ANALYZING A CANINE IN A RADIOACTIVE CONTAMINATED WORKING ENVIRONMENT

A Thesis

by

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ABSTRACT

When it comes to saving lives after a destructive and catastrophic crisis, urban search and rescue (USAR) dogs are an essential emergency response component, where each dog can perform the equivalent work of 20 to 30 people. However, based on current practices, if any crisis contained the dispersal of nuclear material, these dogs and their handlers may not be able to take part on their lifesaving missions due to few protective guidelines. In this study a 9.29 m^2 area was sprayed with 200 MBq of ^{18}F, and a dog executed minor search activities in this contaminated area. Using a positron emission tomography (PET) scanner both internal and external contamination from the dog was localized and quantified. Total contamination on the dog as quantified by the PET scan was 3.4 kBq with external and internal contamination being 2.1 kBq and 1.3 kBq, respectively. Total external dose received to the dog during the exercise was 0.19 mGy, and total internal dose was 1.1 μGy. Overall, this contamination exercise proved a viable method to simulate a radioactive environment safe enough for a dog to participate in but strong enough to create detectable contamination. This will allow researchers to gain insight into health concerns that may arise if a USAR dog took part in a real-world contamination event.

DEDICATION

To all the puppies that allowed me to pet them, to all the Americans I hope to protect as I grow my knowledge in nuclear security, and to my mother for always telling me I had to get a masters

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All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

CBRNE	chemical, biological, radiological, nuclear, and explosive
CT	computed tomography
DRCF	dose rate conversion factor
FDG	fluorodeoxyglucose
FRMAC	Federal Radiological Monitoring and Assessment Center
GUI	graphical user interface
IACUC	Institutional Animal Care and Use Committee
ICRU	International Commission on Radiation Units and Measurements
IND	improvised nuclear device
IRB	Institutional Review Board
FEMA	Federal Emergency Management Agency
NIST	National Institute of Standards and Technology
OSLD	optically stimulated luminescence dosimeter
PET	positron emission tomography
PPE	personal protection equipment
RDD	radiological dispersal device
ROI	region of interest
SNM	special nuclear material
SUV	standardized uptake value
USAR	urban search and rescue

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1. INTRODUCTION

The United States employs numerous emergency responders who are equipped to deal with crises. These events range from natural disasters, chemical spills, radiological contamination, terrorist attacks, and many more. Since these events are often unpredictable and leave unthinkable consequences, responding to these events often requires unique solutions. This is why among the many heroes in emergency response who risk and sacrifice their lives, urban search and rescue (USAR) dogs are also a part of that life-saving team. USAR dogs are valuable assets when it comes to locating or identifying those who have been lost or trapped after a destructive incident.

Although USAR dogs have been used to save lives after natural disasters and terrorist attacks, they have yet to face an event that involves radioactive contamination. This kind of event could occur from an accidental radioactive release during an earthquake, flooding of a hospital that contains nuclear material, or even from a radiological dispersal device (RDD) deployed by an adversary. However, should any of these types of radiological events occur, the handlers of these dogs would have a difficult choice to make as there are little guidelines and protective equipment that could be utilized by USAR dogs in this type of environment. The handlers would have to decide between risking the health or lives of their canine companions by exposing them to radiation or choose not to operate in this dangerous environment in order to protect their dogs.

While risking some lives in order to save some others will always be a difficult choice to make, gaining more insights and knowledge into the dangers these dogs face will aid in making this decision a more educated one. This research focuses on gaining an understanding of where radioactive material deposits both internally and externally after a canine has been exposed to a radioactive contaminated environment. This research also offers recommendations to handlers, based on this insight. In this study a Yellow Labrador Retriever was exposed to a ^{18}F contaminated room for 10 minutes and then imaged with a PET (positron emission tomography) scan to see where internal and external contamination accumulated. This gave insights into the locations and degrees of contamination a dog could face while working in a radioactive environment, and based

on these findings, recommendations were given on how these dogs can perform more effectively in this type of environment.

2. BACKGROUND

2.1 USAR Dogs & Previous Studies

USAR dogs are critical assets in many emergency response teams. They are often used to locate missing or trapped people in urban environments after natural disasters or mass casualty events. It is estimated that one USAR dog can perform the equivalent amount of searching as 20 to 30 humans.[5] In addition to their efficiency in the field, USAR dogs require significant investment in handler and canine evaluation, development, and training time - on average 1-2 years - to prepare them for certification as a FEMA USAR canine. It takes years of training and about $15,000-$20,000 to get a dog to its peak performance, and it will be required to re-certify 2-3 more times over its career.[6] These dogs are valuable team members that could be called upon to operate in contaminated environments following a natural or man-made disaster. Therefore, more information is needed in terms of how USAR dogs are most vulnerable to exposures from a contaminated environment and how to mitigate the occurrences of contamination that may occur in and on the dog during its mission.

Often times USAR dogs cannot wear protective equipment as it may interfere with their safety or performance (as seen in Figure 2.1). For example, if a dog wore a mask, the dog would be unable to use its nose or mouth to smell and track scents. If a dog wore a vest, it could become caught on debris and injure the dog, or shoes could cause the dog to slip. This leaves the dogs with little protection when performing their lifesaving duties.[7][8] No experimental research has been performed on USAR dogs under working conditions in a contaminated environment. Therefore, if USAR dogs were utilized during a radiological incident, it would be critical to limit the exposure risks the dog may come in contact with. Although research on canines exposed to radioisotopes during search and rescue missions is sparse, some analyses have been done on sedated canines exposed to radioactive aerosols, and limited research has been completed using models to estimate canine radiation dose after working in a contaminated environment.[9][10]

Figure 2.1: USAR dog training at rubble pile. Reprinted from "Susan and Gryphon Pass USAR Test".[1]

The studies which utilized canines and aerosol radioactive particles were mostly done to discover the morbidity and mortality of the animals and how it relates to humans.[10][9] In these experiments, long lived and alpha emitting isotopes were used, and stochastic and nonstochastic effects of radiation exposure were tracked and measured.[10][9] This research offered significant contributions in terms of gaining insight into the effects of actinide exposure as well as the severe effects that come from prolonged exposure to radiation. However they did not provide insight into healthy, working dogs under normal conditions. The focus on actinides is also not a major component of this study given that contamination events that could be responded to would most likely not include these types of isotopes. Accidents caused by natural disasters are more likely to include medical or industrial isotopes while if a nuclear terrorism event were to occur, a radiological device would be easier for an adversary to acquire than an atomic weapon.[11] Radiological devices are less likely to be constructed with special nuclear material (SNM) and are more likely to include more readily available isotopes such as cesium-137 (^{137}Cs), medical, or industrial isotopes.[12] The isotope ^{137}Cs is prevalent because it is produced in reactors during transmutation. It is also used

in universities, hospitals, and commercial industries. Other examples of medical isotopes include technetium-99m (^{99m}Te), fluorine-8 (^{18}F), cobalt-60 (^{60}Co), iridium-192 (^{192}Ir), and iodine-125 (^{125}I). Industrial isotopes include americium-241 (^{241}Am), krypton-85 (^{85}Kr), and chromium-51 (^{51}Cr).

2.2 Radioisotope ^{18}F

The radioisotope ^{18}F positron decays (97% of the time) to stable ^{18}O with a half-life of 110 minutes (see Figure 2.2). While ^{18}F can come in many forms, one form of particular usefulness for this study was fludeoxyglucose (FDG) which is glucose applied with the radioactive ^{18}F. FDG is a water-soluble compound used for PET scans for diagnostic imaging. This compound is usually injected into the patient where the FDG is absorbed and used throughout the body in the same ways as regular glucose. Organs or other tissues in the body with high metabolic rates (e.g. cancerous tumors) will absorb more glucose and therefore, more ^{18}F.

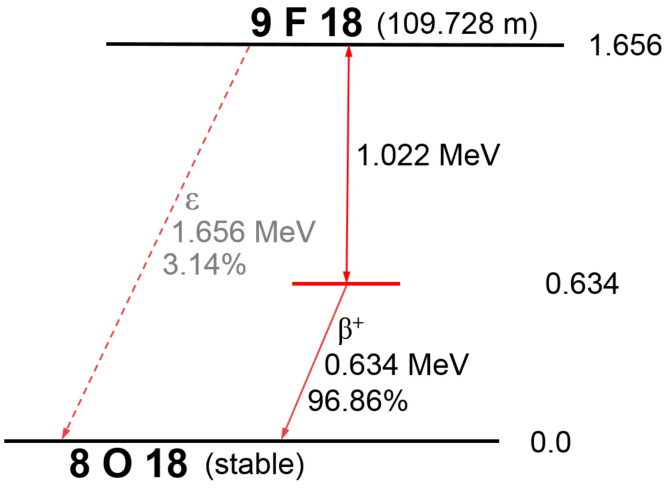

Figure 2.2: Decay scheme for ^{18}F.

Aside from PET scans being a proven method to measure internal and external contamination from ^{18}F, theoretical research has been done on contaminating large areas with ^{18}F.[13] Given the results of this previous work, it might be possible to do a full contamination exercise in the future

to help canines and handlers to train for this kind of environment. There exists guidelines for how ^{18}F could be distributed over a large area outdoors while still taking into account public safety limits.[13]

Lastly, ^{18}F has potential to relate to possible RDD materials. When considering which radioactive materials might be used for this type of device, three major criteria are considered: material availability, source strength, and transportability.[14] Medical and industrial sources usually rank highest in these categories with ^{137}Cs being an isotope that is frequently analyzed as one of the most likely materials to be included in an RDD.[14][15]

Despite the opposite locations of ^{18}F and ^{137}Cs on the periodic table, these two isotopes share similar properties that make ^{18}F a reasonable substitute for a potential RDD material. The isotope ^{137}Cs is known for its 662 keV gamma ray, high water solubility, and high reactivity.[16] Like all halogens, ^{18}F also has a high water solubility and high reactivity. Although ^{137}Cs is known for its 662 keV gamma, it actually comes from a metastable isotope ^{137m}Ba which is produced by ^{137}Cs beta decay. While the 511 keV gammas that are associated with ^{18}F come from the positrons it emits that then annihilate with electrons in the environment, both ^{137}Cs and ^{18}F produce gamma rays in indirect ways. It is also important to note that the 662 keV gamma from ^{137}Cs is the same order of magnitude as the 511 keV gammas from ^{18}F; although, beta annihilation produces two gammas at the same time. ^{137}Cs creates gammas 85% of the time, while ^{18}F creates two gammas 97% of the time. Lastly, it is important to explain the major differences between ^{137}Cs and ^{18}F for this study. The first is that the half lives are drastically different, 30.1 years and 110 minutes, respectively. The second is the size of these isotopes; ^{137}Cs is over 7.5 times heavier than ^{18}F. While these differences may have caused slight deviations in this study, the safety benefits of using ^{18}F over ^{137}Cs far outweighed the advantages of using actual ^{137}Cs in this experiment.

Overall, ^{18}F was chosen as the radioactive element for this study because it was readily available, medically used, can be visualized through a PET scan, easily distributed, and has a short half life.

2.3 PET Scans

2.3.1 How They Work

FDG can be used for medical imaging due to the nuclear interactions between ^{18}F and body tissues. When the ^{18}F decays, the positron it emits annihilates with electrons found in these tissues to create two, 511 keV photons that travel 180° from each other. [2] This is shown in Figure 2.3. The 511 keV energies of both photons come from the mass to energy conversion of the positron

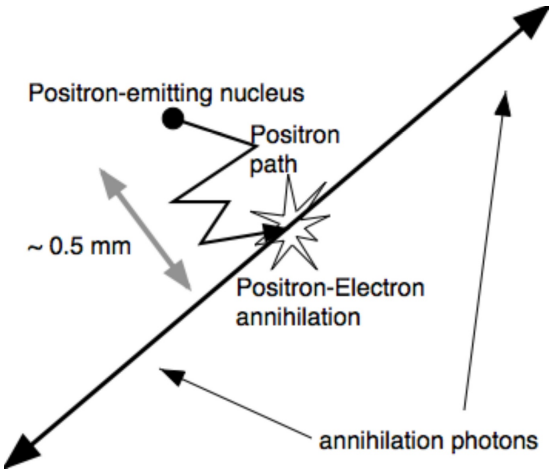

Figure 2.3: Depiction of positron-electron annhilation with a positron emitted from an isotope. Reprinted from "The physics of pet\ct scanners".[2]

and electron using Einstein's famous formula $E = mc^2$.

In order to detect and measure these photons, scintillation detectors are placed throughout the PET scanner.[17] Scintillation detectors convert incident photons into electrons. Then, these electrons are multiplied in a photomultiplier tube to create an electrical current that is used to measure the relative amount of radiation present. Constructing a ring of scintillation detectors around a patient and allowing the patient to slowly move through the ring keeps track of these gamma rays and thus allows for the creation of a three dimensional PET scan image of where radiation is in or on the body.

Identifying where the ^{18}F goes in the body uses a phenomenon called coincidence counting. Due to the two gamma rays that are produced at the same time, they should theoretically be counted at the same time (within 3.3 ns) by two detectors across from each other since both gamma rays are moving at the speed of light in opposite directions.[2] Figure 2.4 shows a depiction of this phenomenon. Like most radiation counting techniques, there is some uncertainty to coincidence counting. Uncertainties come from scattering or absorption of the gamma rays, the gamma rays missing a detector, or one gamma ray scattering into an unexpected detector. Issues can also arise from detecting gamma rays from ^{18}F that already exists in the environment or if a patient moves during a scan. Despite all these factors, PET scans have a resolution of 10 mm and can be further refined for clarity by overlaying the PET scan image with a computed tomography (CT) scan image.[2]

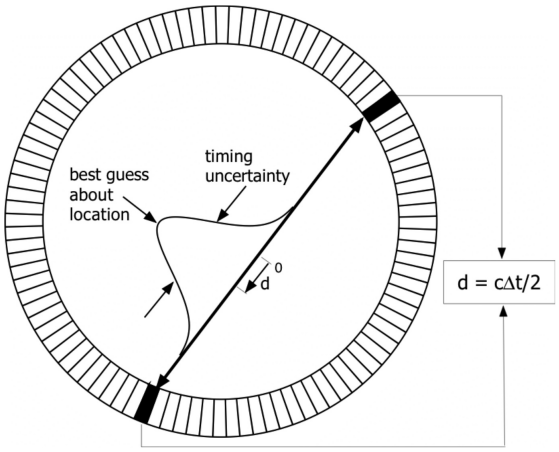

Figure 2.4: Depiction of how ^{18}F is located in a patient by using coincidence counting.Reprinted from "The physics of pet\ct scanners".[2]

2.3.2 Analyzing Scan Data

After performing a PET scan, viewing software is used to analyze the uptake of ^{18}F in the body. The viewing software helps to process the initial scan data into information that can then be used to compare different areas of the body. This is done by decay correcting different sections of the

scan so that the whole body can be evaluated together. This is necessary due to the relatively long time a PET scan takes (i.e., about 30 minutes) compared to the half life of ^{18}F. After correcting for decay, portions of the scanned body are divided into ROIs (regions of interests). These ROIs are then analyzed either by their activity of ^{18}F or standardized uptake values (SUVs). The method of calculating a SUV is given in Eq. 2.1.[18]

$$SUV = \frac{rc}{(a'/w)} \tag{2.1}$$

where:

SUV = Standard uptake value

r = Activity concentration measured by the PET scanner within an ROI [Bq/ml]

c = Conversion factor assuming 1 ml of tissue weights 1 g [ml/g]

a' = Decay corrected amount of FDG [Bq]

w = Weight of patient [g]

SUVs are utilized to compare relative uptakes of FDG based on a patient's body weight.[18] While SUVs are typically used for instances where FDG has been injected into a patient, they will still be used in this study so that ^{18}F uptake in each ROI can be compared. The activity of ^{18}F can be used to understand the contamination or dose received to a specific ROI while SUVs shed more light on the significance of the uptake.

2.3.3 Advantages

For this study, PET scanning was an even more advantageous method for measuring contamination because the PET scanner was just a few rooms away from the contaminated area. This was critically important as the half life of the radioactive material used in this experiment had a relatively short half life, so the time between contamination and scanning had to be minimized. The short distance between rooms also greatly aided in simplifying the logistics of transporting a

contaminated dog as the facilities used were equipped to deal internal transportation of a contaminated animal. The staff from this facility was also able to assist and support the dog continuously from pre-scan care, contamination, scanning, and recovery. They were also very experienced in dealing with animals injected with ^{18}F who might possible be externally contaminated.

2.4 Dose Calculations

Throughout this study the source of interest, ^{18}F, is manipulated into many geometrical forms. First, it is seen as a point source, then a cylindrical source, and lastly a finite plane source. These different shapes affect how dose rates are calculated. However, for this study, only the dose rate from the plane source will be analyzed since the dog was only exposed to this geometrical form. For computing dose rates, it was assumed that ^{18}F decays 97% of the time via positron. This means dose rate calculations will include potential doses from each positron as well as the two gammas they create when annihilating with electrons in their environment.

All dose rates measured and computed throughout this study are equivalent dose rates. $\dot{H}_T$, as given by Eq. 2.2 but are referred to as dose rates for simplicity. In this equation the W represents a weighting factor to account for different types of radiation, R. W_R equals 1 for both positrons and gammas throughout this study.[19] Lastly, the calculation of absorbed dose, $\dot{D}$, is dependent on the geometrical shape of the source and has a direct relationship to $\dot{H}_T$.

$$\dot{H}_T = \sum_R W_R \cdot \dot{D}_{T,R} \approx \dot{D} \tag{2.2}$$

where:

$\dot{H}_T$ = Equivalent dose rate into the entire item T $\left[\frac{J}{kg \cdot s}\right]$ or $\left[\frac{Gy}{s}\right]$

W_R = Radiation weighting factor for radiation R

$\dot{D}_{T,R}$ = Absorbed dose rate from radiation R into the entire item T $\left[\frac{J}{kg \cdot s}\right]$ or $\left[\frac{Gy}{s}\right]$

$\dot{D}$ = Mass averaged absorbed dose rate into the entire item $\left[\frac{J}{kg \cdot s}\right]$ or $\left[\frac{Gy}{s}\right]$

For this study the external absorbed dose had to be calculated in a unique way since most dose calculation methods and models do not involve such a large source and canines. Dose rate conversion factors (DRCFs) for USAR dogs, based on those from the Federal Radiological Monitoring and Assessment Center (FRMAC), were used.[20] This included DRCFs for both the positrons and the photons. These DRCFs were especially useful due to the fact that they took into account the height differences between humans and canines.

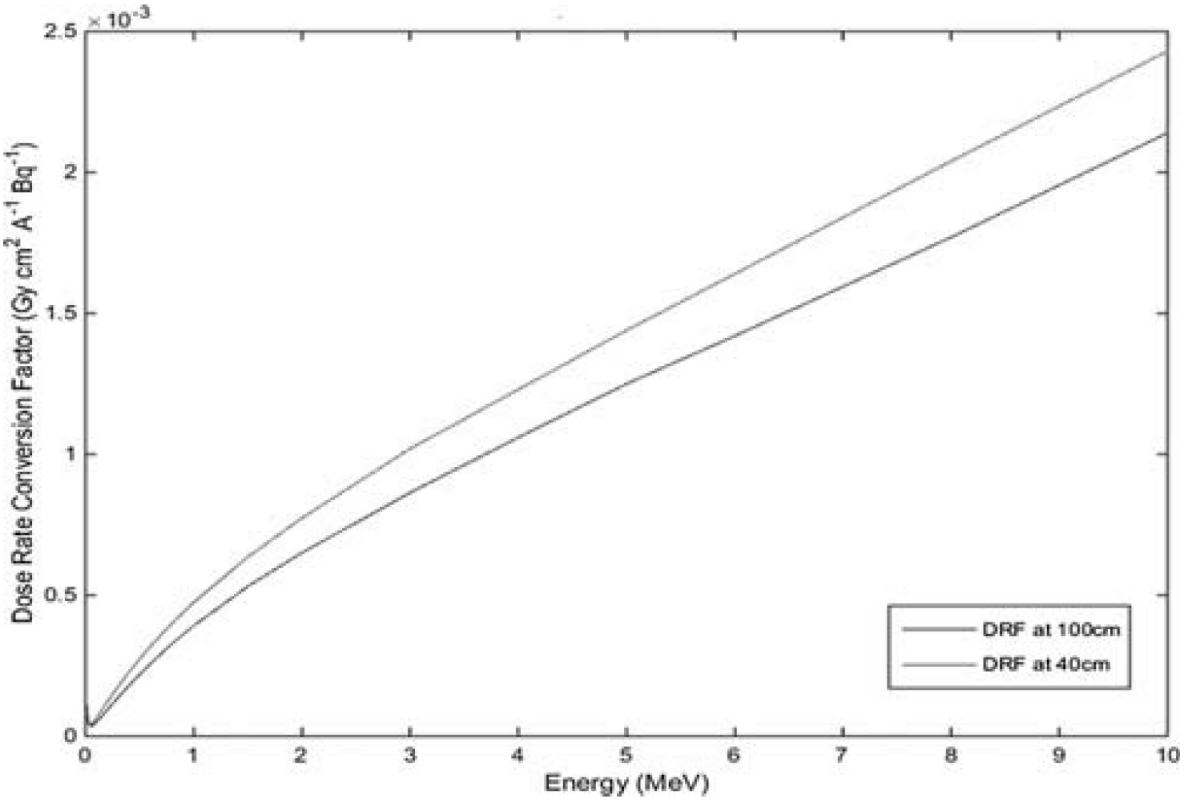

Figure 2.5: Graph showing the comparison of DRCFs for humans and canines. Reprinted from "Calculation of Canine Dose Rate Conversion Factors for Photons and Electrons".[20]

As shown by Figure **??**, in order to calculate the total absorbed dose, the DRCF is used along with the source area, source activity, and time exposed to the source. Therefore, to calculate the dose received, the source's change in activity while the canine was in the room had to be accounted for. A version of Bateman's equation shown in Eq. 2.3 was used to correct for this.

$$\bar{A} = \int_T A_0 e^{-\lambda t}\, dt \tag{2.3}$$

where:

$\bar{A}$ = The average source activity during time period T $[Bq]$

A_0 = Initial activity of the source $[Bq]$

λ = Decay constant $[s^{-1}]$

t = Time $[s]$

T = Time period of interest $[s]$

Lastly, in order to use these DRCF, a few additional assumptions were made. Positron and gamma shielding from air, minor protective equipment, and fur was considered negligible when calculating whole body dose. This is due to the low stopping power and attenuation coefficient of air for short distances (e.g. meters) as well as the minor amount of protective equipment and the uncertainty related to fur thickness (i.e. fur doesn't cover the paws). Also, all background radiation was considered negligible to the dose rate calculation since background was measured at 17-20 μR hr^{-1} while contamination levels were above 300 μR hr^{-1}. Lastly, it was assumed that every positron created two gammas in the contaminated area. If the ^{18}F was on the floor it was assumed that one gamma contributed to the dose, and the other gamma was absorbed by the floor. This was a reasonable assumption since the gammas travel in opposite directions. In reality, some gammas could have scattered before they reached the dog, but this gave a "worst" case scenario. The DRCF used for this study was 6.39 mGy cm^2 Bq^{-1} yr^{-1} (or 0.729 μGy cm^2 Bq^{-1} hr^{-1}).

In order to calculate internal dose to the dog, similar information to calculating external dose was used. However, it was assumed that if the source was inside the dog, there was no shielding and that 100% of the source's particles and energies were being absorbed into the area around it.

The equation for calculating internal dose is given by Eq. 2.4.

$$\dot{D} = kA_{\beta^+}E_{\beta^+}p_{\beta^+} + 2kA_{\beta^+}E_{\gamma}p_{\gamma} \tag{2.4}$$

where:

k = Proportionality constant $\left[\frac{Gy \cdot g}{MeV}\right]$

A_{β^+} = Activity of source [Bq]

E_{β^+} = Energy of positrons $[MeV]$

E_{γ} = Gamma ray energy $[MeV]$

p_{β^+} = Portion of positrons absorbed by the material

p_{γ} = Portion of gamma rays absorbed by the material

3. METHODOLOGY

3.1 Pre-Experimental Approval

The first step in preparing for this experiment was getting approval from the Institutional Animal Care and Use Committee (IACUC) and Institutional Review Board (IRB). IACUC ensures that experiments involving animals are done in the most humane ways possible and that they are only done if the experiments have significant scientific gains. IRB is a similar organization but is concerned with the humans involved to ensure they are treated appropriately during an experiment. The IACUC protocol number for this study is 2017-0344, and the IRB protocol number for this study is 2017-0956. The IACUC protocol was approved with the greatest risk to the dog being from the anesthetic. The IRB protocol was reviewed by the board but ultimately received a status of 'Not Human Research Determination' as this experiment did not focus on gaining experimental data from humans. However, in order to keep the humans involved as safe as possible, an experimental protocol was presented to the institution's radiation safety office and approved. University radiation safety was also present during the entire experiment.

3.2 Choosing a Canine for the Study

USAR dogs are typically limited to a few specific breeds: Labrador Retrievers, Golden Retrievers, Border Collies, Belgian Malinois, German Shepherds, and mixes of these breeds.[21] They also must be healthy: mentally, physically, and emotionally in order to perform their duties.[22] While these dogs may differ in their looks, stature, and thickness of fur, they are all required to take and pass the same certification test to become a Federal Emergency Management Agency (FEMA) rescue dog.[22] Although each breed has these differences, this study was less focused on accounting for the nuances between dogs and more focused on developing a way to measure and identify contaminates on and in a canine after it has been working in a radioactive contaminated environment.

The dog chosen for this study was an adult, neutered-male, yellow Labrador Retriever with a

weight of 33.1 kg (see Figure 3.1). The breed and size of this dog (i.e., a healthy weight) were typical of other USAR dogs.[23] Before the dog could participate in this study, it underwent a general health and wellness exam to ensure it was fit enough to receive anesthetic for the PET scan, identify any possible previous medical conditions, and to get a baseline of health to compare to after the study. During this examination no previous medical conditions were discovered, and the dog was deemed fit to perform the experiment and receive anesthetic.

Figure 3.1: Dog chosen for the contamination experiment.

After the health and wellness exam, the requirements of the dog were determined. During this study, the dog was expected to perform actions as close to regular USAR duties as possible. This included walking, sniffing, exploring, and investigating in and around a debris pile. These activities stimulated different movements and modes of breathing which were important for gaining an accurate picture of how USAR dogs are at risk in receiving internal and external exposure from a radioactive contaminated environment.

In order to get the dog comfortable performing this experiment, the facilities and staff were

available for familiarization and dry runs. This allowed the dog to become adjusted to its environment and more focused on following instructions when asked. This task could have been skipped if the participating dog was a trained USAR dogs as they are taught to handle and work in stressful environments.

3.3 Contamination Location

After selecting a canine for participation, the next important step for this study was finding an area suitable for radioactive contamination. While USAR dogs usually train and work outside, for this initial proof of concept study, an indoor facility was chosen for a more controlled environment. The room to be contaminated was a post-procedure room used to house animals that have just undergone a PET scan or other tests that involve medical radioisotopes. Thus, it was suitable for handling radioactive ^{18}F. This room included a flat and sanitary floor, limited air exchanges, no windows, thick concrete walls, and a single set of doors.

Another major advantage of this post-procedure room was its location. It was in the same facility as the PET scanning room connected by a hallway. The time and distance in which the dog would have to travel was an important consideration for this experiment for two reasons: to prevent the decay of the isotope before it could be measured and traveling with a contaminated canine in a vehicle would have resulted in complications to the study that would have made completion more difficult. Excessive travel and new places can also be stressful for a dog if they are not trained to experience these situations. Keeping the dog indoors throughout this whole study, limiting the travel time between rooms, and keeping the number of rooms visited to a minimum helped the make this study possible and eliminate stress on the dog.

3.4 Pile Construction

3.4.1 Structure

Once the facilities were decided upon, the next task was to create a suitable debris area for the dog to explore. Unlike other search dogs, USAR dogs are usually performing their duties in rubble piles and confined places. Rubble piles consist of many urban materials including concrete, rebar,

sheetrock, electrical wiring, plumbing, etc. as well as domestic items found in buildings such as paper, plastic, fabrics, etc. The placements of all of these materials are haphazard, random, and completely dependent on the destruction that affected them. These piles are often unstable and dangerous containing smoke, ash, and other debris. In the safety interest of the dog and personnel involved in this study, the rubble pile constructed for contamination posed no threats to anyone involved. A photo of the pile can been found in Figure 3.2.

Figure 3.2: Photo of the simulated rubble pile used during the study.

In order to create this rubble pile, a 3.05 m by 3.05 m (10 ft by 10 ft) area was measured off in the room and filled with a mismatched pile of different materials, items, and structures. Most items were lightweight and consisted of everyday types of items the dog may have come into contact before. By haphazardly laying the items and creating areas for the dog to explore, this

chaotic set-up of the simulated rubble pile was similar to the areas USAR dogs usually face during a mission.

The man-made pile consisted of a rubber ball, four car tires, a plastic rubbish bin, paint bucket, storage container, child's play pool, drainage pipe section, three crates, and a cat carrier. The items were stacked in a way so that they fit in the designated 9.29 m^2 (100 ft^2). The items were also stacked in a way so that they created nooks and crannies for the dog to explore and investigate. Scented food containers and boxes as well as crushed kibble were also added to the pile in order to create a deeper desire in the dog to explore and sniff. These added items are shown in Figure 3.3.

Figure 3.3: The simulated rubble pile after being dusted with corn starch.

3.4.2 Dusting

In addition to creating the debris area, another feature that needed to be addressed was the dirt and dust that are usually found within and around the pile. Actual dirt and debris could be potentially harmful to the respiratory tracks of humans and animals, so this study utilized corn starch to simulate the typical air and ground environment during a search and rescue. About 100 grams (1 cup) of corn starch was applied to the entire area of the rubble pile using a hand pump garden duster with a fan tip. The duster used for this figure is shown in Figure 3.4.

Figure 3.4: Garden duster used to apply corn starch to the rubble pile.

The garden duster aerated the corn starch, so that it created puffs of dust that then fell and coated the debris pile. It also left the air around the rubble pile dusty and hazy which settled by the time the dog and handler entered the room. The intent was to cover the entire area of the rubble pile with the corn starch as this would most likely resemble the distribution of dust on a pile in the field. This is shown in Figure 3.3. However, due to the inability to control the precise amount of corn starch released per puff some spots of the rubble pile may have received larger amounts of starch than others. Although, this was considered insignificant since there is usually some randomness in debris and dust placement in an urban search and rescue environment.

When dusting the pile, corn starch was not only chosen due to safety reasons, but it also had an appropriate particle size to represent the other types of particles that may be found in an actual rubble pile.[4] Below, Table 3.1 compares the particle size of corn starch to typical particles that may actually be distributed throughout a rubble pile in the field. While many different particle types and sizes can be found in an USAR environment, Table 3.1 highlights some of the major

particle types that could be found following a catastrophic event. As shown in Table 3.1, corn starch does not exceed a particle size of 1 μm. This meant that corn starch was a viable option for substituting other small particles that are harmful to inhale, while still creating the characteristic volatile environment found in a rubble pile.

Table 3.1: Particle sizes of debris found in a rubble pile. Reprinted from "Particle Sizes".[4]

Particle	Particle Size (μm)
Corn Starch	0.1 - 0.8
Dust	0.5 - 100
Fly Ash	1 - 1000
Radioactive Fallout	0.1 - 10
Smoke	0.01 - 50

3.5 Prepping for Contamination

Before the FDG was applied, monitoring equipment was set up and the handler and canine got ready to enter the room. An air sampler was set up outside of the contamination area in order to measure any possible resuspended material. The handler donned (personal protection equipment) PPE including a Tyvek® suit, goggles, and a respirator. The handler also wore an optically stimulated luminescence dosimeter (OSLD) in order to get a dose measurement from being in the contaminated area.

The canine did not receive any PPE as this is usually the standard for canines working in a rubble pile. However, for the purpose of this study it was important to measure the dose to the dog. This was done in the same manner as the handler by using OSLDs. The canine donned an OSLD on its left, front leg right below its elbow; another OSLD on its collar around its neck; and lastly, another OSLD clipped to a band around its chest with the OSLD positioned at the lowest part of the dog's ribcage. Placements of OSLDs on the dog are shown in Figure 3.5.

In addition to receiving dosimeters, the canine also underwent preparation for the PET scan. Prepping the dog as much as possible before contamination served two purposes. The first was to

Figure 3.5: Placement of OSLDs on the dog before it entered the contaminated room.

minimize the contact between veterinary staff and the dog after the dog had been contaminated. The second reason was to minimize the time between the dog becoming contaminated and the PET scan. Prepping for the PET scan included shaving the left, front foreleg and inserting an IV catheter so that the dog would immediately be ready to receive anesthetic and an IV solution. This catheter was protected by a guard which can be seen in Figure 3.5. A urinal catheter was also inserted into the dog and taped down to the back leg so that it would interfere less with the dog's walking. This catheter was necessary for when the dog received anesthetic.

3.6 Spraying FDG

After the simulated rubble pile was dusted and the canine was prepped, the ^{18}F contamination could begin. The saline solution of FDG was received inside a 5 mL medical syringe with a needle. This is the standard method of transporting FDG as it is typically administered intravenously before a PET scan. The activity of the ^{18}F was 200.503 MBq (5.419 mCi). In order to get an even distribution of the FDG covering the pile, a weed sprayer with a misting tip was used to cover the pile in the FDG solution. A 2 gallon, hand-pumped, weed sprayer containing 473 ml (2 cups) of water was mixed with the 5 mL FDG and saline solution.

The weed sprayer was mixed and pumped for 60 seconds and sprayed for 109 seconds over the entire area of the pile and its objects. The person spraying sought to evenly distribute the FDG solution over the entire pile. However, since the flow rate of the mist and the rate of spraying the mist over the pile were not measured, some variance in activity per area could have existed throughout the pile. However, this was considered minor as in a real life contamination event it is unlikely that contamination would be evenly distributed throughout the area.

After spraying, the rubble pile was left to dry. This served two purposes. The first was to ensure the pile had a layer of corn starch that could potentially be inhaled. The second reason was to prevent the safety hazard of slipping while walking around the wet pile. After 37 minutes moisture was no longer visible on the pile, and the dog and handler were free to enter.

3.7 Exploring the Pile

The dog and the handler spent a total of 9 minutes and 22 seconds inside the contaminated area. An USAR dog spends an extremely variable amount of time depending on how difficult it is for the dog to traverse and search the area. This time could range from 10 minutes to 25 minutes. However, for this study, the dog and handler spent less than 10 minutes inside the contaminated area for safety reasons. While the dog was in the contaminated room, it performed most actions similar to USAR dogs while on a mission. During the time in the room, the dog was prompted by its handler to perform simple tasks. This included walking around the pile, investigating scents, exploring the pile, and detecting a few pieces of hidden kibble. Scents of interest to the dog were created using items that had been left on a farm, empty treat containers, and sprinklings of kibble powder. Large food rewards were not utilized as the dog had to be unconscious and intubated for the PET scan.

While in the contaminated area, the dog also briefly sat. This increased external contamination to the dog. However, this is typical of some USAR dogs once they have helped their handler locate their target. While, the dog in this study did not undergo intensive aerobic exercise, major climbing, and crawling, it still had the ability to move around freely and investigate its environment. However, the lack of these activities is not seen to have a significant impact on the overall findings

of this study as canine movement during a mission is always extremely varied mission to mission.

Two actions performed by the dog in this study that USAR dogs are not train to do, but do anyways, were eating a couple pieces of kibble and licking around the kibble. These activities led to radioactivity in the digestive track. This was useful in determining the degree of internal contamination that comes from eating or licking in a radioactive contaminated environment. While these were unintended actions for the dog, this gave a realistic element to the study. Despite the extensive training a dog goes through, they are often tempted by the smells around them, and it can be impossible to stop a dog from licking and eating if the handler is not around when the dog finds something its interested in.

3.8 Medical Imaging

After the dog and handler left the contaminated area, the dog was escorted to a PET scan room to prepare it for medical imaging. Specific measures were taken in order to transport the dog from one room to another without contaminating the hallway. The dog was loaded into a covered, rolling crate at the exit of the contaminated room as shown in Figure 3.6. This kept contamination on the outside of the crate to a minimum, so that it could be rolled down the hallway without spreading contamination. As extra protection the hallway was also marked off with barriers and signs while radiation safety officers trailed behind the crate with radiation detectors so that contamination levels could be measured. However, no contamination levels were detected in the hallway.

Once the dog was in the scan room and situated on the scan table, the medical imaging began. The imaging started with a computed tomography (CT) scan and then a PET scan. The CT scan was administered 17 minutes after the dog had exited the contaminated area, and the PET scan followed at 23 minutes after exiting. The CT scan took a total of 6 minutes while the PET scan took a total of 38 minutes. After the PET scan the dog was sequestered overnight in a post-procedure room to ensure that all of the ^{18}F had decayed by the time of release.

Figure 3.6: Picture of the rolling crate used to transport the dog after it had been contaminated. The blanket on top of the crate was draped over the top and sides of the crate during transportation for extra protection.

4. RESULTS

4.1 Experimental Details

While the outcomes of this study are intended to benefit and assist USAR dogs and their handlers, a non-USAR dog was chosen for this experiment for a few reasons. This was a proof of concept study, so it was not necessary to use a trained USAR dog. Since no dog has ever experienced a radioactive contaminated environment under working conditions, a dog of USAR build was sufficient enough. Also, if any unexpected harm came to the dog (such as complications with anesthetic), this would have ended the USAR dog's career and maybe the handlers as well. Choosing a house pet for this study and its owner as its handler mimicked the same strong bond that a handler has with its USAR dog. Despite radiation doses being well below dangerous levels and keeping risks to a minimum, the dog and its owner still had to assume some risk for this study. Putting this relationship on the line to prove that the methods of this study are possible and that valuable information can be obtained from them gives great validity to this work in terms of understanding the emotional risks of allowing a dog to participate in this type of experiment. Lastly, since USAR canines and their handlers are often deployed during times of crisis with little notice, using a house pet also offered less logistical issues. The dog and the handler chosen for this study were readily available for training and evaluation before the actual contamination day. There was also no added work in planning for the ^{18}F to arrive, since there was no risk of the dog and handler being called away on duty.

4.2 PET/CT Scan Images

The participating canine received both a CT and PET scan over its whole body. The CT scan was done first so that the PET scan could be overlaid on top of it in order to gain a better understanding of the locations of internal and external contamination (hotspots). The scan was then divided up into 19 ROIs. All SUVs per ROI as well as the CT/PET scan images are located in Appendix A. The ROIs that showed significant SUVs (i.e., over 1) are shown in Table 4.1.

Table 4.1: ROIs that showed significant SUVs and their equivalent activity.

ROI	Location	SUV	Activity [Bq]
1	Right front paw	3.8027	644.6
5	Stomach	3.5392	748.3
6	Stomach	3.5099	595.0
13	Left back paw	3.4095	1008.9
12	Right back paw	3.2943	418.3
2	Left front paw	2.8041	236.8
4	Esophagus	0.6468	328.5
16	Esophagus	0.5073	278.9

Overall a total of 22 SUVs were calculated for the whole body. This equated to an activity of 3.392 kBq dispersed throughout the dog. External and internal contamination was also analyzed by splitting up ROIs based on location. As shown in Table 4.2, external contamination was represented by the paws and around mouth area by ROIs 1, 2, 12, 13, and 15. Internal contamination was represented by the rest of the ROIs: 3, 4, 5, 6, 7, 8, 9, 10, 11, 14, 16, 17, 18, and 19. External and internal contamination saw a total of 13.4 and 8.5 SUVs, respectively. This equated to an activity of 2.137 kBq externally and 1.256 kBq internally. External contamination represented 63% of total contamination while internal was 37%.

The highest levels of contamination were located in the areas that came into the most direct contact with the FDG, the paws. Contamination was also seen on the tail as shown in Figure 4.1 by the yellow highlighted area towards the bottom of the scan image. However, this was not characterized as an ROI by the viewing software. Other interesting locations that showed levels of contamination were the stomach and esophagus. While internal contamination was expected due to the dustiness of the rubble pile and resuspended ^{18}F, it was thought that the lungs, nose, or mouth would have shown the highest levels of internal contamination due to a dog's extensive use of smell.

Based on the the SUVs for the esophagus and stomach, it is clear that this internal contamination came from the ingestion of FDG. This is also validated by the experimental observation of the canine licking contaminated items and consuming a couple bits of contaminated kibble. Al-

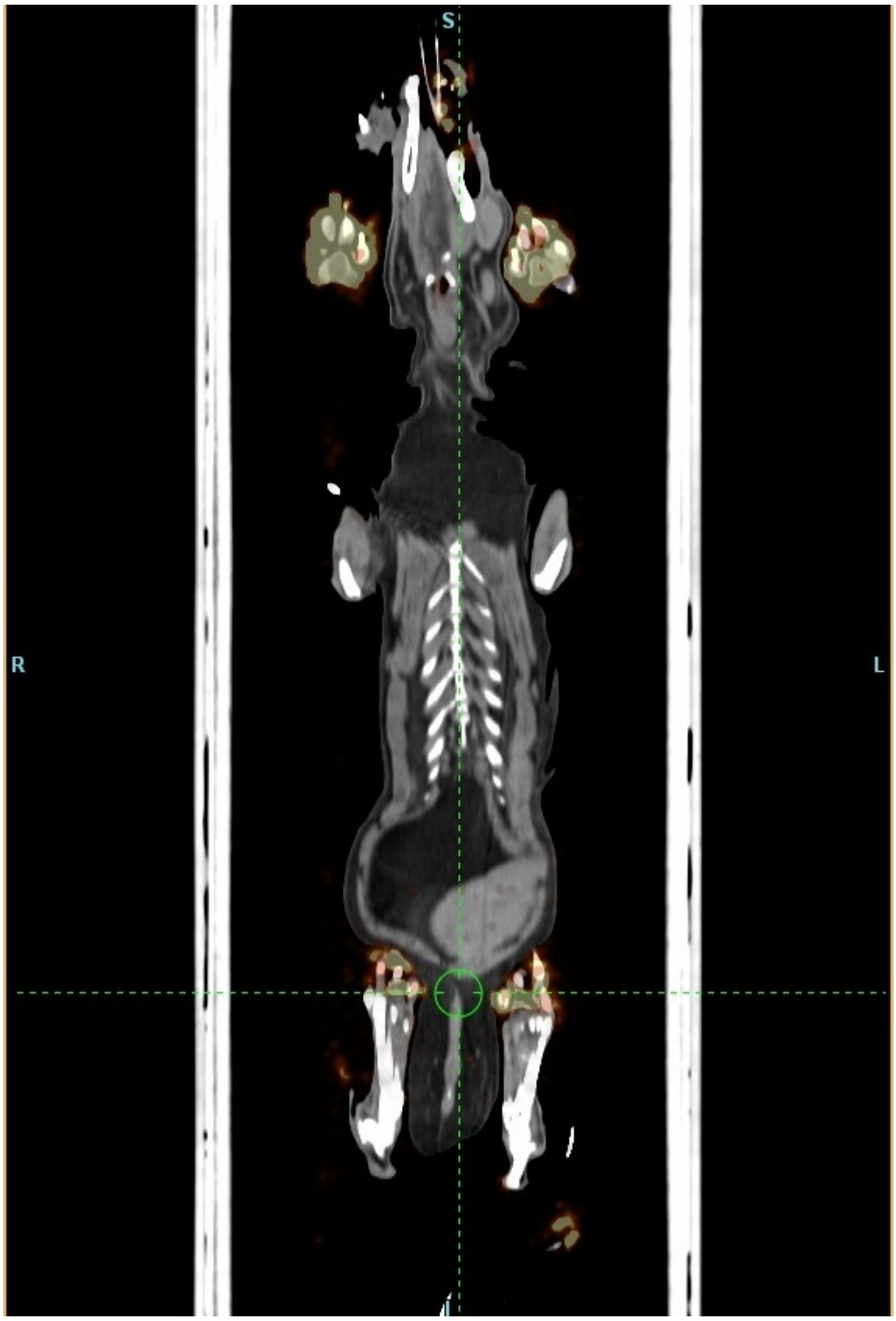

Figure 4.1: PET scan image of the underside view of the canine highlighting contamination on the back paws.

Table 4.2: Locations of contamination levels and SUVs detected from the PET scan.

ROI	Volume $[mm^3]$	Mean $[Bq/ml]$	SD $[Bq/ml]$	SUV	Location
1	27.9	23104.8	997.5	3.8027	Right front paw
2	34.8	17037.2	623.5	2.8041	Left front paw
3	27.9	109	47.2	0.0179	Trachea
4	48.7	3929.7	451.7	0.6468	Esophagus
5	20.9	21503.9	1365.2	3.5392	Stomach
6	13.9	21325.9	876.6	3.5099	Stomach
7	83.6	48.9	35	0.0080	Liver
8	90.5	0.94174	1	0.0002	Spleen
9	34.8	37.3	27.1	0.0061	Left kidney
10	34.8	0	0	0.0000	Right kidney
11	83.6	9.7	6.4	0.0016	Bladder
12	20.9	20015.4	1587.5	3.2943	Right back paw
13	20.9	20715.9	1035.8	3.4095	Left back paw
14	62.7	740.8	202.8	0.1219	Tracheal anterior wall
15	62.7	760.4	189.5	0.1252	Around mouth
16	62.7	3082.1	1153.8	0.5073	Esophagus
17	62.7	1100.8	257.8	0.1812	Esophagus
18	550	0	0	0.0000	Right lung
19	550	0.0039338	0.029464	0.0000	Left lung

though it is near impossible to keep a canine from eating and licking in the field, abstaining from these behaviors can drastically reduce internal contamination. While the total activity for internal contamination was 1.255 kBq yielding a dose of 1.19 mGy, the estimated uptake due to eating and licking (i.e., total contamination found in the esophagus and the stomach and not the lungs, trachea, or other organs) was 1.200 kBq, giving a dose of 1.14 mGy. This contributed to 96% of the total internal activity and 34% of overall activity as registered by the PET scan.

Overall, given the data from the PET scan and decay correcting to the time the dog first entered the room, the dog was contaminated (internally and externally) by 0.00265% of the total amount of ^{18}F released into the room.

4.3 External Dose & Contamination Analysis

Given a planned, initial source activity of 185 MBq (5 mCi) to an actual activity 200.5 MBq (5.419 mCi), this incurred a higher dose rate than originally estimated by about 10%. However, this

higher dose rate was still acceptable for this experiment and may have helped PET scan results. In addition to PET scanning and OSLDs placed on the dog, after the dog left the contaminated area, swipes were taken around the rubble pile and analyzed along with the air filter sample. The total set-up of the experiment can be found in Figure 4.2. Equipment and swipe locations are given in Table 4.3 and Table 4.4, respectively. The following subsections show how doses and dose rates were calculated throughout this study and how these computations related to the experimental data on contamination levels.

Table 4.3: Types of equipment and their location in the contaminated room as shown in Figure 4.2.

Letter	Item
A	air sampler
B	sink
C	camera/video recorder
D	cat carrier
E	kiddie pool
F	large black trash can
G	tire pile
H	gray trash can
I	outline of contaminated area

Table 4.4: Predetermined swipe locations for the contaminated room as shown in Figure 4.2.

Number	Item
1	on ground at the left, front corner the of contaminated box
2	on ground at the left, back corner the of contaminated box
3	on ground behind the pile of tires
4	on ground at the right, front corner the of contaminated box
5	inside the floor of the kiddie pool
6	on ground near the air sampler
7	air sampler filter

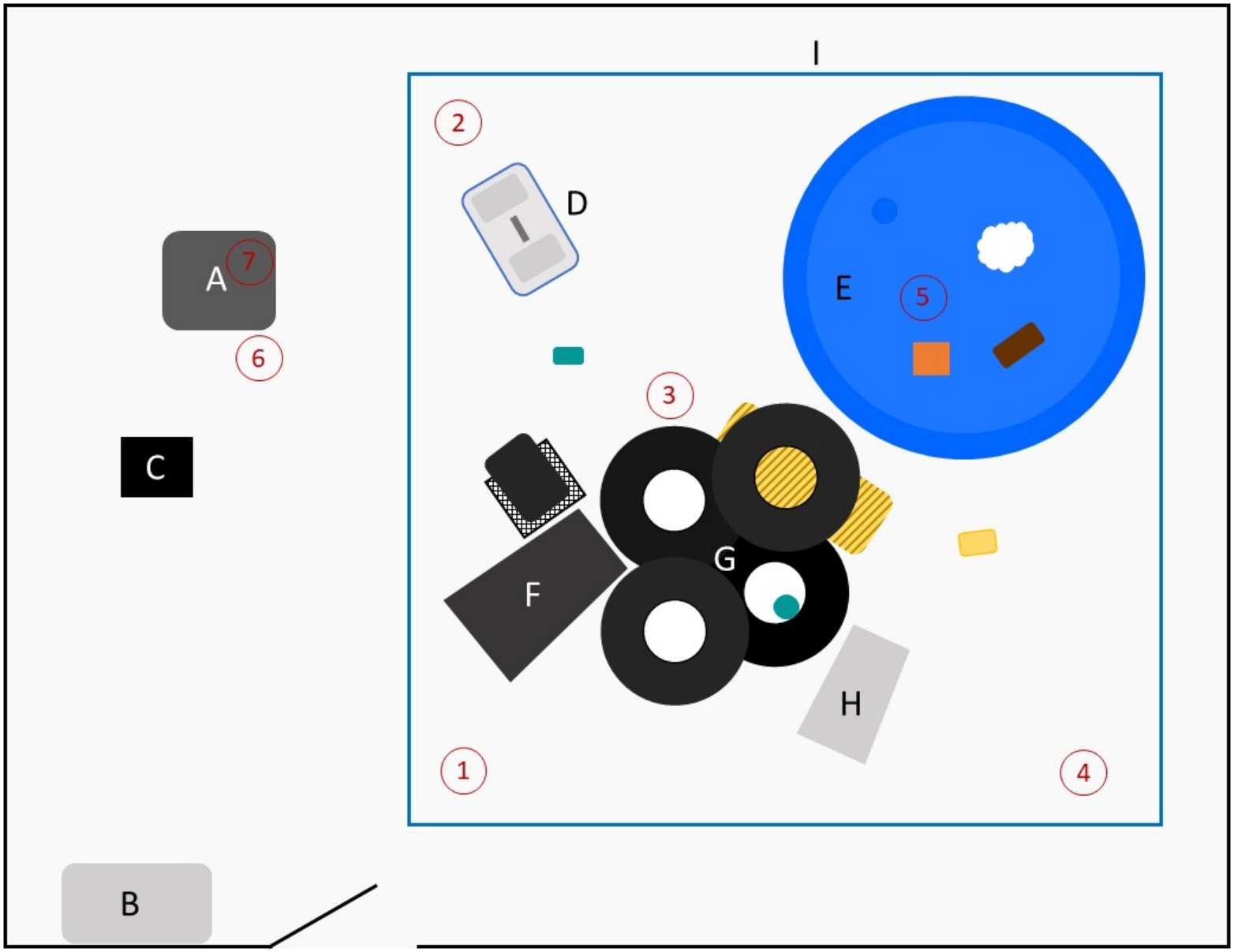

Figure 4.2: A diagram representing the experimental set-up of this study. (Not to scale.)

4.3.1 Whole Body Dose Analysis

The OSLDs on the dog registered 0.03 mGy for the one on the collar and 0.04 mGy for the other two. However, the minimum detectable quantity for photons was 1 mrem $\pm$ 2 mrem and 10 mrem $\pm$ 2 mrem for positrons (0.01 $\pm$ 0.02 mGy and 0.10 $\pm$ 0.02 mGy, respectively).[24] This means that there could have been up to 0.12 mGy of positron dose not registered by the OSLDs. Using the DRCF of 6.93 mGy cm^2 Bq^{-1} yr^{-1} and decay correcting the initial activity of the source, theoretically the dog should have received a dose of 0.19 mGy using this method. The theoretical dose yields a higher calculated value because it does not take into account the movement of the canine. [20] Due to the objects present in the contaminated pile, the dog spent most of its time walking around the inside perimeter of the pile. This yields a smaller dose compared to if it had spent the whole time in the middle of the pile.

Given the total activity at the time the dog entered the room and the area of the contaminated pile, if the FDG was evenly distributed, there should have been an average 0.169 MBq per 100 cm^2, or per swipe sample. Swipe samples and their activities, decay corrected for when the dog first entered the contaminated room, are given in Table 4.5. Aside from swipes 6 and 7, which were outside the contaminated area, each swipe taken is well above the calculated value. This could be for a few reasons. The most likely is due to uneven spraying since there was no way to regulate activity per area when applying the FDG to the pile. The second reason is that the room was slightly sloped at the edges because there was a drain around the inside perimeter of the room. This could contribute to the right side of the pile showing a higher activity. Lastly, since only five samples were taken inside the pile, more samples would have needed to be taken in order to get a better idea of the distribution of the contamination throughout the pile. Calculating an average activity of 1.138 $\pm$ 0.212 MBq per 100 cm^2 area from Table 4.5 gives a total contaminated area activity of 1057 $\pm$ 197 MBq. Therefore the dose to the dog from the pile using this activity and DRCF was calculated to be 1.30 $\pm$ 0.24 mGy. However, using the swipe data to calculate dose this way proved inaccurate because only a total of 200 MBq was sprayed over the pile.

Each dose value and their method of calculation is given in Table 4.6. Calculating the theo-

Table 4.5: Detected activity from swipes around and inside the contaminated area. Swipes 1-6 covered an 100 cm^2 area while swipe 7 was from the air filter.

Location	Corrected Activity (MBq)	Error (MBq)
1	0.495	0.0317
2	0.342	0.0219
3	0.854	0.0546
4	1.040	0.0666
5	2.960	0.1894
6	0.011	0.0009

Table 4.6: Whole body dose calculations to the dog based on various methods.

Method	Dose [mGy]	Uncertainty [mGy]
OSLDs reading	0.0367	0.02*
Theoretical with DRCFs	0.1867	-
Calculated from swipes	1.2960	0.2409

*(Although up to 0.10 mGy may have been undetected.)

retical dose to the dog using the swipes yielded the highest dose, but the OSLDs registered the lowest dose. These two methods were different by nearly an order of magnitude. However, the OSLDs readings were within two sigmas of the theoretical dose calculation with the DRCFs. In the future using swipe data could be more accurate to calculate total dose by taking more samples and ensuring each swipe is only over an 100 cm^2 area.

4.3.2 Skin Dose Analysis with VARSKIN

In order to analyze the absorbed dose into the dog's metacarpal and digital pads (i.e., the skin located on the bottom of the dog's paws), VARSKIN was used. VARSKIN is a software that calculates dose or dose rate to a designated area of skin based on different sources, types, and source geometry. Since VARSKIN is a software created to calculate dose for humans, some assumptions were made in order to apply it to canines.

The first assumption was that the surface areas on the bottom of the dog's paws received a direct dose from the ^{18}F. The ^{18}F suspended in the air was considered insignificant and attenuated

by air and fur. Each front paw measured an area of 38.5 cm^2, while each back paw measured an area of 30 cm^2. This includes the areas of the pads and the skin connecting them together. Another assumption that was made was the thickness of the dog's skin. VARSKIN requires an input of either skin thickness or skin density; however, both of these inputs cannot be given at once. It was assumed that the skin on the bottom of the paws had a thickness of 10.1 μm which is about one third thicker than human skin.[25] This is an average because the metacarpal and digital pads are usually thicker than other skin on a canine's body. The metacarpal pad is also constructed differently from the human skin, not only in terms of texture, but there is also an extra fatty layer under the pad to provide more cushion to the dog when it walks. Lastly, canines have sweat glands underneath their paw pads which is a major difference between humans and canines. This may affect how radiation is absorbed through the skin. However, despite all of these differences, they were considered negligible so that VARSKIN could be used.

The last major assumptions pertained to the geometry of the experiment. Initially the room was to be modeled as a finite plane source with an even source density, not taking into account the items that were placed in the contaminated area. However, the VARSKIN user manual recommended using a cylinder source to model this slab or plane like geometry, as the writers of the manual stated that the cylinder source geometry is actually more accurate.[26] Both geometries were modeled so that they could be compared. Another assumption was the perfectly even distribution of ^{18}F throughout the contaminated area. This was necessary because VARSKIN was unable to handle the 100 ft^2 area, so the problem was scaled down to just the paw area. This was done by taking a ratio of the paw area and the contaminated area and multiplying this ratio times the total activity on the ground to get the amount of activity that would have been located on the dog's paw. Ultimately, this modeled a disk source on the bottom of the dog's paw with the same area. Lastly, VARSKIN models the dose calculations by assuming that the skin is above the middle of the source geometry given. However, since this dose calculation uses the same area of skin and source this will give an absorbed dose rate lower than expected since the whole area of the pile cannot be modeled, but this is considered a reasonable estimate since this is only analyzing the dose received to the paws.

After general assumptions were made, the dose calculations were computed. VARSKIN is a relatively simple program that includes a graphical user interface (GUI) that requires the user to input values each time they use the program. A sample input screen for calculating the dose to one front paw is shown in Figure 4.3 with the outputs shown in Figure 4.4. Absorbed dose values to different paws based on different geometry types are located in Table 4.7.

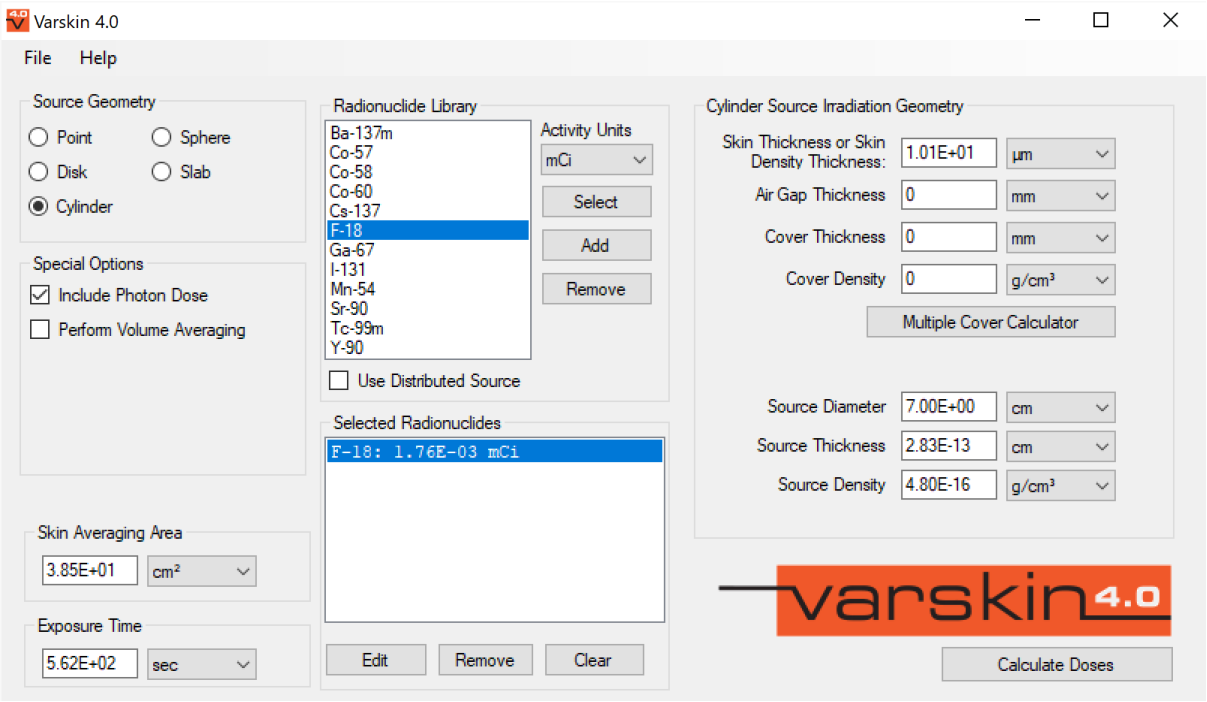

Figure 4.3: A screen shot of the VARSKIN GUI used to input parameters to calculate dose to the skin.

As mentioned by the VARSKIN manual, some uncertainty can be caused from the slab geometry. It produces an absorbed dose about 50% greater in the back paw than in the front paw, even though both paws were exposed to the same activity per area, yet the back paw has less area. These doses are also 5 to 8 times lower than what the disk geometry calculated. Based on the disk geometry, the canine would have received a total dose of 0.323 mGy to the skin on its paws, while based on the slab geometry, the canine would have received a total dose of 0.0528 mGy to the skin on its paws. The 0.323 mGy from the disk geometry offers a more conservative value.

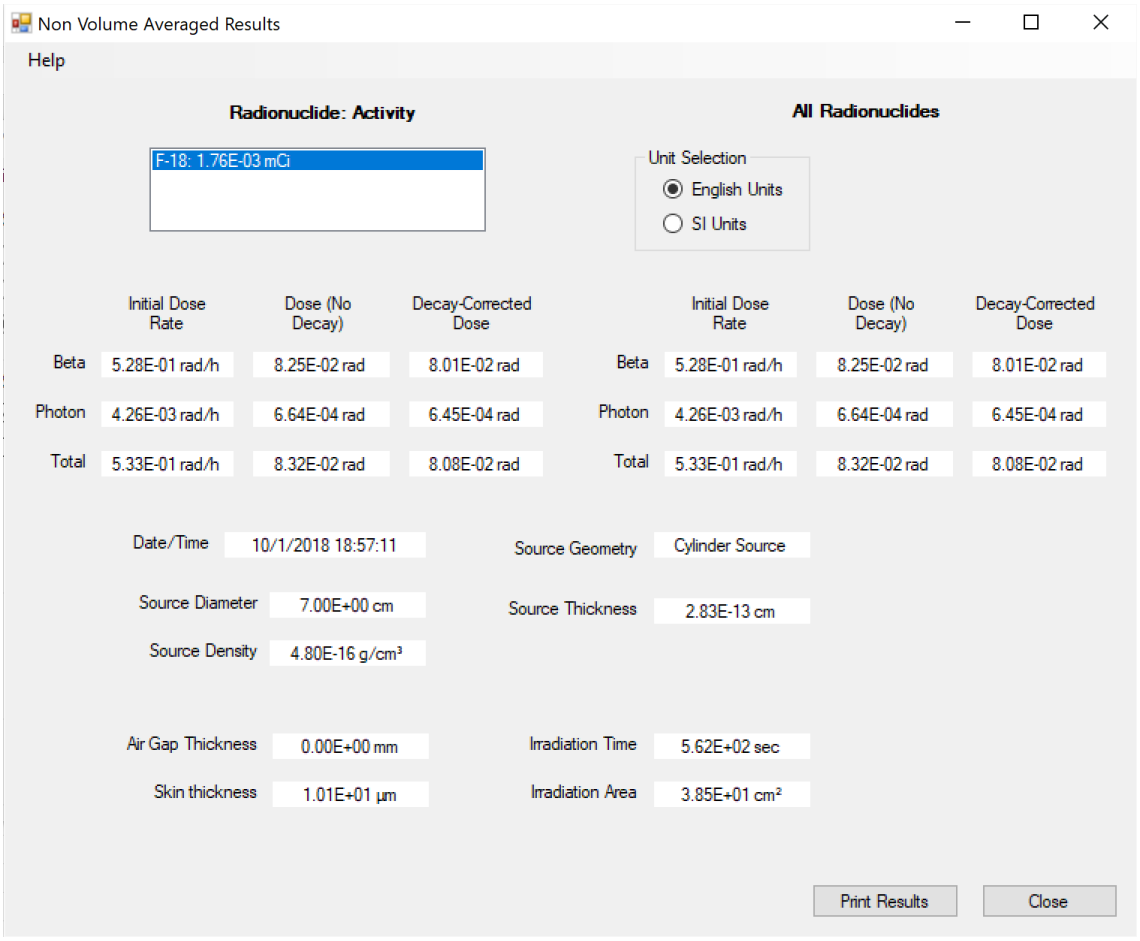

Figure 4.4: A screen shot of the outputs generated by VARSKIN after a dose calculation has completed.

4.4 Internal Dose & Contamination Analysis

Using the PET scan activity data, the total internal contamination to the dog was analyzed. Due to the lack of research and information on tissue weighting factors for canines, the total internal absorbed dose was calculated. This was done by averaging the dimensions and compositions of the dog and creating a representative sphere with a radius of 19.9 cm and a density of 1 g cm^{-3} (the density of water). The radius was determined using the weight of the canine (33.1 kg) and the density of water. After creating the sphere to represent the dog, the total internal contamination from each ROI was totaled and assumed to be located in the center of the constructed sphere in order to simplify dose calculations. Figure 4.5 shows this set-up.

Table 4.7: Absorbed dose outputs from VARSKIN based on different source geometries.

Paw	Source Geometry	Decay Corrected Dose [mGy]		
		Beta	Photon	Total
Back	Cylinder	7.99E-04	6.18E-06	0.806
Front	Cylinder	8.01E-04	6.45E-06	0.808
Back	Slab	1.57E-04	2.79E-06	0.159
Front	Slab	1.02E-04	2.87E-06	0.105

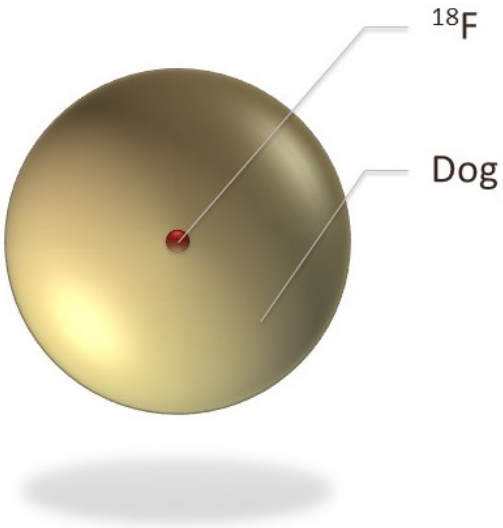

Figure 4.5: Figure representing the averaged dog sphere and collection of all internal ^{18}F into the center of the sphere.

Eq. 2.4 was used to calculate internal absorbed dose. It was assumed that 100% of positrons and 85% of gamma rays were absorbed into the dog. This was determined by using simply attenuation calculations and assuming that all radiation that interacted with the dog was 100% absorbed. This gave a most conservative dose estimate. These assumptions and calculations yielded an internal absorbed dose of 1090 μGy with 1044 μGy coming from the dog eating in the field.

In addition to PET scan data on total internal contamination, lung contamination was further analyzed by using data from the air filter sample. While airborne radioisotopes contribute to external contamination, they yield a higher dose if they become internal contaminates. The air filter was initially turned on right before the spraying of ^{18}F began and right after the dog left the room. This means that the air filter was exposed to more contaminated air than the dog. However, using contamination information from this air filter is still insightful because it can give the maximum possible activity inhaled by the dog.

In order to find the volume of contaminated air breathed in by the dog, the time the dog spent in the contaminated pile and the respiratory minute volume was used. This was done by multiplying the tidal volume (amount of air moved by breathing) by the average number of breaths per minute. For a dog this size, the tidal volume was equal to 15 mL kg^{-1}, and the average number of breaths per minute was 24.[27][28] This equated to 111 L of air that passed through the dog's lungs while it was exploring the pile. Given the activity of the air filter from Table 4.5 and that the air sampler processed 3200 L of air in one hour, a maximum of 120 Bq (3.23 nCi) could have been inhaled by the dog.

As shown by values in Table 4.2 the total internal contamination related to breathing (lung and trachea ROIs) was 49.5 Bq. While this value should be lower than the calculated value since the dog was only exposed to ^{18}F in the air due to resuspension, there are some other factors that would affect the 2.5 times difference between the calculated activity and the actual inhaled activity. The first was that the air sampler was not directly placed inside the pile, and the second was that the air sampler was not at the breathing height of the dog. If the sampler was placed in the pile, at a lower level, and only filtered during the time the dog was in the room, this would have given

air concentrations closer to what the dog actually experienced. The air sampler was originally not placed in this manner due to safety reasons for the dog and so that the air filter would not be sprayed on directly. The air filter could not be turned on for only when the dog was in the room because it was needed to measure the airborne activity for the whole duration of the experiment.

Given the activity found in the dog's respiratory system, the absorbed dose rate from internal contamination for each ROI was calculated using Eq. 2.4. Then, using those absorbed dose rates and Eq. 2.2, the equivalent dose rates were calculated. Those values can be found in Table 4.8. As expected, those dose rates were considerably lower than the dose rates from external contamination. The highest internal contamination found in the respiratory track was in the tracheal anterior wall. There was little, if any, internal contamination found in the lungs.

Table 4.8: Dose rates from internal contamination in the respiratory track.

ROI	SUV	Location	Activity $[Bq]$	Dose Rate $\left[\frac{\mu Gy}{hr}\right]$
3	0.018	Trachea	3.041	2.90
14	0.122	Tracheal anterior wall	46.448	44.3
18	0.000	Right lung	0.000	0.00
19	0.000	Left lung	0.002	0.00

The tracheal anterior wall is the inside wall of the trachea, opposite of the esophagus. A depiction of this anatomy is found in Fig. 4.6. The accumulation of ^{18}F in the tracheal anterior wall could be due to the method in which a dog follows scents. When tracking or identifying smells, a dog most often keeps its head low to the ground causing a dog's trachea to be more parallel to the ground than a human's normally would be. Gravity could cause denser molecules to settle more into the trachea before they reach the lungs causing a higher dose rate than in the lungs or any other part of the trachea.

Respiratory internal contamination is of particular concern because it cannot easily be removed from the body. Unlike contamination in the digestive track, which can be excreted from the body through natural processes, the body offers few similar processes in the respiratory system aside

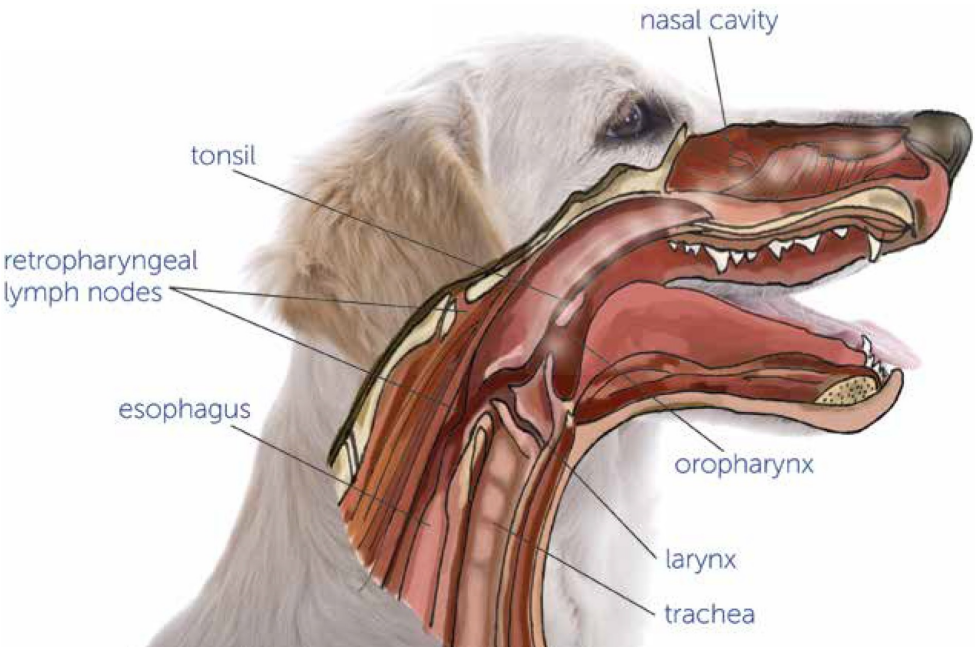

Figure 4.6: Drawn depiction of the upper anatomy of a dog. Reprinted from "Anatomy of dog trachea". [3]

from coughing and sneezing. The lack of internal contamination found in the respiratory system of the canine is a critical finding because it shows dogs may not be as susceptible to this type of contamination as originally thought.

5. CONCLUSIONS

Overall, PET scanning proved to be a very viable way to identify internal and external ^{18}F contamination in and on a canine. PET scanning also provided valuable insight into the locations of higher levels of radioactive contaminant accumulation. In terms of external contamination, it validated that the dog would experience highest contamination levels on locations where the dog was continuously and directly exposed to the radioactive isotope. In the future, PET scans could be useful in identifying the contamination risks USAR dogs face by navigating through contaminated rubble piles, thus, increasing their risk for external contamination. In terms of internal contamination, PET scans could provide insight into how increased aerobic activity (i.e., increased respiratory minute volume) affects the total amount of activity found in lungs after radioactive exposure.

This study also showed that an USAR dog can drastically reduce its internal exposure by refraining from eating, drinking, or licking in a contaminated environment. Although, it is impossible to completely prevent a canine from consuming while on the pile, keeping the dog well fed and hydrated will offer some assistance in mitigating this issue. External contamination is also not avoidable by a working dog. Therefore, during decontamination, it is recommended to emergency responders to focus on the paws of the dog (or anywhere else that comes into constant and direct contact with radioactive contamination). Detailed external decontamination is important in order to prevent further internal contamination from when a dog grooms. In the future PET scans could even be used to determine the effectiveness of a decontamination bath.

Lastly, but most importantly, this proof of concept experiment was proven possible and successful. This method of contamination and analysis provides the first stepping stone to gaining further knowledge into assisting and better understanding USAR dogs in a radioactive contaminated environment. Future works can include more dogs in order to get a statistical understanding of hot spot locations, utilizing trained USAR dogs on a typical mission, include air sampler and dosimeters at dog level or on the dog to get even a clearer understanding of the dose rates they face, and lastly, expand this type of study to include different isoptopes, longer exposure times,

or even a wider or outdoor area. Overall, completing this proof of concept study provides just as many opportunities to continue to serve the USAR dog community as they have served for us.

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APPENDIX A

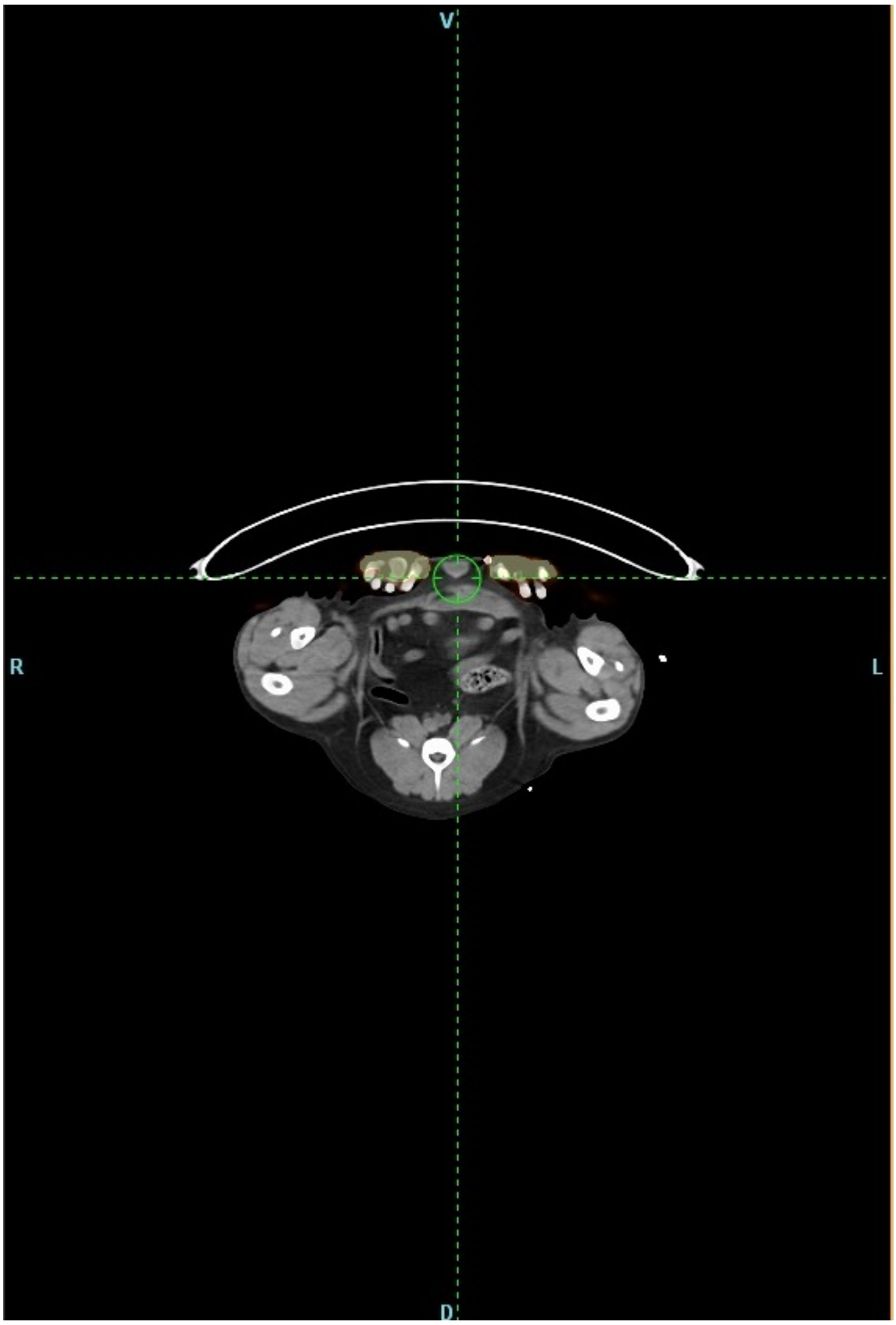

Figure A.1: Cut through PET scan image highlighting contamination on the back paws of the canine.

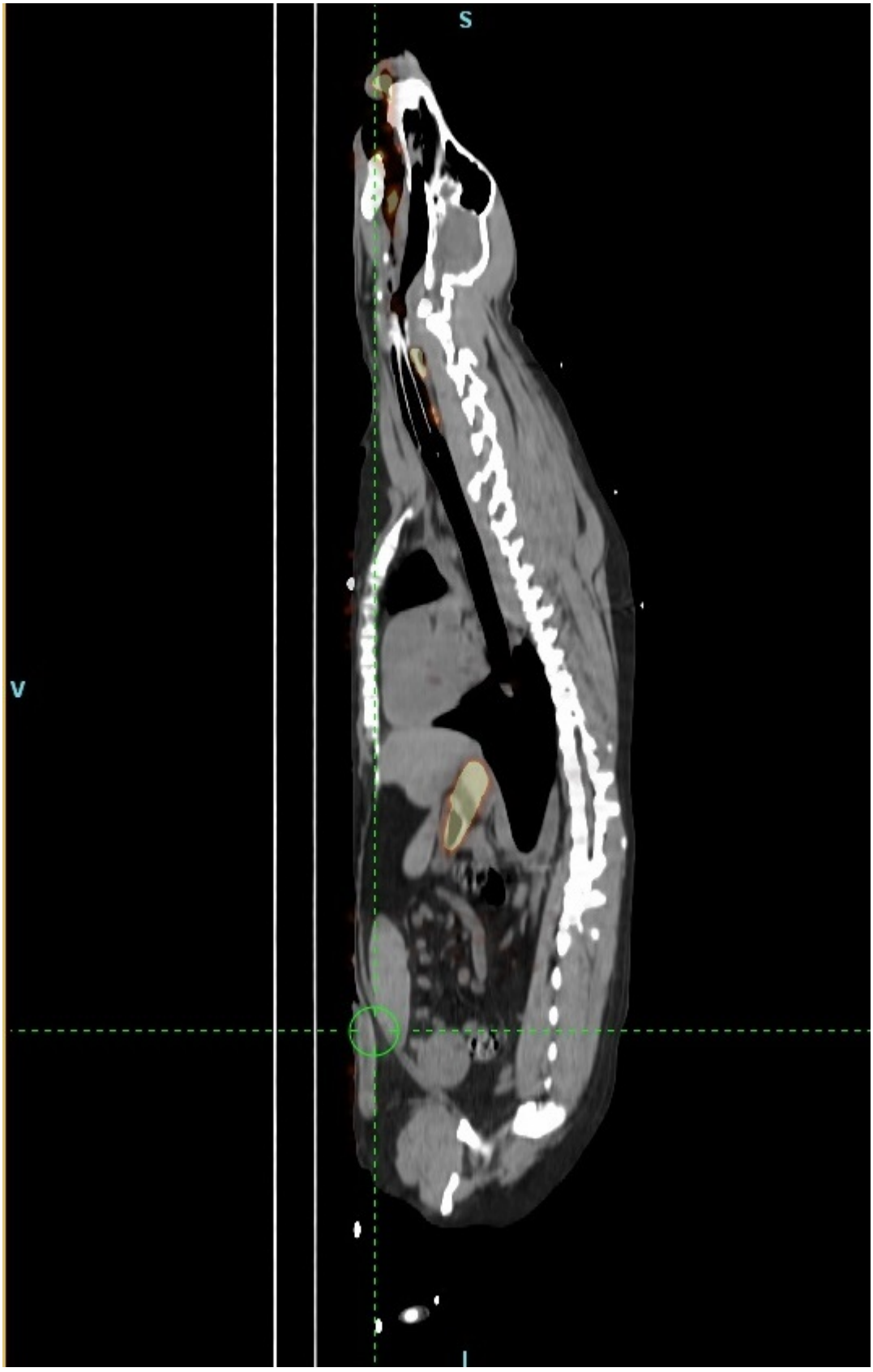

Figure A.2: PET scan image of the side view of the canine highlighting contamination on the back paws.

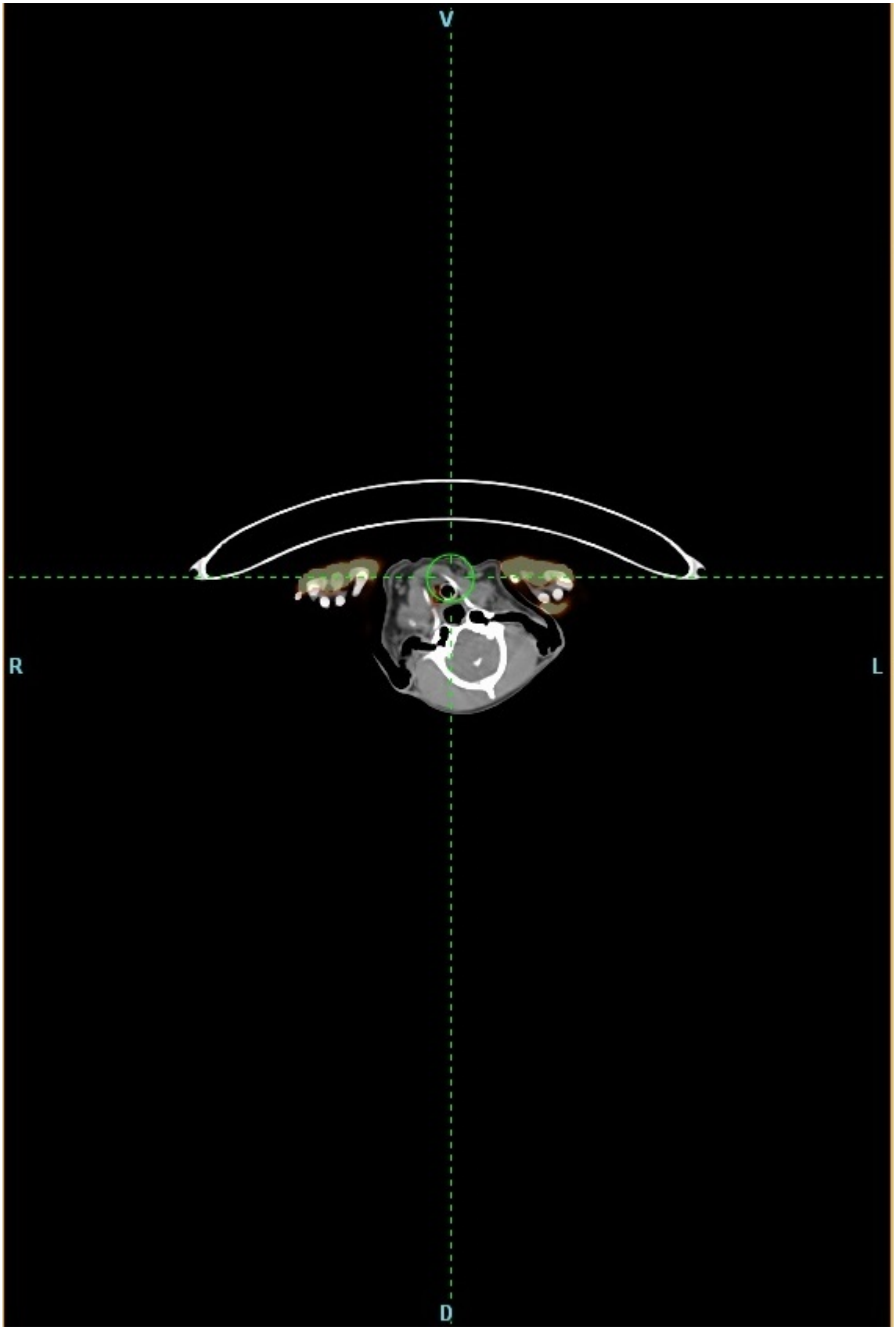

Figure A.3: PET scan image cut through the front of the canine highlighting contamination on the front paws.

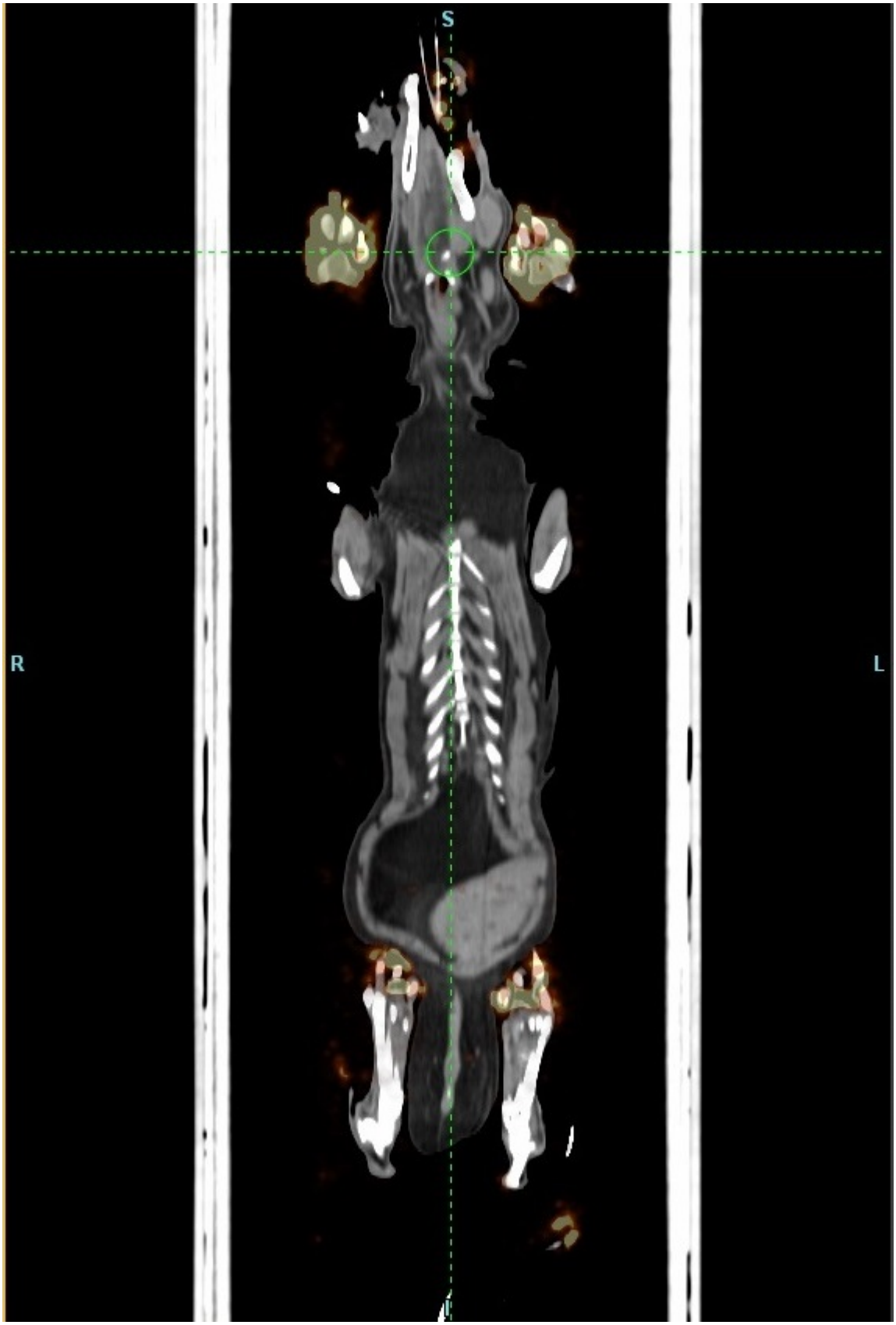

Figure A.4: PET scan image of the underside view of the dog highlighting contamination on its front paws.

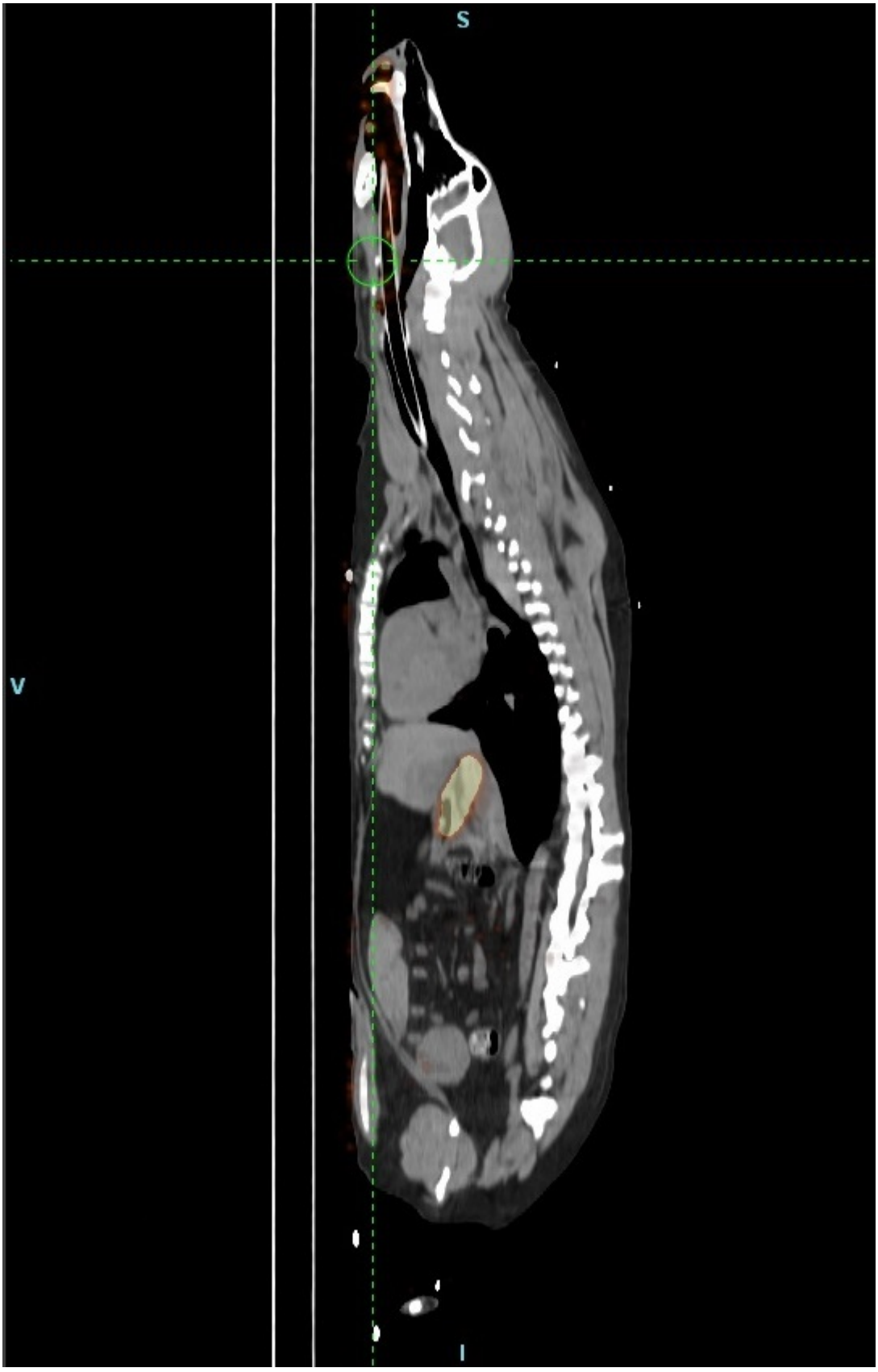

Figure A.5: PET scan image of the side of the canine highlighting contamination on its front paws.

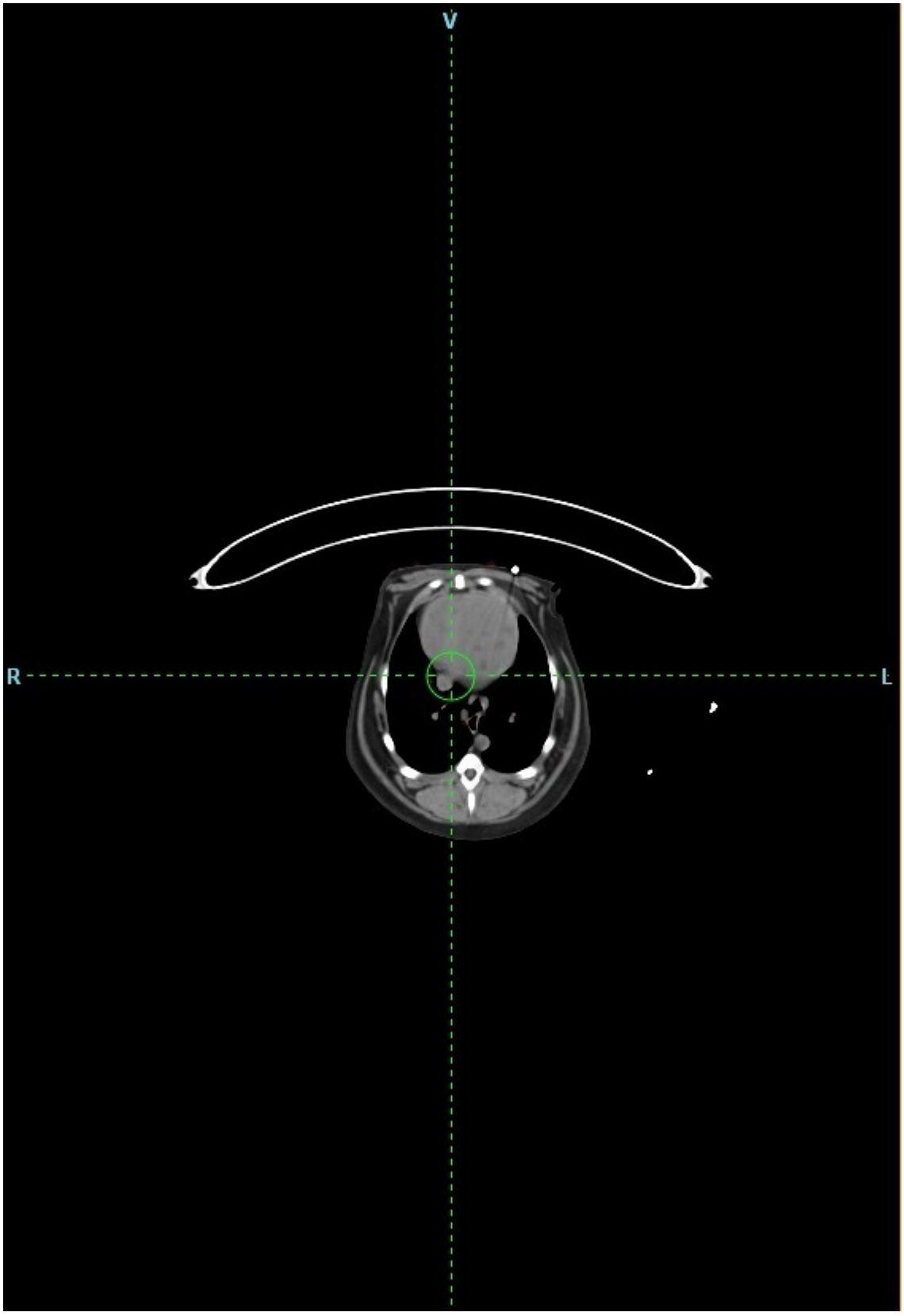

Figure A.6: PET scan image cut through the middle of the dog highlighting contamination in the digestive track.

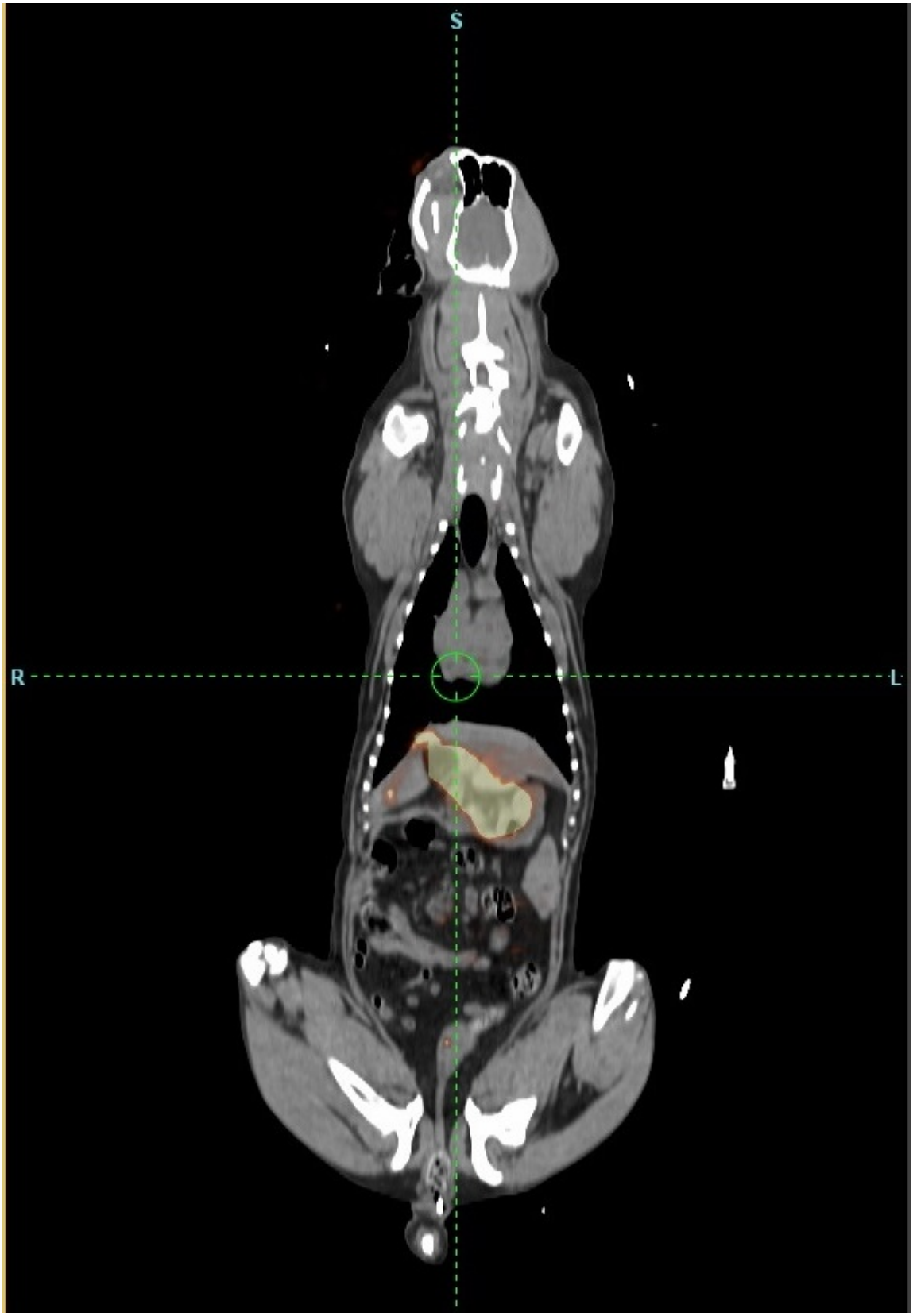

Figure A.7: PET scan image of the underside view of the dog highlighting the contamination in the digestive track.

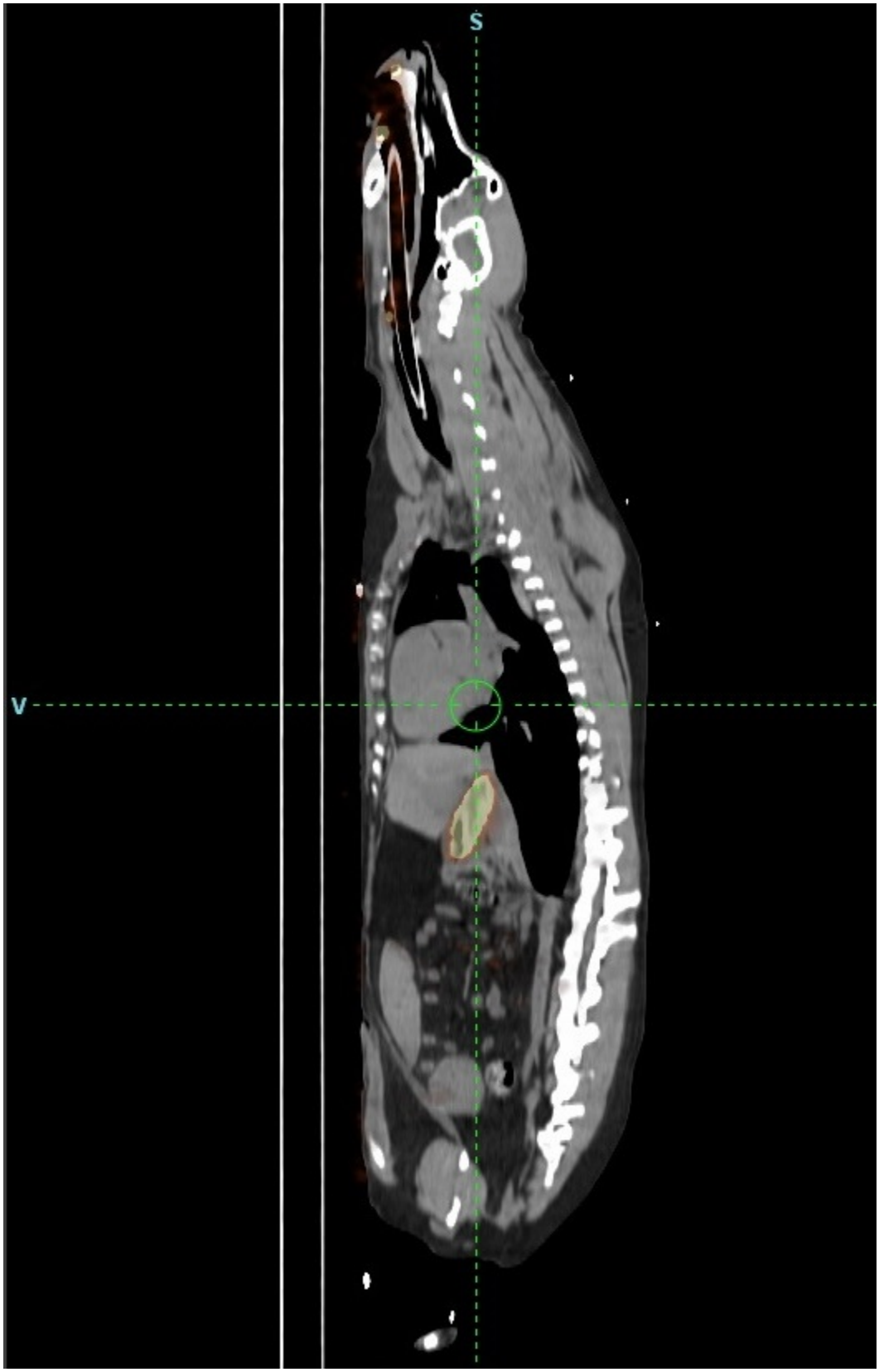

Figure A.8: PET scan image of the side view of the dog highlighting the contamination in the digestive track.