatically. Therefore, the first recommendation is for the VTH to replace the older EPDs with small, lightweight, and easily read electronic dosimeters, such as MCP DMC

2000S EPDs or other EPD with the same capability, along with a reader to enable automatic recording and archiving of dose.

It is very likely that dosimeter (badge) placement affects the staff members measured dose, even if other factors may confound the actual effect in this study, due to the limited amount of data available. Most tables and carts are waist high, which would provide some shielding/attenuation. Also, wearing a badge at the waist would not account for leaning over a patient on the table, as during injection. A follow up study should be conducted to consider this difference, possibly placing two dosimeters on each person: one at the waist and one at the chest. Following this study, badge placement should be standardized for consistency.

Also, it is recommended that an on-going study of this nature be implemented, with each anesthetist being given an identifier, to see how doses vary among the anesthesia technologists, to better assess radiation practices and the effectiveness of radiation protection training.

For a complete picture of patient self-attenuation and the relative importance of patient size, we recommend setting up stations with area monitors to determine the dose field(s) for the various types of patients. The dose fields are unlikely to be isotropic; knowing the dose field can give the technologists an idea of the best place to stand to minimize radiation dose when around the patient. Additionally, it is well known that dose rate varies with distance, and in fact falls off as the square of the distance for point sources. How dose rate varies close to the patient (i.e. when the

source is no longer a point source) would also be an item of interest, especially as technologists interact closely with the patient.

This study should also be repeated with specific focus on each individual aspect of the PET imaging process, possibly adjusting the current PET protocol in order to reduce dose. Knowledge of the radiation dose received per task would also contribute to refinement of the dose estimate model discussed above.

The ultimate goal of this study was to provide information that will enable educated decisions in the improvement of the VTH radiation safety policies. In fact, this study has sparked new interest in radiation safety optimization within the VTH. The real time indication of dose provided by the EPDs was well received by the staff, and Colorado State University's Radiation Control Office has even decided to purchase EPDs for similar use. Immediate feedback of received dose gives good indication of how well an individual is keeping their exposure as low as reasonably achievable (ALARA). Also, an audible alarm, which can be set at different levels, further contributes to practice optimization [77]. Because EPDs provide direct and immediate dose measurements, they are referred to as "active" dosimeters. Dosimeters that provide dose readings retrospectively, such as OSL dosimeters and TLDs, are referred to as "passive" dosimeters. Comparisons have shown that active personal dosimeters (including the MGP DMC 2000S) have comparable dosimetric performance to passive personal dosimeters [77-78], which have long been used as the legal dose of record. Moreover, EPDs can provide the additional benefit of confirming regular dosimetry and helping catch potentially erroneous OSL readings, as in this study. EPDs also have a lower

detection limit (1 μSv) than the OSL dosimeters (10 μSv). However, OSLs may be reread, whereas with EPDs the radiation dose may be logged, but not reassessed. Additionally, EPDs are battery powered, and OSL dosimeters require no external power supply during the issue period. Although EPDs do have an audible indication of low battery power, it is possible for an EPD to fail before the battery can be changed. Therefore, a redundant dosimetry system is often utilized; many locations employ dual dosimetry programs with primary passive dosimeters and secondary active dosimeters [79]. Consequently, it is recommended that EPDs become standard, in addition to OSL dosimeters, for those working with PET, including any temporary workers.

The final recommendation of this study is to improve communication between radiation safety personnel and the personnel working around radiation (specifically PET procedures.) Personnel in charge of radiation protection should routinely assess behaviors for appropriate ALARA practices and provide radiation safety training as deemed necessary. Additionally, questions from personnel should be encouraged and concerns should be addressed as soon as possible. Actively and positively encouraging radiation awareness and protection will result in an improved radiation safety culture, hopefully resulting in the development of improved work practices, and a consequent reduction in future exposure.

In summary, the following are recommendations for procedure changes and future studies at the VTH:

- update dosimetry used for visitors,
- implement dual (passive and active) dosimetry,

- standardize badge placement,
- increase communication and provide continued education,
- refine and validate the dose model,
- determine patient dose field,
- determine per patient doses for individual tasks, and
- determine per patient doses for each technologist.

APPENDIX A

PET FDG AND NAF PROTOCOL

Small animal

Dogs or cats that are undergoing PET scans will be handled and housed in ACC room 162, the nuclear medicine therapy ward, or ACC room 160, the diagnostic nuclear medicine ward. Patients will only be housed in ACC room 160 when ion chamber readings are < 5 mR/h. Measurements will be documented and recorded on a log sheet.

The F18-radiopharmaceutical will be provided as a unit dose to ACC room 159A, the nuclear medicine radiopharmacy room, where the standard protocols for receiving radioactive materials (RAM) will be followed. The dose will be measured in the dose calibrator, placed directly into a leaded syringe shield and the dose-syringe shield combination placed into a leaded dose carrier ("suitcase"). The suitcase containing the dose will be placed on a transport gurney and wheeled through the specified hallways to the PET/CT scanning suite, VTH H106. The dose of F18-radiopharmaceutical (typically F18-deoxyglucose of F18-sodium fluoride) will be administered per an indwelling IV catheter. All personnel handling the patient will take the expected precautions of minimizing number of people involved, minimizing patient contact time, maximizing shielding and wearing appropriate dosimetry badges, protective gloves, eyewear, and barrier clothing, including a gown and plastic shoe covers, when working with the animal. Two pair of gloves will be worn each time a person interacts with the PET patient. Gloves will be changed each time the room is exited and a personal exit survey will be performed. All personnel involved in the handling and monitoring of the patient will undergo training in the appropriate radiation safety modules.

General anesthesia will be induced and the patient instrumented in anesthesia prep VTH room C-108. Anesthesia personnel should make every effort to place "courtesy tabs" on the patient following the PET procedure, thereby minimizing the time spent in close contact with the patient.

Anesthesia will be maintained per inhalation prior to injection of the F18-radiopharmaceutical dose. This will accomplish two things. The animal must be kept very still following injection to minimize false positives from uptake in normal tissues such as muscle, plus general anesthesia is necessary for the scan procedure. Having the dog pre-anesthetized will minimize radiation exposure to anesthesia personnel who much instrument the animal.

After induction of general anesthesia and prior to radiopharmaceutical injection, an indwelling urinary catheter and collection bag will be placed by a member of the CCU staff, anesthesia staff, or primary clinician.

Once anesthetic induction and necessary instrumentation is complete, the patient will be moved into the PET/CT suite VTH H-106 in preparation for the CT examination and for radiopharmaceutical injection. If required for future radiation therapy planning, the anesthetized patient will undergo fabrication of a radiation therapy immobilization device prior to radiopharmaceutical injection. After the anesthetized animals have been injected with the F18 radiopharmaceutical dose (doses of 2.5 – 8 mCi are anticipated), they will be kept on the CT table prior to PET imaging. Pre-and post contrast CT examinations will occur during the uptake time of the radioisotope which is approximately one hour. Following the uptake time, the PET scan will be performed.

During these procedures, the patient will be monitored via a remote physiological monitoring system and closed circuit cameras by personnel in the CT control room, VTH H-108, again to minimize radiation exposure to personnel. Personnel may have access to the anesthetized patient after injection with the radioisotope, but should make every effort to minimize the time spent near the patient, use appropriate shielded barriers, and wear two sets of gloves while working with the patient. Exit surveys and removal of gloves will be performed prior to leaving the PET/CT suite and entering the CT control room.

After completion of the scan, the patient will be transported back to ACC room 162 on a gurney and recovered from anesthesia. The north hallway of the VTH will be used during transport to minimize exposure to passersby in the hallways. Personnel transporting the patient will make all attempts to maximize the distance between themselves and the patient, and to minimize the number of bystanders in the hallway during transport. Radioactive material signs will be placed on or near the patient to alert hospital personnel that radioisotopes are in use. A spill kit will also be transported with the patient. Prior to transport to ACC room 162, the urinary catheter will be removed and the catheter, collection tubing, and urine bag disposed of in the lead shielded container located in the PET/CT suite. If the urinary catheter is considered necessary during the transport of the patient to ACC room 162, then prior to leaving the PET/CT suite, an empty collection bag will be attached to the urinary catheter and the connection between the collection bag and catheter will be taped together to decrease the risk of separation during patient transport. The empty urinary collection bag will be

placed on the gurney with the patient. The urinary catheter will remain indwelling with urine collected into a bag and for eventual disposal (see below). This step is to be primarily performed by a nuclear medicine technologist, radiology resident, or radiologist.

The indwelling urinary catheter and collection bag may be removed from the patient upon return to ACC room 162 and placed in an appropriately shielded container. The IV catheter and endotracheal tube will be removed at such time that assessment by anesthesia personnel indicates is appropriate. These items, and all other waste items (gloves, cotton balls, gauze, tape, blankets, etc) will also be placed in an appropriately shielded container within ACC room 162 for decay. All de-instrumentation of the patient should occur while the patient is laying upon the transport gurney, prior to being moved into the recovery kennel.

If anesthesia personnel feel it is necessary to be inside ACC room 162 in order to monitor the patient during recovery, they should minimize time with the patient and make all attempts to remain behind the shielded partition near the kennels.

The patient may be walked within the designated nuclear medicine fenced area at any time after recovery from anesthesia as there is no limit on the exposure rate when taking a patient into a controlled area

Once ion chamber readings of the patient are < 2 mR/h, the patient may be released to the owner, general public, or other areas of the hospital. The patient MAY NOT be released to the general public or other areas of the hospital until the ion chamber readings are < 2 mR /h

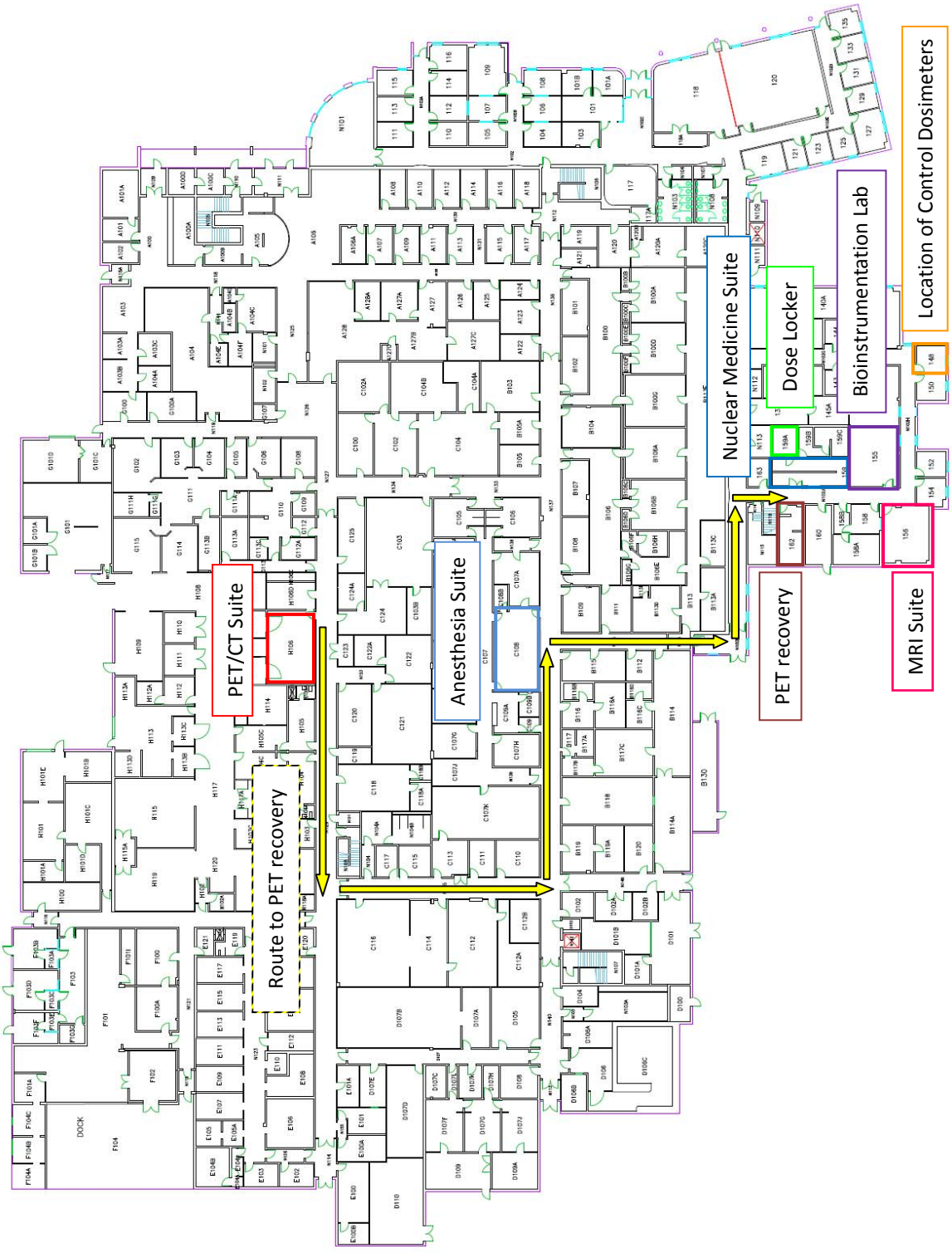
Items placed in the shielded containers will be decayed in storage in ACC room 162 until radiation levels reach background as determined. At such time, waste items may be placed into the general trash and the endotracheal tubes, or other equipment, returned to anesthesia for cleaning and reuse. This will be documented and recorded on an appropriate log sheet.

All personnel involved in the handling of each injected patient will perform an exit survey using a Geiger counter on their hands and clothing prior to leaving ACC rooms 159 or 162, or VTH H-106, and interacting with other people and pets. Personnel must initial the "exit survey" paperwork located on a clipboard near the Geiger counters in each area. For ACC room 162, the barrier wall in room 162 delineates the "clean" zones from the "hot" zones of the room. Exit surveys and removal of gloves, booties, and other protective clothing will occur behind the barrier wall.

APPENDIX B

VTH FLOOR PLAN[4]

[4] VTH and ACC combined floor plan provided courtesy of CSU Facilities Management


PET/CT Suite
Route to PET recovery
Anesthesia Suite
Nuclear Medicine Suite
Dose Locker
Bioinstrumentation Lab
Location of Control Dosimeters
PET recovery
MRI Suite

APPENDIX C

VTH BACKGROUND RADIATION

Badge	Location	EPD Reading (mrem)			Days Elapsed	Bkgd per day	Comments
		Initial	Final	Diff			
ANESTHESIA	ACC 148	0.0	0.3	0.3	1	0.30	20Jan to 21Jan
SPARE	ACC 148	0.0	0.3	0.3	1	0.30	
OBSERVER1	ACC 148	0.0	0.3	0.3	1	0.30	
ANESTHESIA	ACC 148	0.3	0.5	0.2	0.7	0.30	08Feb to 09Feb: Prev reading afternoon, around 4; next reading morning around 8
SPARE	ACC 148	0.3	0.5	0.2	0.7	0.30	
OBSERVER1	ACC 148	0.3	0.5	0.2	0.7	0.30	
ANESTHESIA	ACC 148	0.0	0.3	0.3	1	0.30	09Feb to 10Feb
SPARE	ACC 148	2.5	2.7	0.2	1	0.20	
OBSERVER1	ACC 148	2.2	2.5	0.3	1	0.30	
ANESTHESIA	ACC 148	0.0	0.5	0.5	1.7	0.30	08Mar to 10Mar; badges reset afternoon of 08Mar, read morning 10Mar
OBSERVER1	ACC 148	0.0	0.5	0.5	1.7	0.30	
NUCMED2	Bioinst Lab	0.0	0.4	0.4	1.7	0.24	
NUCMED3	PET/CT	0.0	0.5	0.5	1.7	0.30	
VET1	Nucmed	0.0	2.9	2.9	10	0.29	VET1 issued 28Feb; not reset with others above
NUCMED3	PET/CT Ctrl Rm	2.7	7.1	4.4	15	0.29	10Mar to 25Mar
VET1	Nucmed	3.6	8.2	4.6	15	0.31	
NUCMED2	Bioinst Lab	1.7	6.9	5.2	15	0.35	
OBSERVER1	ACC 148	0.0	5.0	5.0	15	0.33	
NUCMED3	PET/CT Ctrl Rm	8.4	9.7	1.3	4	0.33	25Mar to 29Mar
VET1	Nucmed	8.6	9.9	1.3	4	0.33	
ANESTHESIA	ACC 148	0.6	1.8	1.2	4	0.30	
OBSERVER1	ACC 148	5.0	6.2	1.2	4	0.30	
VET1	Nucmed	0.6	0.9	0.3	1	0.30	29Mar to 30Mar
NUCMED2	Bioinst Lab	0.2	0.5	0.3	1	0.30	
ANESTHESIA	ACC 148	1.4	3.3	1.9	7	0.27	15Apr to 22Apr
SPARE	ACC 148	2.9	4.8	1.9	7	0.27	
OBSERVER1	ACC 148	3.0	5.0	2.0	7	0.29	
NUCMED3	PET/CT Ctrl Rm	1.4	3.4	2.0	7	0.29	
ANESTHESIA	ACC 148	3.3	4.5	1.2	4	0.30	22Apr to 26Apr

SPARE	ACC 148	4.8	6.0	1.2	4	0.30	
OBSERVER1	ACC 148	5.0	6.1	1.1	4	0.28	
NUCMED3	PET/CT Ctrl Rm	0.0	1.2	1.2	4	0.30	
NUCMED2	Bioinst Lab	1.6	4.2	2.6	11	0.24	15Apr to 26Apr
VET1	Nucmed	1.9	5.5	3.6	11	0.33	
NUCMED3	PET/CT Ctrl Rm	0.3	2.8	2.5	7	0.36	27Apr to 04May
VET1	Nucmed	0	2.3	2.3	7	0.33	
NUCMED2	Bioinst Lab	0.1	1.8	1.7	7	0.24	
SPARE	ACC 148	6.3	8.1	1.8	7	0.26	
OBSERVER1	ACC 148	0.3	2.2	1.9	7	0.27	
ANESTHESIA	ACC 148	0.5	2.2	1.7	7	0.24	
NUCMED3	PET/CT Ctrl Rm	2.1	2.3	0.2	0.83	0.24	04May to 05May
VET1	Nucmed	0	0.3	0.3	1	0.30	Readings taken at different
NUCMED2	Bioinst Lab	2.2	2.5	0.3	0.83	0.36	times of day
SPARE	ACC 148	8.3	8.6	0.3	1	0.30	
OBSERVER1	ACC 148	2.4	2.7	0.3	1	0.30	
ANESTHESIA	ACC 148	0.7	0.9	0.2	0.83	0.24	
NUCMED3	PET/CT Ctrl Rm	2.7	10.2	7.5	25.6	0.29	05May @1715 to 31May
VET1	Nucmed	0	8.4	8.4	25.6	0.33	@0815
NUCMED2	Bioinst Lab	1.1	7.5	6.4	25.6	0.25	
ANESTHESIA	ACC 148	3.2	10.2	7	25.6	0.27	
ANESTHESIA	ACC 148	0.6	2.3	1.7	5.88	0.29	31May @ 1320 to 06Jun @
OBSERVER1	ACC 148	0.1	1.9	1.8	5.88	0.31	1030
NUCMED3	PET/CT Ctrl Rm	3.0	4.9	1.9	5.88	0.32	
NUCMED2	Bioinst Lab	0.0	1.5	1.5	5.88	0.26	
VET1	Nucmed	0.5	2.4	1.9	5.88	0.32	
ANESTHESIA	ACC 148	2.3	2.8	0.5	1.92	0.26	06Jun to 08Jun @0830
OBSERVER1	ACC 148	1.9	2.4	0.5	1.92	0.26	
NUCMED3	PET/CT Ctrl Rm	4.9	5.4	0.5	1.92	0.26	
NUCMED2	Bioinst Lab	1.5	2	0.5	1.92	0.26	
VET1	Nucmed	2.4	3	0.6	1.94	0.31	08Jun @ 900
ANESTHESIA	ACC 148	0.6	2.8	2.2	8	0.28	31May to 08Jun
OBSERVER1	ACC 148	0.1	2.4	2.3	8	0.29	
NUCMED3	PET/CT Ctrl Rm	3.0	5.4	2.4	8	0.30	
NUCMED2	Bioinst Lab	0.0	2	2.0	8	0.25	
VET1	Nucmed	0.5	3	2.5	8	0.31	

ANESTHESIA	ACC 148	0.3	0.5	0.2	0.81	0.25	08Jun @1300 to 09Jun
OBSERVER1	ACC 148	0.1	0.3	0.2	0.81	0.25	@0840
NUCMED3	PET/CT Ctrl Rm	0.6	0.9	0.3	0.81	0.37	
VET1	Nucmed	0.1	0.3	0.2	0.81	0.25	

APPENDIX D

OSL READING INFORMATION

COLORADO STATE UNIV
ATTN [redacted]
RADIATION CONTROL OFC
GENERAL SERVICE BLDG
FORT COLLINS CO 80523

LANDAUER®

Landauer, Inc. 2 Science Road Glenwood, Illinois 60425-1586
Telephone: (708) 755-7000 Facsimile: (708) 755-7016
Customer Service: (800) 323-8830 Customer Service Technical: (800) 438-3241
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luxel®

RADIATION DOSIMETRY REPORT

ACCOUNT NO.	SERIES CODE	ANALYTICAL WORK ORDER	REPORT DATE	DOSIMETER RECEIVED	REPORT TIME IN WORK DAYS	PAGE NO
180061	CTS	1115740337	06/10/11	06/06/11	4	1 OF 1

PARTICIPANT NUMBER	NAME / ID NUMBER / BIRTH DATE / SEX	DOSIMETER	USE	RADIATION QUALITY	DOSE EQUIVALENT (MREM) FOR PERIODS SHOWN BELOW: DEEP DDE	EYE LDE	SHALLOW SDE	QUARTERLY ACCUMULATED DOSE EQUIVALENT (MREM): DEEP DDE	EYE LDE	SHALLOW SDE	YEAR TO DATE DOSE EQUIVALENT (MREM): DEEP DDE	EYE LDE	SHALLOW SDE	LIFETIME DOSE EQUIVALENT (MREM): DEEP DDE	EYE LDE	SHALLOW SDE	RECORDS FOR YEAR	INCEPTION DATE (MM/YY)
FOR MONITORING PERIOD:					01/01/11 - 06/30/11			QTR 1			2011							
00CTS	CONTROL	Pa	CNTRL		M	M	M	N/A	N/A	N/A							1	09/03
02470	ANESTHESIA	Pa	AREA		M	M	M	N/A	N/A	N/A	M	M	M	M	M	M	1	11/10
02471	NUCMED 1	Pa	AREA	P	M	M	3	N/A	N/A	N/A	M	M	3	M	M	3	1	11/10
02472	NUCMED 2	Pa	AREA	P	10	11	12	N/A	N/A	N/A	10	11	12	10	11	12	1	11/10
02473	NUCMED 3	Pa	AREA	P	19	21	23	N/A	N/A	N/A	19	21	23	19	21	23	1	11/10
02474	VET 1	Pa	WHBODY	P	10	10	11	N/A	N/A	N/A	10	10	11	10	10	11	1	11/10
02475	VET 2	Pa	AREA		M	M	M	N/A	N/A	N/A	M	M	M	M	M	M	1	11/10
02476	OBSERVER 1	Pa	AREA	P	2	2	2	N/A	N/A	N/A	2	2	2	2	2	2	1	11/10
02477	OBSERVER 2	Pa	AREA		M	M	M	N/A	N/A	N/A	M	M	M	M	M	M	1	11/10

M: MINIMAL REPORTING SERVICE OF 1 MREM
ELECTRONIC MEDIA TO FOLLOW THIS REPORT

QUALITY CONTROL RELEASE: SEB

20 - PR 9777 - RPT1305- N1 - 15737

J.T. 6/21/11 6/22/11 6/22/11

NVLAP®

Gmail by Google

Nicole Martinez <nicole16180@gmail.com>

CTS

Landauer Customer Service Records
<LandauerCustomerServiceRecords@landauerinc.com>
To: nicole16180@gmail.com

Thu, Jun 23, 2011
at 1:47 PM

Hello,

It appears from the data that this package was either exposed before it was received at your facility or at your facility or on the way back. The doses are reading anywhere from 63 mrem to 89 mrem.

Thank you

Landauer Inc

APPENDIX E

ACTIVITY RECORD SHEET CONSOLIDATION

Date:	20-Jan-11	Scan number:	1		
Patient:	C1	Isotope:	FDG-18	End Study Survey:	5.2 mR/h
Species:	Feline	Admin Activity:	0.681 mCi	End St Surv Time:	1200
Breed:	Domestic Shorthair	Injection Time:	1034	Release Survey:	1.95 mR/h
Mass:	4.2 kg	PET Bed Time:	0:17:20	Release Surv Time:	1500

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 1	NUCMED 1	0.2	1.1	0.9	Dose check-in, patient transport, assist anesthesia tech
NUCMED 2	NUCMED 2	0.2	0.3	0.1	Injection
OBSERVER 1	OBSERVER 1	0	0	0	Observation only
Notes: Initial patient positioning done prior to injection; anesthesia tech – No EPD; vet – No EPD; Node aspiration and ultrasound post PET; 5.2 mR/h should reading at 1154					

Date:	21-Jan-11	Scan number:	2		
Patient:	D1	Isotope:	NaF	End Study Survey:	2.6 mR/h
Species:	Canine	Admin Activity:	1.131 mCi	End St Surv Time:	1307
Breed:	Bernese Mountain Dog	Injection Time:	1157	Release Survey:	1.8 mR/h
Mass:	47 kg	PET Bed Time:	1:03:36	Release Surv Time:	1400

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	0	0.5	0.5	Injection, patient transport, assist anesthesia tech
NUCMED 2	NUCMED 2	0.6	0.8	0.2	Dose check-in, patient transport
----------	ANESTHESIA	0	0.2	0.2	Anesthesia; multiple room entries etc
OBSERVER 1	OBSERVER 1	0	0	0	Observation
Notes: Wrong dose (1/5 of what was ordered); 2.6 mR/h shoulder reading at 1259; able to recover in anesthesia rather than ACC162. Technologist who was originally wearing NUCMED1 is now wearing NUCMED3; EPD and OSL badges were accidentally pulled off when positioning a patient, EPD was found underneath the patient on the CT bed when it started alarming. The OSL was found the next day in the CT gantry.					

Date:	8-Feb-11	Scan number:	3		
Patient:	C2	Isotope:	FDG-18	End Study Survey:	8.2 mR/h

Species:	Feline	Admin Activity:	0.814 mCi	End St Surv Time:	1237
Breed:	Domestic Shorthair	Injection Time:	1118	Release Survey:	1.9 mR/h
Mass:	4.8 kg	PET Bed Time:	0:14:41	Release Surv Time:	1645

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	5.8	6.4	0.6	Dose check-in, injection, patient transport
----------	ANESTHESIA	0	0.4	0.4	
OBSERVER 1	OBSERVER 1	0	0	0	
Notes: Only one nuc med tech available today					

Date:	9-Feb-11	Scan number:	4		
Patient:	C3	Isotope:	FDG-18	End Study Survey:	5.1 mR/h
Species:	Feline	Admin Activity:	0.545 mCi	End St Surv Time:	1255
Breed:	Domestic Shorthair	Injection Time:	1051	Release Survey:	1.75 mR/h
Mass:	3.5 kg	PET Bed Time:	0:16:36	Release Surv Time:	1600

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	0.3	0.5	0.2	Dose check-in, patient transport
NUCMED 2	NUCMED 2	5.6	5.8	0.2	Dose assay, injection

Date:	10-Feb-11	Scan number:	5		
Patient:	D2	Isotope:	FDG-18	End Study Survey:	18.1 mR/h
Species:	Canine	Admin Activity:	10.39 mCi	End St Surv Time:	1210
Breed:	Great Pyrenees	Injection Time:	1009	Release Survey:	1.98 mR/h
Mass:	58 kg	PET Bed Time:	0:34:54	Release Surv Time:	1630

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	0.3	2.4	2.1	Dose check-in, patient transport
NUCMED 2	NUCMED 2	6.1	7.1	1	Injection (5.8 prev, 0.3 bkgd)

Date: 23-Feb-11 Scan number: 6

Patient:	C4	Isotope:	FDG-18	End Study Survey:	
Species:	Feline	Admin Activity:	0.742 mCi	End St Surv Time:	
Breed:	Domestic Shorthair	Injection Time:	1030	Release Survey:	1.45 mR/h
Mass:	4.7 kg	PET Bed Time:		Release Surv Time:	1515
Date:	24-Feb-11	Scan number:	7	PET Bed Time:	
Patient:	D2	Isotope:	FDG-18	End Study Survey:	
Species:	Canine	Admin Activity:	9.92 mCi	End St Surv Time:	
Breed:	Great Pyrenees	Injection Time:	1000	Release Survey:	1.74 mR/h
Mass:	58 kg	PET Bed Time:		Release Surv Time:	1740
Date:	25-Feb-11	Scan number:	8	PET Bed Time:	
Patient:	D3	Isotope:	FDG-18	End Study Survey:	
Species:	Canine	Admin Activity:	10.8 mCi	End St Surv Time:	
Breed:	Rottweiler	Injection Time:	1020	Release Survey:	
Mass:	61 kg	PET Bed Time:		Release Surv Time:	

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 2	NUCMED 2	11.6	14.1	2.5	
Notes: 3 scans over the course of the week; control badge read 6.1 mrem but initial reading unknown, prev NM2 reading 7.1 mrem; Billie out of town, Liz helping out but not badged. Background estimated at 0.3 mrem per day (mini bkgd study) for the 15 total elapsed days since the last PET/CT.					

Date:	8-Mar-11	Scan number:	9	PET Bed Time:	0:13:18
Patient:	C5	Isotope:	FDG-18	End Study Survey:	6 mR/h
Species:	Feline	Admin Activity:	0.669 mCi	End St Surv Time:	1200
Breed:	Domestic Shorthair	Injection Time:	1020	Release Survey:	1.65 mR/h
Mass:	2.77 kg	PET Bed Time:	0:13:18	Release Surv Time:	1540

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	1.8	2.1	0.3	On the “outskirts” today
----------	ANESTHESIA	0	1	1	
NUCMED 2	NUCMED 2	1.4	1.6	0.2	**injection**
Notes: Control EPD 1.7 mrem today, NM2/NM3 actual initial readings					

Date:	10-Mar-11	Scan number:	10	PET Bed Time:	0:36:33
Patient:	D3	Isotope:	FDG-18	End Study Survey:	15 mR/h
Species:	Canine	Admin Activity:	10.24 mCi	End St Surv Time:	1215
Breed:	Rottweiler	Injection Time:	1024	Release Survey:	1.92 mR/h
Mass:	61 kg	PET Bed Time:	0:36:33	Release Surv Time:	1710

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	0.5	2.7	2.2	**injection**
----------	ANESTHESIA	0	2.2	2.2	
NUCMED 2	NUCMED 2	0.4	1.7	1.3	
VET 1	VET 1	2.9	3.6	0.7	**dose assay, transport**
Notes: Control EPD 0.5 mrem today, NM2/NM3/VET1 actual initial readings; according to anesthesia tech, Tyson's a "good dog" under anesthesia, so she didn't have to make many room entries. However, there was some difficulty in the recovery room getting the dog to breathe on his own; VET1 should actually be NUCMED4					

Date:	25-Mar-11	Scan number:	11		
Patient:	D4	Isotope:	FDG-18	End Study Survey:	10.1 mR/h
Species:	Azia Ely	Admin Activity:	4.183 mCi	End St Surv Time:	1200
Breed:	266802	Injection Time:	1019	Release Survey:	1.81 mR/h
Mass:	25.5 kg	PET Bed Time:	0:33:50	Release Surv Time:	1630

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
OBSERVER 1	OBSERVER 1	5.0	5.0	0.0	
----------	ANESTHESIA	0.0	0.6	0.6	
NUCMED 3	NUCMED 3	7.1	8.4	1.3	Dose injection
VET 1	VET 1	8.2	8.6	0.4	Dose assay, transport
Notes: NM2 out; OBS bkgd 5.0, NM2 bkgd 5.2					

Date:	29-Mar-11	Scan number:	12		
Patient:	D5	Isotope:	NaF	End Study Survey:	5.8 mR/h
Species:	Jesse Rodeck	Admin Activity:	3.86 mCi	End St Surv Time:	1310
Breed:	267084	Injection Time:	1110	Release Survey:	1.7 mR/h
Mass:	55 kg	PET Bed Time:	0:36:24	Release Surv Time:	1550

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
OBSERVER 1	OBSERVER 1	0.0	0.0	0.0	
NUCMED 2	NUCMED 2	0.0	0.2	0.2	Patient positioning
NUCMED 3	NUCMED 3	0.0	0.5	0.5	Came in after injection
VET 1	VET 1	0.0	0.6	0.6	Dose assay/transport/injection
----------	ANESTHESIA	0.0	0.4	0.4	
Notes: NaF dose half of previous standard					

Date:	30-Mar-11	Scan number:	13		
Patient:	C4	Isotope:	FDG-18	End Study Survey:	8.3 mR/h
Species:	Feline	Admin Activity:	0.955 mCi	End St Surv Time:	1230
Breed:	Domestic Shorthair	Injection Time:	1046	Release Survey:	1.7 mR/h
Mass:	4.7 kg	PET Bed Time:	0:14:02	Release Surv Time:	1615

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
VET1	VET1	0.9	----------	----------	Out
NUCMED 3	NUCMED 3	0.0	0.7	0.7	Patient positioning
----------	ANESTHESIA	0.0	0.1	0.1	EPD worn in pants pocket
OBSERVER 1	OBSERVER 1	0.0	----------	----------	Out
NUCMED 2	NUCMED 2	0.0	1.2	1.2	**injection**
Notes: 2 vets performing patient care post PET scan (node aspiration); no badge. Lots of people around. Woke up cat in suite and transported to recovery without anesthesia cart					

Date:	5-Apr-11	Scan number:	14		
Patient:	C6	Isotope:	FDG-18	End Study Survey:	8 mR/h
Species:	Feline	Admin Activity:	0.923 mCi	End St Surv Time:	1234
Breed:	Domestic Shorthair	Injection Time:	1041	Release Survey:	1.87 mR/h
Mass:	4.26 kg	PET Bed Time:	0:13:18	Release Surv Time:	1510

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
VET1	VET1	0.0	0.2	0.2	
NUCMED 3	NUCMED 3	0.0	0.3	0.3	**injection**
NUCMED 2	NUCMED 2	0.0	0.2	0.2	
----------	ANESTHESIA	0.0	0.3	0.3	

OBSERVER 1	OBSERVER 1	0.0	0.0	0.0	

Date: 7-Apr-11 Scan number: 15
Patient: D4 Isotope: FDG-18 End Study Survey: 1205 mR/h
Species: Canine Admin Activity: 4.155 mCi End St Surv Time: 16.4
Breed: Greyhound Injection Time: 1016 Release Survey: 1.93 mR/h
Mass: 25.5 kg PET Bed Time: 0:33:01 Release Surv Time: 1600

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 2	NUCMED 2	0.6	2.1	1.5	Check in, transport, injection, help with patient transport, good at standing back, recovery w/anesthesia tech
----------	ANESTHESIA	0.0	1.0	1.0	
NUCMED 3	NUCMED 3	0.0	1.7	1.7	Helped anesthesia more patient for transport, helped in recovery when bladder became a concern
VET 1	VET 1	0.8	0.8	0.0	Helped at the end of recovery
OBSERVER 1	OBSERVER 1	0.6	0.6	0.0	Observe
Notes: Dog didn't put out any urine during procedure, became cause for concern. Staff wondering if bladder may have ruptured, considered ultrasound, but CT from earlier showed intact bladder. Becomes emotional issue, comfort animal. Patient was taken outside verry soon after and encouraged to void her bladder					

Date: 14-Apr-11 Scan number: 16
Patient: D6 Isotope: FDG-18 End Study Survey: 7.8 mR/h
Species: Canine Admin Activity: 3.77 mCi End St Surv Time: 1209
Breed: Walker Hound Injection Time: 1029 Release Survey: 1.9 mR/h
Mass: 26.5 kg PET Bed Time: 0:29:48 Release Surv Time: 1500

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
----------	ANESTHESIA	0.0	2.1	2.1	Also had students shadowing, although students stayed well back; tech also stayed back pretty well
VET 1	VET 1	0.0	1.0	1.0	0.7 in CT set up; transport, recovey
NUCMED 2	NUCMED 2	0.2	1.7	1.5	Injected, check in
NUCMED 3	NUCMED 3	0.0	0.8	0.8	0.7 in CT set up

Notes: Research study for the normal dogs (baseline brain scans): MR→injection→CT→PET, so injection done in MR vice CT; Vet came in during recovery to help out, remove catheters, comfort (no badge) Super sweet dog.

Date:	15-Apr-11	Scan number:	17	PET Bed Time:	0:28:09
Patient:	D7	Isotope:	FDG-18	End Study Survey:	
Species:	Canine	Admin Activity:	3.611 mCi	End St Surv Time:	
Breed:	Walker Hound	Injection Time:	1029	Release Survey:	1.94 mR/h
Mass:	25 kg	PET Bed Time:	0:28:09	Release Surv Time:	1515

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	0.0	1.4	1.4	
NUCMED 2	NUCMED 2	0.7	1.6	0.9	injection
VET 1	VET 1	1.4	1.9	0.5	transfer
----------	ANESTHESIA	0.7	1.4	0.7	
Notes: Research study for the normal dogs: MR→injection→CT→PET, so injection done in MR vice CT; bkgd 0.3					

Date:	26-Apr-11	Scan number:	18		
Patient:	D8	Isotope:	FDG-18	End Study Survey:	13.7 mR/h
Species:	Canine	Admin Activity:	3.98 mCi	End St Surv Time:	1200
Breed:	Walker Hound	Injection Time:	1010	Release Survey:	1.95 mR/h
Mass:	28.5 kg	PET Bed Time:	0:31:36	Release Surv Time:	1535

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	0.0	1.2	1.2	
NUCMED 2	NUCMED 2	0.0	1.3	1.3	injection
VET 1	VET 1	0.0	----------	----------	Out (in x-ray)
OBSERVER 1	OBSERVER 1	0.0	0.0	0.0	
----------	ANESTHESIA	0.0	0.6	0.6	Good at standing back
Notes: Research study for the normal dogs: MR→injection→CT→PET, so injection done in MR vice CT; bkgd 0.3					

Date:	27-Apr-11	Scan number:	19	PET Bed Time:	0:13:30
Patient:	D9	Isotope:	FDG-18	End Study Survey:	4.7 mR/h
Species:	Canine	Admin Activity:	0.65 mCi	End St Surv Time:	1155
Breed:	Shih-Tzu	Injection Time:	1034	Release Survey:	1.99 mR/h

Mass: 4 kg PET Bed Time: 0:13:30 Release Surv Time: 1410

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 2	NUCMED 2	0.0	0.1	0.1	Transport
NUCMED 3	NUCMED 3	0.0	0.3	0.3	Injection. 0.1 of 0.3 received in recovery
----------	ANESTHESIA	0.0	0.5	0.5	Badge put on 10 min in

Date: 4-May-11 Scan number: 20 PET Bed Time: 0:31:27
Patient: D10 Isotope: FDG-18 End Study Survey: 10.1 mR/h
Species: Canine Admin Activity: 6.65 mCi End St Surv Time: 1200
Breed: Mixed Breed Injection Time: 1008 Release Survey: 1.89 mR/h
Mass: 53.3 kg PET Bed Time: 0:31:27 Release Surv Time: 1520

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 2	NUCMED 2	0.0	2.2	2.2	Quite a bit of time spent in recovery
NUCMED 3	NUCMED 3	0.0	2.1	2.1	Quite a bit of time spent in recovery (1.7 post initial recovery), **injection**
----------	ANESTHESIA	0.0	0.7	0.7	EPD worn in pants pocket
Notes: NM2 and NM3 spent more time than usual with the patient in recovery "babysitting"/comforting; Dante was unhappy/dysphoric, concerned if breating ok, etc. If patient gets excessively upset, can injure themselves					

Date: 5-May-11 Scan number: 21
Patient: C6 Isotope: FDG-18 End Study Survey:
Species: Feline Admin Activity: 0.737 mCi End St Surv Time:
Breed: Domestic Shorthair Injection Time: 1042 Release Survey: 1.95 mR/h
Mass: 4.08 kg PET Bed Time: 0:13:03 Release Surv Time: 1530

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 2	NUCMED 2	0.0	0.4	0.4	Helping anesthesia
NUCMED 3	NUCMED 3	0.0	0.7	0.7	Helping anesthesia, more distance than NM2, **injection**
----------	ANESTHESIA	0.0	1.1	1.1	Picked up & carried cat from door of ACC162 to kennel; very sympathetic

Notes: Some issues with the leads during the scan. Unhooking the cat, moving to cart, waking up, assessment, prep for transport: 12 minutes. Transport from CT to recovery: 2.5 min (no anesthesia cart)

Date:	5-May-11	Scan number:	22		
Patient:	S1	Isotope:	FDG-18	End Study Survey:	18 mR/h
Species:	Ovine	Admin Activity:	11.26 mCi	End St Surv Time:	1700
Breed:		Injection Time:	1525	Release Survey:	
Mass:	76.4 kg	PET Bed Time:	0:33:06	Release Surv Time:	

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 2	NUCMED 2	0.4	1.1	0.7	
NUCMED 3	NUCMED 3	0.7	2.7	2.0	Just from injecting dose went to 2.1
----------	ANESTHESIA	1.1	3.2	2.1	Sheep difficult to respirate b/c lungs filled with nodules
OBSERVER 1	OBSERVER 1	0.0	0.0	0.0	

Notes: Several people around (2 addt anesthesia, although not around long; 3 sheep people, around but not around Eleanore until the end for euthanasia and transport; RCO came in at the end with a hand held dose rate meter, an additional vet was also there at the end. Eleanore was sick, belly filling with air, and PET/CT was for educational purposes. She was humanely euthanized rather than recovered, and transported to the necropsy cooler. Readings to be taken in the morning to ensure FDG decay before necropsy.

Date:	31-May-11	Scan number:	23		
Patient:	D11	Isotope:	FDG-18	End Study Survey:	19.5 mR/h
Species:	Canine	Admin Activity:	5.299 mCi	End St Surv Time:	12:45
Breed:	English Setter	Injection Time:	1050	Release Survey:	1.98 mR/h
Mass:	25.0 kg	PET Bed Time:	0:29:48	Release Surv Time:	1830

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	0.0	3	3.0	Injection, removing catheters, patient transport and recovery
VET 1	VET 1	0.0	0.5	0.5	Dose check-in/calibration, dose transport, residual assay
----------	ANESTHESIA	0.0	0.6	0.6	

OBSERVER 1	OBSERVER 1	0.0	0.1	0.1	Badge worn chest level, picture taking
Notes: Initially FDG injection would not pass through the catheter; typically, a catheter will be flushed with saline pre-injection to make sure it is not blocked. In this instance though, the catheter was not tested and had to be repositioned. More time was spent injecting the dose than usual. Post PET, 2030 to remove catheters, change hoses, and move to transport cart. 4:40 to transport to recovery, 5:50 to recover and move to the kennel, 4:40 assessment of patient					

Date:	8-Jun-11	Scan number:	24		
Patient:	D12	Isotope:	FDG-18	End Study Survey:	8.6 mR/h
Species:	Canine	Admin Activity:	3.24 mCi	End St Surv Time:	12:45
Breed:	Golden Lab	Injection Time:	1045	Release Survey:	1.97 mR/h
Mass:	26.4 kg	PET Bed Time:	0:28:18	Release Surv Time:	1630

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	0.0	0.6	0.6	Aligned/prep dog leg for biopsy, removing rear catheters, prep for transport
NUCMED 2	NUCMED 2	0.0	0.9	0.9	Dose check in, calibration, transport, injection (0.5 after injection), prep for transport to recovery, recovery
VET 1	VET 1	0.0	----------	----------	Out
----------	ANESTHESIA	0.0	0.3	0.3	
OBSERVER 1	OBSERVER 1	0.0	0.1	0.1	Badge worn chest level, note and picture taking
Notes: CT guided biopsy conducted for this dog. Two vets came in post-PET scan to participate (not badged). Vet 1: shave, clean, biopsy, aspirate. Vet 2: observe and hold slides for aspiration. Third vet came in after aspiration to help out. 7 minutes to set up/reposition for biopsy (NM3) 6 min to shave and clean, 4 min to align, 6 min to aspirate, 9 min to clean up (NM2/NM3/Vet 3), 4 min move to cart (NM2/NM3/Vet 3), 3.5 min to recovery (NM2/Vet 3/Anes), 9 min recovery (NM2/Anes), 3 min observe (NM2/Anes). Biopsy done post PET scan because there is concern that doing the biopsy before injection may change the site uptake (b/c resultant bleeding, etc)					

Date:	9-Jun-11	Scan number:	25		
Patient:	D13	Isotope:	FDG-18	End Study Survey:	17.7 mR/h
Species:	Canine	Admin Activity:	6.1 mCi	End St Surv Time:	12:36
Breed:	Rottweiler	Injection Time:	1100	Release Survey:	
Mass:	35.9 kg	PET Bed Time:	0:26:19	Release Surv Time:	

OSL Label	EPD Label	EPD Initial Read (mrem)	EPD Final Read (mrem)	Dose (mrem)	Comments
NUCMED 3	NUCMED 3	0.0	2	2.0	Injection (to catheter extension); unhook post PET
NUCMED 2	NUCMED 2	0.0	0.8	0.8	Dose check in, calibration, transport, (0.3 at this point) prep for transport to recovery, recovery
VET 1	VET 1	0.0	----------	----------	Out
----------	ANESTHESIA	0.0	0.9	0.9	Took temp of dog in recovery
OBSERVER 1	OBSERVER 1	0.0	0.2	0.2	Badge worn chest level, note and picture taking
Notes: At 1240 OBS at 0.1 mrem, NM2 at 0.6 mrem, ANES at 0.4 mrem. 7 min to removing catheters (NM3), plus 5 min addt prep for transport (NM2/3), 3 min move to cart (NM2/NM3/ANES), 5 min prep for moving (NM2/NM3/ANES), 3 min to recovery (NM2/NM3/Anes), 8 min recovery (NM2/NM3/Anes), 8 min observe/assess (NM2/Anes).					

APPENDIX F

RAW DATA USED IN ANALYSIS[5] WITH MINITAB SUMMARY

[5] Dogs and cats administered ^{18}F-FDG only, no repeat scans

RAW DATA USED IN ANALYSIS

Job:	1	Tech 1
	2	Tech 2
	3	Tech 3
	4	Anesthesia
	5	Observer
Injection:	0	No
	1	Yes
Badge Location:	0	Waist
	1	Chest
Species:	0	Cat
	1	Dog

Scan number	Species	Admin activity (MBq)	Dose (uSv)	Mass (kg)	Badge Location	Injection	Job
1	0	25.2	9	4.2	1	0	1
1	0	25.2	1	4.2	0	1	2
1	0	25.2	0	4.2	0	0	5
3	0	30.1	6	4.8	1	1	1
3	0	30.1	4	4.8	1	0	4
3	0	30.1	0	4.8	0	0	5
4	0	20.2	2	3.5	1	0	1
4	0	20.2	2	3.5	0	1	2
5	1	384.4	21	58	1	0	1
5	1	384.4	10	58	0	1	2
9	0	24.8	3	2.77	1	0	1
9	0	24.8	2	2.77	0	1	2
9	0	24.8	10	2.77	1	0	4
10	1	378.8	22	61	1	1	1
10	1	378.8	13	61	0	0	2
10	1	378.8	7	61	0	0	3
10	1	378.8	22	61	1	0	4
11	1	154.8	13	25.5	1	1	1
11	1	154.8	4	25.5	0	0	3
11	1	154.8	6	25.5	1	0	4
11	1	154.8	0	25.5	0	0	5
13	0	35.3	7	4.7	1	0	1

13	0	35.3	7	4.7	0	1	2
13	0	35.3	1	4.7	0	0	4
14	0	34.2	3	4.26	1	1	1
14	0	34.2	2	4.26	0	0	2
14	0	34.2	2	4.26	0	0	3
14	0	34.2	3	4.26	1	0	4
16	1	139.5	8	26.5	1	0	1
16	1	139.5	15	26.5	0	1	2
16	1	139.5	10	26.5	0	0	3
16	1	139.5	21	26.5	1	0	4
17	1	133.6	14	25	1	0	1
17	1	133.6	9	25	0	1	2
17	1	133.6	5	25	0	0	3
17	1	133.6	7	25	1	0	4
18	1	147.3	12	28.5	1	0	1
18	1	147.3	13	28.5	0	1	2
18	1	147.3	6	28.5	1	0	4
18	1	147.3	0	28.5	0	0	5
19	1	24.1	3	4	1	1	1
19	1	24.1	1	4	0	0	2
19	1	24.1	5	4	1	0	4
20	1	246.1	21	53.3	1	1	1
20	1	246.1	22	53.3	0	0	2
20	1	246.1	7	53.3	0	0	4
23	1	196.1	30	25.5	1	1	1
23	1	196.1	5	25.5	0	0	3
23	1	196.1	6	25.5	1	0	4
23	1	196.1	1	25.5	1	0	5
24	1	119.9	6	26.4	1	0	1
24	1	119.9	10	26.4	0	1	2
24	1	119.9	1	26.4	0	0	3
24	1	119.9	3	26.4	1	0	4
24	1	119.9	1	26.4	1	0	5
25	1	225.7	20	35.9	1	1	1
25	1	225.7	8	35.9	0	0	2
25	1	225.7	9	35.9	1	0	4
25	1	225.7	2	35.9	1	0	5

MINITAB SUMMARY

Cat model

Regression Analysis: uSv versus badge

```
The regression equation is
uSv = 1.89 + 3.33 badge


Predictor    Coef  SE Coef     T      P
Constant   1.8889   0.8435  2.24  0.040
badge       3.333    1.193  2.79  0.013


S = 2.53037   R-Sq = 32.8%   R-Sq(adj) = 28.6%


Analysis of Variance

Source          DF       SS      MS     F      P
Regression       1   50.000  50.000  7.81  0.013
Residual Error  16  102.444   6.403
Total           17  152.444
```

Dog model

Regression Analysis: uSv versus job, MBq, badge

```
The regression equation is
uSv = 8.62 - 2.64 job + 0.0337 MBq + 3.59 badge


Predictor      Coef   SE Coef      T      P
Constant      8.619     2.799   3.08  0.004
job         -2.6392    0.6001  -4.40  0.000
MBq        0.033662  0.008777   3.84  0.000
badge         3.592     1.682   2.14  0.039


S = 5.33543   R-Sq = 53.4%   R-Sq(adj) = 49.7%


Analysis of Variance

Source          DF       SS      MS      F      P
Regression       3  1208.78  402.93  14.15  0.000
Residual Error  37  1053.27   28.47
Total           40  2262.05


Source  DF  Seq SS
job      1  683.75
MBq      1  395.23
badge    1  129.79
```

APPENDIX G

IRB CONSENT AND PARTICIPANT INFORMATION FORMS

Consent to Participate in a Research Study
Colorado State University

TITLE OF STUDY: Occupational Radiation Exposure to Persons Involved in Veterinary Positron Emission Tomography (PET) Studies

PRINCIPAL INVESTIGATOR: Thomas Johnson, Department of Environmental and Radiological Health Sciences, PhD, (970) 491-0563

CO-PRINCIPAL INVESTIGATOR: Nicole Martinez, Department of Environmental and Radiological Health Sciences, Health Physics Master's Candidate, n.martinez@colostate.edu

WHY AM I BEING INVITED TO TAKE PART IN THIS RESEARCH? All personnel involved with PET scan procedures at the Veterinary Teaching Hospital are being invited to participate in this research. This includes technologists, anesthesiology staff as applicable, and students or veterinarians observing the procedures. The study hinges on personnel conducting themselves as they normally would during his or her work day.

WHO IS DOING THE STUDY? Dr. Tom Johnson, CHP is the principal investigator, and Nicole Martinez is the co-principal investigator. Additional persons who will likely be involved in doing this study are Dr. Debbie Gibbons and Dr. Stewart Ryan, who are on Nicole's committee, as well as CSU's Radiation Safety Officer, Jim Abraham.

WHAT IS THE PURPOSE OF THIS STUDY? We would like to compare the radiation exposures of veterinary technologists using PET scanners to those of human technologists utilizing PET scanners and also to area monitoring calculations done by the RCO**.**

WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST? Our study will take place at Colorado State University's James L. Voss Veterinary Teaching Hospital. The duration of the study will be dependent on the number of ^{18}F and NaF studies completed. Since the number of studies is dependent on clinical load, and we do not want to interfere with any of the work processes, it is anticipated that you will be monitored for less than six months.

WHAT WILL I BE ASKED TO DO? *Y*ou will be asked to wear an additional whole body badge, an additional ring badge, and if applicable, an electronic pocket dosimeter for specific PET studies and remove them for all other duties. The dosimeters used for our study will be in addition to those used for legal purposes. You will also be asked to describe your job duties and responsibilities and record information about the animal PET patients/studies conducted.

ARE THERE REASONS WHY I SHOULD NOT TAKE PART IN THIS STUDY? The only reason to not take part in this study would be if you would not be involved with PET apart from participating in this study or you did not feel comfortable finding out the specific radiation dose associated with a procedure.

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

- There are no known risks to participation in the study, other than the risks inherent in your normal, everyday job.
- It is not possible to identify all potential risks in research procedures, but the researcher(s) have taken reasonable safeguards to minimize any known and potential, but unknown, risks.

ARE THERE ANY BENEFITS FROM TAKING PART IN THIS STUDY? If radiation doses to the subjects are unusual, then the Radiation Control Office may choose to implement specific procedures to help minimize radiation doses. The veterinary community as a whole will benefit from knowledge of the radiation doses associated with PET procedures.

DO I HAVE TO TAKE PART IN THE STUDY? Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled.

WHO WILL SEE THE INFORMATION THAT I GIVE? We will keep private all research records that identify you, to the extent allowed by law.

Your information will be combined with information from other people taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. You will not be identified in these written materials. We may publish the results of this study; however, we will keep your name and other identifying information private.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. For example, your name will be kept separate from your research records and these two things will be stored in different places under lock.

WILL I RECEIVE ANY COMPENSATION FOR TAKING PART IN THIS STUDY? You will not receive compensation for taking part in this study.

WHAT IF I HAVE QUESTIONS?
Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions about the study, you can contact the investigator, Nicole Martinez at (843) 412-9041. If you have any questions about your rights as a volunteer in this research, contact Janell Barker, Human Research Administrator at 970-491-1655. We will give you a copy of this consent form to take with you.

This consent form was approved by the CSU Institutional Review Board for the protection of human subjects in research on 28 October 2010.

WHAT ELSE DO I NEED TO KNOW? This study hinges on participants performing their job as he or she normally would while wearing the additional dosimetry.

Your signature acknowledges that you have read the information stated and willingly sign this consent form. Your signature also acknowledges that you have received, on the date signed, a copy of this document containing two pages.

_____ _____
Signature of person agreeing to take part in the study Date

_____
Printed name of person agreeing to take part in the study

_____ _____
Name of person providing information to participant Date

_____
Signature of Research Staff

Occupational Radiation Exposure to Persons Involved in Veterinary Positron Emission Tomography (PET) Studies

Participant Information Form

Job Title/Position:

Years Experience in Related Field:

Time in Current Position:

Job Description and Responsibilities:

Please comment on your involvement with PET studies, if not addressed above:

Any additional comments:

APPENDIX H

LOG SHEETS

ACTIVITY RECORD SHEET

Date: Patient:

OSL Dosimeter Label	EPD Label	EPD Initial Reading	EPD Final Reading	Staff Activity	Comments

Date: Patient:

OSL Dosimeter Label	EPD Label	EPD Initial Reading	EPD Final Reading	Staff Activity	Comments

PET/CT PATIENT LOG

DATE:

MRN: **NAME:**

DOB: **Gender:** **Species:** **Breed:** **Weight:**

Diagnosis: **Body Location(s) Affected:**

Blood Glucose (for FDG):

Isotope/Compound: **Calibrated Dose & Time:**

Measured Dose: **Residual:** **Injected Dose:**

Isotope Injection Time: **Isotope Injection Route:**

Contrast Media: **Dose:** **Route/Location:**

Contrast Administration Time 1: **Contrast Administration Time 2:**

Separate Positioning and Post-Contrast Study For XRT? Yes/No (Yes = ldCT 1 has residual contrast.)

ldCT Acquisition Time # 1 (Traditional Pre-Contrast)1:

ldCT Acquisition Time # 2(Traditional Post-Contrast Pass):

ldCT Acquisition Time #3 (Delayed Post-Contrast Pass Just Prior To PET Acquisition):

PET Acquisition Start Time: **Bed Time:** **Total Time:**

End Study Survey: **Time:** **mR/hr**

IV Catheter Residual:

Subsequent Surveys:

Time: **mR/hr:** **Time:** **mR/hr:** **Time:** **mR/hr:**

Cleared By: **Time:** **mR/hr:**

Patient Injection and Release Log
Nuclear Medicine
CSUVTH

Date	Patient	Case #	Acc#	Scan	Inj Time, Dose, Route, Site, Isotope	Release			Ion Chamber			Initials
						Date	Time	mR/h	1651	3802	3459	

APPENDIX I

DOSE ESTIMATES FOR VETERINARY PROTOCOL COMPARISON

Gamma ray constant, Γ:	0.000184 mSv m^2 MBq^{-1} h^{-1}
Activity, *A*:	155.8 MBq
Distance between sources, y_1:	0.35 m
Linear attenuation coefficient, μ:	0.097 cm^{-1}
Half life, $t_{1/2}$:	109.7 min
Decay constant, λ:	0.379 h^{-1}
Uptake time:	60 min
Scan time:	30 min

Primary Nuclear Medicine Technologist, CSU Protocol: 21.8 μSv

(1) Injection

Time: 1 min
Distance: 0.25 m
Dose: 7.63 μSv

(2) Catheter removal; end position

Initial activity per source: 29.4 MBq (after 60 min uptake and 30 min scan)
Distance from patient: 0.25 m
Time spent: 7 min
Final activity per source: 28.2 MBq

Source	y_2 (m)	*B*	*H* (μSv)
Near end	0.10	2.3	4.48
Middle	0.45	14.8	0.24
Far end	0.80	39.5	0.01
		Total dose:	4.73

(3) Additional preparation, transport, recovery; side position

Action	*t* (min)	A_{final} (MBq)	x_1 (m)	x_2 (m)	B_x	H_x (μSv)	h_1 (m)	h_2 (m)	B_h	H_h (μSv)	*H* (μSv)
Add prep	8	26.78	0.1	0.5	2.34	1.66	0.12	0.58	2.64	1.20	4.06
Move pt	0.5	26.70	0.1	0.1	2.34	0.91	0.20	0.20	4.72	0.17	1.24
Final prep	5	25.87	0.1	1	2.34	0.29	0.10	1.05	2.43	0.27	0.83
Transport	3	25.38	0.1	1	2.34	0.17	0.10	1.05	2.43	0.16	0.48
Recovery	5	24.59	0.1	0.5	2.34	0.94	0.12	0.58	2.64	0.68	2.31
										Total dose:	8.92

(4) Observation and assessment; end position

Distance from patient: 0.5 m
Time spent: 3 min

Source	y_2 (m)	*B*	*H* (μSv)
Near end	0.10	2.3	0.55
Middle	0.45	14.8	0.05
Far end	0.80	39.5	0.00
		Total dose:	0.60

Anesthetist, CSU Protocol: 9.8 µSv

(1) Injection

Time: 1 min
Distance: N/A
Dose: 0.0 µSv

(2) Catheter removal; end position

Initial activity per source: 29.4 MBq (after 60 min uptake and 30 min scan)
Distance from patient: N/A
Time elapsed: 7 min
Final activity per source: 28.2 MBq
Dose: 0.0 µSv

(3) Additional preparation, transport, recovery; side position

Action	t (min)	A_{final} (MBq)	x_1 (m)	x_2 (m)	B_x	H_x (µSv)	h_1 (m)	h_2 (m)	B_h	H_h (µSv)	H (µSv)
Add prep	8	26.78	0.1	0.5	2.34	1.66	0.12	0.58	2.64	1.20	4.06
Move pt	0.5	26.70	0.1	0.1	2.34	0.91	0.20	0.20	4.72	0.17	1.24
Final prep	5	25.87	0.1	1	2.34	0.29	0.10	1.05	2.43	0.27	0.83
Transport	3	25.38	0.1	1	2.34	0.17	0.10	1.05	2.43	0.16	0.48
Recovery	5	24.59	0.1	0.5	2.34	0.94	0.12	0.58	2.64	0.68	2.31
									Total dose:		8.92

(4) Observation and assessment; end position

Distance from patient: 0.5 m
Time spent: 5 min

Source	y_2 (m)	B	H (µSv)
Near end	0.10	2.3	0.92
Middle	0.45	14.8	0.08
Far end	0.80	39.5	0.00
		Total dose:	1.00

Primary Nuclear Medicine Technologist, Alternate Protocol: 44.6 µSv

(1) Injection

Time: 1 min
Distance: 0.25 m
Dose: 7.63 µSv

(2) Anesthesia and positioning; side position

Initial activity per source: 35.6 MBq (after 60 min uptake)
Final activity per source: 29.5 MBq

Action	t (min)	A_{final} (MBq)	x_1 (m)	x_2 (m)	B_x	H_x (µSv)	h_1 (m)	h_2 (m)	B_h	H_h (µSv)	H (µSv)
Anesthesia	20	31.37	0.1	0.5	2.34	5.04	0.12	0.58	2.64	3.66	12.35

Positioning	10	29.45	0.1	0.25	2.34	6.74	0.14	0.35	3.19	3.08	12.89
										Total dose:	25.24

(3) Catheter removal; end position

Initial activity per source: 24.4 MBq (after 30 min scan)
Distance from patient: 0.25 m
Time spent: 7 min
Final activity per source: 23.3 MBq

Source	y_2 (m)	B	H (μSv)
Near end	0.10	2.3	3.71
Middle	0.45	14.8	0.20
Far end	0.80	39.5	0.01
		Total dose:	3.91

(4) Additional preparation, transport, recovery; side position

Action	t (min)	A_{final} (MBq)	x_1 (m)	x_2 (m)	B_x	H_x (μSv)	h_1 (m)	h_2 (m)	B_h	H_h (μSv)	H (μSv)
Add prep	8	22.16	0.1	0.5	2.34	1.37	0.12	0.58	2.64	0.99	3.36
Move pt	0.5	22.09	0.1	0.1	2.34	0.75	0.20	0.20	4.72	0.14	1.03
Final prep	5	21.40	0.1	1	2.34	0.24	0.10	1.05	2.43	0.22	0.68
Transport	3	21.00	0.1	1	2.34	0.14	0.10	1.05	2.43	0.13	0.40
Recovery	5	20.35	0.1	0.5	2.34	0.78	0.12	0.58	2.64	0.56	1.91
										Total dose:	7.38

(5) Observation and assessment; end position

Distance from patient: 0.5 m
Time spent: 3 min

Source	y_2 (m)	B	H (μSv)
Near end	0.10	2.3	0.46
Middle	0.45	14.8	0.04
Far end	0.80	39.5	0.00
		Total dose:	0.50

Anesthetist, Alternate Protocol: 33.4 μSv

---

(1) Injection

Time: 1 min
Distance: N/A
Dose: 0.0 μSv

(2) Anesthesia and positioning; side position

Initial activity per source: 35.6 MBq (after 60 min uptake)
Final activity per source: 29.5 MBq

Action	t (min)	A_{final} (MBq)	x_1 (m)	x_2 (m)	B_x	H_x (μSv)	h_1 (m)	h_2 (m)	B_h	H_h (μSv)	H (μSv)

Anesthesia	20	31.37	0.1	0.5	2.34	5.04	0.12	0.58	2.64	3.66	12.35
Positioning	10	29.45	0.1	0.25	2.34	6.74	0.14	0.35	3.19	3.08	12.89
										Total dose:	25.24

(3) Catheter removal; end position

Initial activity per source: 24.4 MBq (after 30 min scan)
Distance from patient: N/A
Time elapsed: 7 min
Final activity per source: 23.3 MBq
Dose: 0.00.0 µSv

(4) Additional preparation, transport, recovery; side position

Action	t (min)	A_{final} (MBq)	x_1 (m)	x_2 (m)	B_x	H_x (µSv)	h_1 (m)	h_2 (m)	B_h	H_h (µSv)	H (µSv)
Add prep	8	22.16	0.1	0.5	2.34	1.37	0.12	0.58	2.64	0.99	3.36
Move pt	0.5	22.09	0.1	0.1	2.34	0.75	0.20	0.20	4.72	0.14	1.03
Final prep	5	21.40	0.1	1	2.34	0.24	0.10	1.05	2.43	0.22	0.68
Transport	3	21.00	0.1	1	2.34	0.14	0.10	1.05	2.43	0.13	0.40
Recovery	5	20.35	0.1	0.5	2.34	0.78	0.12	0.58	2.64	0.56	1.91
										Total dose:	7.38

(5) Observation and assessment; end position

Distance from patient: 0.5 m
Time spent: 5 min

Source	y_2 (m)	B	H (µSv)
Near end	0.10	2.3	0.76
Middle	0.45	14.8	0.06
Far end	0.80	39.5	0.00
		Total dose:	0.82

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GLOSSARY[6]

-A-

Absorbed dose (D): The energy imparted per unit mass by ionizing radiation to matter at a specific point. The SI unit of absorbed dose is joule per kilogram (J/kg). The special name for this unit is gray (Gy). The previously used special unit of absorbed dose, the rad, was defined to be an energy absorption of 100 erg/g. Thus, 1 Gy = 100 rad [46].

Activity: the number of spontaneous nuclear transformations occurring in an amount of radionuclide in a particular energy state in a given time interval. The unit of activity in the SI system is the reciprocal second (s^{-1}) (i.e., one nuclear transformation per second), with the special name becquerel (Bq). The special unit previously used was curie (Ci); $1\ \text{Ci} = 3.7 \times 10^{10}\ \text{Bq}$ [70].

Administered activity: The amount, in terms of activity, of a radionuclide given to a patient during a diagnostic or therapeutic procedure [70].

Ambient dose equivalent, H*(d): The dose equivalent that would be produced by the corresponding aligned and expanded field in the ICRU sphere at a depth d on the radius opposing the direction of the aligned field [80].

Annihilate: (of a particle and its antiparticle) to vanish or cease to exist by coming together and changing into other forms of energy (as photons) [81].

Annual dose: The dose due to external exposure in a year plus the committed dose from intakes of radionuclides in that year [80].

As low as reasonably achievable: A principle of radiation protection philosophy that requires that exposures to ionizing radiation be kept as low as reasonably achievable, economic and societal factors being taken into account. The protection from radiation exposure is as low as reasonably achievable when the expenditure of further resources would be unwarranted by the reduction in exposure that would be achieved [70].

[6]Definitions are verbatim from indicated references.

Assay: analysis to determine the presence, absence, or quantity of one or more components [81].

Attenuation: The reduction in intensity of radiation passing through matter due to processes such as absorption and scattering [80].

-B-

Background: The radiation in the natural environment, including cosmic rays and radiation from the naturally radioactive elements, both outside and inside the bodies of humans and animals. Also called natural radiation. The term also may mean radiation that is unrelated to a specific experiment [46].

Becquerel (Bq): The SI unit of activity, equal to one transformation per second. Supersedes the non-SI unit curie (Ci). $1\ \text{Bq} = 27\ \text{pCi}$ approximately. $1\ \text{Ci} = 3.7 \times 10^{10}\ \text{Bq}$ [80].

Biopsy: The removal of a small portion of a tumor to allow a pathologist to examine it under a microscope and provide a diagnosis of tumor type [46].

Bone scanning: Conventional whole body scan utilizing the adsorption of radiolabeled diphosphonates to hydroxyapatite crystals in the bones. Used for staging of bone involvement in cancer patients [5].

-C-

Calibration: A measurement of, or adjustment to, an instrument, component or system to ensure that its accuracy or response is acceptable [80].

Cancer: A malignant tumor of potentially unlimited growth, capable of invading surrounding tissue or spreading to other parts of the body by metastasis [69].

Carcinoma: A malignant growth made up of epithelial cells tending to infiltrate the surrounding tissues and giving rise to metastases [5].

Catheter: A tubular medical device for insertion into canals, vessels, passageways, or body cavities usually to permit injection or withdrawal of fluids or to keep a passage open [81].

Coincidence: A feature of protection system design such that two or more overlapping or simultaneous output signals from several channels are necessary in order to produce a protective action signal by the logic [80].

Coincidence imaging: Based on the near simultaneous detection of two events such as the annihilation photons by two detectors. Typically the events fall within 0.5 to 20

nanoseconds of each other. The coincidence event helps to position the location of the annihilation event during the process of image reconstruction [5].

Compton effect: Scattering of x-rays resulting in ionization and loss of energy. The energy lost by the photon is given to the ejected electron as kinetic energy [46].

Computed tomography (CT): An imaging procedure that uses multiple x-ray transmission measurements and a computer program to generate tomographic images of the patient [70].

Conduction band: The range of permissible energy values which an electron in a solid material can have that allows the electron to dissociate from a particular atom and become a free charge carrier in the material [81].

Cosmic rays: Radiation of many sorts, but mostly protons and heavier atomic nuclei with very high energies originating outside the earth's atmosphere. Cosmic radiation is part of the natural background radiation. Some cosmic rays are more energetic than any human-made forms of radiation [46].

Consumer product: Device such as a smoke detector, luminous dial, or ion generating tube that contains a small amount of radioactive substances. More generally, an item readily available to members of the public without any requirements being imposed related to any radiation source therein [80].

Curie (Ci): Unit of activity, equal to 3.7×10^{10} Bq (exactly). Superseded by the Becquerel (Bq). Originally, the activity of a gram of radium [80].

-D-

Deterministic effect: A health effect of radiation for which generally a threshold level of dose exists above which the severity of the effect is greater for a higher dose. Examples of deterministic effects include erythema and acute radiation syndrome [80].

Differential uptake ratio: Ratio of glucose metabolic activity within a tumor to the glucose metabolic activity in the non-affected site [5].

Diode: An electronic device that has two electrodes or terminals and is used especially as a rectifier [81].

Dose: A measure of the energy deposited by radiation in a target [80]. A general term used when the context is not specific to a particular dose quantity [70].

Dose assessment: Assessment of the dose(s) to an individual or group of people [80].

Dose limit: The value of the effective dose or the equivalent dose to individuals form planned exposure situations that shall not be exceeded [49].

Dosimeter: Dose measuring device [70].

Dosimetry: The science or technique of determining radiation dose [70].

Dysphoria: A state of feeling unwell or unhappy [81].

-E-

Effective dose: The radiation dose allowing for the fact that some types of radiation are more damaging than others, and some parts of the body are more sensitive to radiation than others. It is defined as the sum over specified tissues of the products of the equivalent dose in a tissue and the weighting factor for that tissue [46]. Values of effective dose from any type(s) of radiation and mode(s) of exposure can be compared directly [80].

Electron: Subatomic charged particle. Negatively charged electrons are parts of stable atoms. Both negatively and positively charged electrons (positrons) may be expelled from the radioactive atom when it disintegrates [70].

Electron volt (eV): A special unit of energy: 1 eV = 1.6×10^{-19} J = 1.6×10^{-12} erg; 1 eV is equivalent to the energy gained by an electron in passing through a potential difference of 1 V [69].

Equivalent dose: A quantity used for radiation protection purposes that takes into account the different probability of effects that occur with the same absorbed dose delivered by radiations with different radiation weighting factor values. It is defined as the product of the average absorbed dose in a specified organ or tissue and the radiation weighting factor values. If dose is in grays, equivalent dose is in sieverts. [46] Equivalent dose is a measure of the dose to a tissue or organ designed to reflect the amount of harm caused. Values of equivalent dose to a specified tissue from any type(s) of radiation can be compared directly [80].

Exempt: Excluded from regulation as hazardous or radioactive material [70].

Exposure: The act or condition of being subject to irradiation. Dose is a measure of the effects of exposure. [80] Exposure is also a defined ionizing radiation quantity [70]: A measure of the quantity of x- or γ-radiation based on its ability to ionize the air through which is passes. The SI unit of exposure is coulomb per kilogram (C/kg). The previously used special unit of exposure was the röntgen (R) [46].

External exposure: Exposure to radiation from a source outside the body [80].

-F-

Fluorine-18 labeled fluorodeoxyglucose: A tracer, 2-deoxy-2-[F-18]fluoro-D-glucose (FDG) for PET imaging. FDG is a derivative of glucose, the predominant energy source for most cells of the body and for tumors. After intracellular phosphorylation via hexokinase, FDG-6-phosphate is not significantly metabolized and remains trapped in the tumor cells [5].

Flush: to pour liquid over or through; especially: to cleanse or wash out with or as if with a rush of liquid [81].

Free radical: An especially reactive atom or group of atoms that has one or more unpaired electrons; especially one that is produced in the body by natural biological processes or introduced from an outside source and that can damage cells, proteins, and NDA by altering their chemical structure [81].

-G-

Gamma rays: Electromagnetic radiation emitted by the atomic nucleus. Gamma rays have high penetrating ability compared with alpha and beta particles [70].

Glycolysis: the enzymatic breakdown of a carbohydrate (as glucose) by way of phosphate derivatives with the production of pyruvic or lactic acid and energy stored in high-energy phosphate bonds of ATP [81].

Gray (Gy): The special name for then SI unit of absorbed dose, kerma, and specific energy imparted equal to 1 J/kg. The previous unit of absorbed dose, rad, has been replaced by the gray. One gray equals 100 rad [46].

Ground state: The state of a nucleus, an atom, or a molecule at its lowest (normal) energy level [46].

-H-

Half-life ($T_{1/2}$): The time taken for the activity of a radionuclide to decay to half its initial value [46].

-I-

ICRP: (International Commission on Radiological Protection) An independent international organization that provides recommendations and guidance on protection against ionizing radiation [69].

Individual monitoring: Monitoring using measurements by equipment worn by individual workers, or measurements of quantities of radioactive material in or on their bodies [80].

International System of Quantities and Units [Systeme Internationale (SI)]: The International System of Quantities and Units as defined by the General Conference of Weights and Measures in 1960 and periodically revised since. These units are generally based on the meter/kilogram/second units, with special quantities for radiation including the Becquerel, gray, and sievert [70].

Ion pair: A closely associated positive ion and negative ion (usually an electron) having charges of the same magnitude and formed from a neutral atom or molecule by radiation [46].

Ionization: The process of adding one or more electrons to, or removing one or more electrons from, atoms or molecules, thereby creating ions. High temperatures, electrical discharges, or nuclear radiations can cause ionization [46].

Ionizing radiation: For the purposes of radiation protection, radiation capable of producing ion pairs in biological material(s) [80].

Isotropic: Exhibiting properties with the same values when measured along axes in all directions [81].

-J-

Justification: The process of determining whether either (1) a planned activity involved radiation is overall, beneficial, i.e. whether the benefits to individuals and to society from introducing or continuing the activity outweighs the harm (including radiation detriment) resulting from the activity; or (2) a proposed remedial action in an emergency or existing exposure situation is likely, overall, to be beneficial, i.e. whether the benefits to individuals and to society (including the reduction in radiation detriment) from introducing or continuing the remedial action outweigh its cost and any harm or damage it causes [49].

-K-

-L-

Limit: The value of a quantity used in certain specified activities or circumstances that must not be exceeded [80].

Linear-no threshold (LNT) hypothesis: The hypothesis that the risk of stochastic effects is directly proportional to the dose for all levels of dose and dose rate (below those at which deterministic effects occur). I.e. that any non-zero dose implies a non-zero risk of stochastic effects [80].

-M-

Magnetic resonance imaging: Commonly referred to as MRI and provides images of the body from the magnetic properties of hydrogen [5].

Metabolism: The sum of all the physical and chemical processes by which living organized substance is produced and maintained (anabolism), and also the transformation by which energy is made available for the uses of the organism (catabolism) [5].

Metastasis: The ability of cancerous cells to invade surrounding tissues, enter the circulatory system, and establish new malignancies in body tissues distant from the site of the original tumor [46].

-N-

Naturally occurring radioactive material (NORM): Materials found in the natural environment containing inherent concentrations of radionuclides. Examples include materials containing long-lived radioactive isotopes of the elements uranium, thorium, and potassium, and of their decay products (e.g., the elements radium and radon) that have always been present in Earth's crust [70].

NCRP: (National Council on Radiation Protection and Measurements) U.S. Council commissioned to formulate and disseminate information, guidance, and recommendations on radiation protection and measurements [69].

Neutrino (ν): An electrically neutral elementary particle with a negligible mass. It interacts very weakly with matter and hence is difficult to detect. It is produced in many nuclear reactions and has high penetrating power. Neutrinos from the sun usually pass right through the earth [46].

Neutron: An uncharged elementary particle having a mass slightly greater than a proton that is usually stable when within the nucleus but is unstable otherwise [70].

-O-

Occupational exposures: Radiation exposures to individuals that are incurred in the workplace as a result of situations that can reasonably be regarded as being the responsibility of management (radiation exposures associated with medical diagnosis of or treatment for the individual are excluded) [70].

Oncology: The study of cancer [46].

Operational quantities: Quantities used in practical applications for monitoring and investigating situations involving external exposure. They are defined for measurements and assessment of doses in the body. In internal dosimetry, no operational dose quantities have been defined which directly provide an assessment of equivalent or effective dose. Different methods are applied to assess the

equivalent or effective dose due to radionuclides in the human body. They are mostly based on various activity measurements and the application of biokinetic models (computational models) [49].

Optically-stimulated luminescent dosimeter: A dosimeter containing a crystalline solid for measuring radiation dose. When sued for personal dosimetry, filters (absorbers) are included to help characterize the types of radiation encountered. When irradiated with intense light, optically-stimulated luminescent crystals that have been exposed to ionizing radiation give off light proportional to the energy they received from the radiation [70].

Optimization of protection (and safety): The process of determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, as low as reasonably achievable, economic and societal factors being taken into account [49].

Organ dose: The mean absorbed dose in a specified tissue or organ of the human body [80].

-P-

Personal dose equivalent Hp(d): An operational quantity: the dose equivalent in soft tissue at an appropriate depth, d, below a specified point on the human body. The unit of personal dose equivalent is joule per kilogram and its special name is sievert. The specified point is usually given by the position where the individual's dosimeter is worn [49].

Photoelectric effect: Absorption of an x-ray by ionization [46].

Photon: Quantum of electromagnetic radiation, having no charge or mass, that exhibits both particle and wave behavior, such as gamma or x ray [70].

Positron: An antiparticle equal in mass to an electron and having an equal but positive charge [70].

Positron emission tomography: Imaging technique that uses coincidence detection and molecules labeled with positron emitting isotopes, such as glucose labeled with fluorine-18, to prove molecular processes of biology in vivo [5].

Practice: Any human activity that introduces additional sources of exposure or additional exposure pathways, or extends exposure to additional people, or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed [80].

Principles of protection: A set of principles that apply equally to all controllable exposure situations: the principle of justification, the principle of optimization of protection, and the principle of application of limits on maximum doses in planned situations [49].

Procedure: A series of specified actions conducted in a certain order or manner [80].

Protection quantities: Dose quantities that the Commission has developed for radiological protection that allow quantification of the extent of exposure of the human body to ionizing radiation from both whole and partial body external irradiation and from intakes of radionuclides [49].

Proton: An elementary nuclear particle with a positive charge equal to the charge of an electron and a mass equal to the nucleus of the ^{1}H atom [70].

-Q-

-R-

Rad: A special unit of absorbed dose, now replaced by the SI unit gray. 1 rad = 0.01 Gy = 100 erg/g [69].

Radiation: Energy emitted in the form of waves or particles by radioactive atoms as a result of radioactive decay or produced by artificial means, such as X-ray generators [69].

Radiation protection: The protection of people from the effects of exposure to ionizing radiation, and the means for achieving this [80].

Radiation protection program: Systematic arrangements which are aimed at providing adequate consideration of radiation protection measures [80].

Radiation weighting factor, w_R: A number by which the absorbed dose in a tissue or organ is multiplied to reflect the relative biological effectiveness of the radiation in inducing stochastic effects at low doses, the result being the equivalent dose [80].

Radioactive decay: The spontaneous transformation of one nuclide into a different nuclide or into a different energy state of the same nuclide. The process results in a decrease, with time, of the number of original radioactive atoms in a sample. Decay generally involves the emission from the nucleus of alpha particles, beta particles, or gamma rays [70].

Radioactivity: The phenomenon whereby atoms undergo spontaneous random disintegration, usually accompanied by the emission of radiation [80].

Radioisotope: A radioactive atomic species of an element with the same atomic number and usually identical chemical properties [69].

Radiology: That branch of healing arts and sciences that deals with the use of images in the diagnosis and treatment of disease [70].

Radionuclide: A radioactive species of an atom characterized by the constitution of its nucleus [69].

Radiopharmaceutical: A radioactive substance administered to a patient for diagnostic or therapeutic nuclear-medicine procedures. A radiopharmaceutical contains two parts, the radionuclide and the pharmaceutical (e.g., ^{99m}Tc DTPA). In some cases, the two are one (e.g., ^{133}Xe gas) [70].

Relative biological effectiveness (RBE): A factor used to compare the biological effectiveness of absorbed doses from different types of ionizing radiation, determined experimentally. Relative biological effectiveness is the ratio of the absorbed dose of reference radiation (usually taken as 250 kVp x rays) to the absorbed dose of the radiation in question required to produce the same level of an identical biological effect in a particular experimental organism or tissue [70].

Rem: The special unit previously used for the quantities equivalent dose and effective dose; 100 rem = 1 Sv [70].

Risk: A chance of injury, loss, or detriment; a measure of the deleterious effects that may be expected as the result of an action or inaction [69].

Röntgen (R): A unit of exposure to ionizing radiation named after Wilhelm Röntgen, the German scientist who discovered x-rays in 1895. It is that amount of γ- or x-rays required to produce ions carrying one electrostatic unit of electrical charge (either positive or negative) in 1 cm^3 of dry air under standard conditions.[46] Equal to 2.58×10^{-4} C/kg (exactly). Superseded by the SI unit C/kg [80].

-S-

Safety culture: The assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance [80].

Scattered radiation: Radiation that, during passage through matter, is changed in direction (the change is usually accompanied by a decrease in energy) [46].

Scintillation cameras: cameras that detect gamma rays from radioactive decay by the production of light when the gamma ray hits the detector of the camera [5].

Semiconductor: Any of a class of solids (as germanium or silicon) whose electrical conductivity is between that of a conductor and that of an insulator in being nearly as great as that of a metal at high temperatures and nearly absent at low temperatures [81].

Sievert (Sv): The special name for the SI unit of equivalent dose, effective dose, and operational dose quantities. The unit is joule per kilogram [49].

Single-photon emission computed tomography (SPECT): An imaging technique in which one or more gamma cameras sample a region of the body from several angles, producing tomographic images ("slices") of the region [70].

Specificity: Accuracy of a test, usually expressed in terms of percent correctly diagnosed, among those tested who actually do not have the condition of interest [5].

Stochastic effect: A radiation induced health effect, the probability of occurrence of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose. Stochastic effects generally occur without a threshold level of dose. Examples include solid cancers and leukemia [80].

Strongly penetrating radiation: Radiation for which limits on effective dose are normally more restrictive than limits on equivalent dose to any tissue or organ, i.e. the fraction of the relevant dose limit received will, for a given exposure, be higher for effective dose than for equivalent dose to any tissue or organ. For most practical purposes, it may be assumed that strongly penetrating radiation includes photons of energy above about 20 – 30 keV [80].

-T-

Terrestrial: Of or relating to Earth or its inhabitants; of or relating to land as distinct from air or water; living on or in or growing from land [70].

Thermoluminescent dosimeter (TLD): A dosimeter containing a phosphor for measuring dose. When used for personal dosimetry, filters (absorbers) are included to help characterize the types of radiation. When heated, TLDs that have been exposure to ionizing radiation give off light proportional to the energy absorbed [70].

Threshold: A level (e.g., of radiation dose) below which there is no observable effect. There is no threshold for induction of cancer by radiation: All levels of radiation are considered harmful [46].

Tissue weighting factor, w_T: Multiplier of the equivalent dose to an organ or tissue used for radiation protection purposes to account for the different sensitivities of different organs and tissues to the induction of stochastic effects of radiation [80].

Tracer: A measureable substance used to mimic, follow, or trace a chemical compound or process without significantly disturbing the process under study [5].

Transmission scan: Using an external radiation source, transmission images are obtained to correct for photon attenuation in tissues localized between the radiation source and the radiation detectors [5].

-U-

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation. A UN committee that publishes periodic reports on sources and effects of ionizing radiation [69].

Uptake: A general term for the processes by which radionuclides enter one part of a biological system from another [80].

-V-

Valence band: The range of permissible energy values that are the highest energies an electron can have and still be associated with a particular atom of a solid material [81].

Veterinary medicine: The branch of medicine that deals with the diagnosis and treatment of diseases and injuries of animals by a licensed veterinarian [70].

-W-

-X-

-Y-

-Z-

ACRONYMS AND ABBREVIATIONS

ALARA	As Low as Reasonably Achievable
ACC	Animal Cancer Center
BEIR	Biological Effects of Ionizing Radiation
Bq	Becquerel
CFR	Code of Federal Regulations
Ci	Curie
CSU	Colorado State University
CT	Computed Tomography
CW-OSL	Continuous Wave Optically Stimulated Luminescence
DNA	Deoxyribonucleic Acid
DSB	Double Strand Break
EPD	Electronic Personal Dosimeter
FDA	Food and Drug Administration
FDG	Fluorodeoxyglucose
Gy	Gray
HDP	Hydroxymethane Diphosphonate
IAEA	International Atomic Energy Association

ICRP	International Commission on Radiological Protection
IRB	Institutional Review Board
IV	Intravenous
kg	Kilogram
LNT	Linear No-Threshold
LYSO	Luttieum Yttrium Oxyorthosilicate
MRI	Magnetic Resonance Imaging
NaF	Sodium Fluoride
NCRP	National Council on Radiation Protection and Measurements
NIST	National Institute of Standards and Technology
NRC	National Research Council
NUCMED	Nuclear Medicine
OSL	Optically Stimulated Luminescence
PET	Positron Emission Tomography
PET/CT	Combined PET and CT imaging
PET/MRI	Combined PET and MRI imaging
PMT	Photomultiplier Tube
POSL	Pulsed Optically Stimulated Luminescence
R	Röntgen
SPECT	Single Photon Emission Computed Tomography
SSB	Single Strand Break

Sv	Sievert
^{99m}Tc	Metastable Technetium-99
TLD	Thermoluminescent Dosimeter
USNRC	Nuclear Regulatory Commission
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
VTH	James L. Voss Veterinary Teaching Hospital
SI	International System of Units