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INTERNAL & EXTERNAL DOSE RESEARCH ON HUMAN EXPOSURE TO PETS RECEIVING MEDICAL ADMINISTRATIONS OF RADIOACTIVE MATERIAL

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EXECUTIVE SUMMARY

In the United States, veterinary uses of radioactive material are regulated by the U.S. Nuclear Regulatory Commission (NRC) and Agreement States. Because growth in the number and variety of veterinary diagnostic and therapeutic procedures has outpaced updates to regulatory requirements and supporting guidance, inconsistencies have arisen in radiological recommendations, administrative controls, expectations by regulatory authorities for demonstrating compliance, and instructions issued to owners and caretakers. Under funding by NRC, RCD Radiation Protection Associates began to investigate potential internal and external dose to humans following the administration of current and emerging radionuclides to felines (cats), canines (dogs), and equines (horses). External and internal doses were assessed based on available information in the literature for potential sources from veterinary administrations of radionuclides. External dose rates were estimated using MCNP6 and the PIMAL software. Internal doses were approximated based on the potential for a human to inhale or ingest radioactive material following the veterinary administration. Conservative assumptions were intentionally applied so that future emphasis and consideration could be devoted to selected procedures with the greatest potential to exceed regulatory limits.

From the perspective of total effective dose equivalent (TEDE), administrations of ^{131}I to felines and canines for cancer therapy represent the greatest potential for exceeding a dose of 1 mSv. A smaller potential exists for exceeding dose limits after ^{117m}Sn radiosynovectomy in canines. Current equine procedures have a very low potential for exceeding dose limits provided that members of the public are prevented from coming into close contact with the animal during ^{192}Ir eyelid brachytherapy and during the first several hours after ^{99m}Tc imaging. Compared to current veterinary procedures, lower risks of exposure were found for emerging radionuclides evaluated in this assessment. Although alpha-emitting radionuclides have yet to be proposed for veterinary use, they can have internal dose coefficients that are more than 10-times greater than those for current veterinary radionuclides. If alpha-emitting radionuclides are ultimately proposed for veterinary use, the transfer potential of the radionuclide (from animal to humans) should be estimated so that internal doses can be assessed. Although conservative assumptions were adopted in this initial assessment, nothing in this report diminishes the obligation of licensees to provide detailed information on specific radionuclides and animals for licensing review.

1 INTRODUCTION

Ionizing radiation in veterinary medicine is used generally to obtain diagnostic information or to achieve a preferred therapeutic outcome. Potential doses to members of the public (including animal owners) who may be exposed to radiation emitted by radiopharmaceuticals following their administration in domestic animals have been estimated. Herein, an analysis of the potential external and internal dose received by members of the public is performed. Because veterinary uses of radioactive materials continue to expand, this report investigates an array of medical procedures performed on three domestic animals (i.e., cats, dogs, and horses). Outcomes of this investigation are to:

1. verify the radiopharmaceuticals of veterinary concern;
2. determine which animal-to-human exposure pathways are most important;
3. estimate radiological doses for potential exposure scenarios; and
4. identify circumstances for which human doses could be above regulatory limits.

Veterinarian use of radiopharmaceuticals is increasing, so there are areas with data gaps that are acknowledged in this report. While these data gaps can be significant, internal dose analysis is still performed, but with specific assumptions. Additionally, this document does not report on original work to close data gaps.

The remainder of this report provides a brief regulatory background; a description of methods used for the external and internal dose assessments; presentation of results for felines, canines, and equines; a discussion of emerging radionuclides; a summary; and recommendations.

2 BACKGROUND

Regulation of ionizing radiation use in veterinary medicine is shared among several federal, state, and local government agencies. The U.S. Nuclear Regulatory Commission (NRC) or the responsible Agreement State has regulatory authority over the possession and use of byproduct material in veterinary medicine. In this case, byproduct material refers to the radionuclides used in veterinary radiopharmaceuticals and devices. A byproduct material veterinary-use license is issued by an Agreement State or NRC pursuant to Agreement State regulation or the federal regulation at 10 CFR Part 30, "Rules of general applicability to domestic licensing of byproduct material."

Animals administered a radioactive compound or receiving implanted radioactive sources cannot be released until the veterinarian has reasonable assurance that radiation dose received by any member of the public from the animal will be within the limits established in 10 CFR Part 20.1301, “Dose limits for individual members of the public." Regulations in 10 CFR Part 20.1301 require that the total effective dose equivalent (TEDE) [which includes dose from both internal and external sources] to an individual member of the public from the licensed operation does not exceed 1 millisievert (mSv) [100 millirem (mrem)] over the course of a year and that the dose rate in any unrestricted area from external sources does not exceed 0.02 mSv [2 mrem] in any one hour. Members of the public include bystanders, pet owners, family members, or other caretakers of the animal not employed by the licensee. Presently, human consumption of treated animals is not credible because no radioactive veterinary drug has been approved for use in animals intended for the human food supply.

Current NRC guidance publications address human-to-human exposure under 10 CFR Part 35, ““Medical use of byproduct material,” rather than animal-to-human exposure under 10 CFR Part 20, “Standards for protection against radiation.” For example, 10 CFR Part 20 contains a restriction on the maximum hourly external dose rate in any accessible area, but there is no equivalent requirement in 10 CFR Part 35. Available methods, tools, and knowledge need to be developed so that licensees have data that are accurate and appropriate at the closest distances necessary for demonstrating regulatory compliance. Some amount of close contact between pets and adults or children can be expected following pet release from medical procedures. Total dose to each exposed individual is the summation of internal and external doses, and a full pathway analysis is justified.

Current veterinary procedures for cats, dogs, and horses are carried out using one of five primary radionuclides, ^{131}I, ^{99m}Tc, ^{117m}Sn, ^{125}I, and ^{192}Ir. Several additional emerging procedures are under consideration and have been studied in the clinical setting, namely, ^{18}F (canine imaging), ^{90}Y (canine skeletal treatments), ^{153}Sm (canine palliative care), ^{166}Ho (equine synovectomy), and alpha-particle emitters (none proposed). This report provides initial analytical results for beginning to address technical questions on external and internal dose assessments for authorizing the release of pets administered radioactive material for medical purposes.

Additional work is needed to assess internal dose pathways, animal biokinetics of emerging radiopharmaceuticals, and guidelines on negligible amounts of administered activity with respect to potential internal doses. Improved dose-based methods for external exposure are needed for demonstrating compliance, including for example geometric and tissue attenuation considerations for adults and children in proximity to pets following radiopharmaceutical procedures.

3 METHODS

This section introduces methods utilized for external and internal dose assessments. External and internal dose results are presented separately for felines (Section 4), canines (Section 5), and equines (Section 6). Because the assessments utilized very conservative assumptions, external and internal doses were not summed to determine total effective dose equivalents (TEDE) in this report.

3.1 External Dose Assessment

MCNP6 was used in conjunction with the PIMAL software (Dewji et al. 2017) to model and calculate dose to humans in various scenarios where animals have undergone therapeutic or diagnostic administration of radionuclides. PIMAL provides a detailed human phantom consisting of 24 separate organs and allows the user to manipulate arm and leg positions. PIMAL then generates an MCNP input file for the phantom in the desired position. For this work, source emission data were obtained from ICRP 107 (2008). All photons with energies greater than 10 keV and yields greater than 0.1% were included in the source distribution. One-hundred million particle histories were performed to pass tally statistical checks. The simulation was run in physics mode "p" to denote photon-only results. Images from the MCNP Visual Editor (VisEd) are included in this report to provide perspective, but readers are cautioned that 2D views of 3D objects can appear skewed in size.

External dose calculations are based on two conservative assumptions: (1) the occupancy factor for all total dose measurements is assumed to be 100%; and (2) no hold times are implemented. In other words, exposure to the individual is considered to begin immediately following administration; this assumption provides a very conservative scenario for post release of the pet. Furthermore, setting the hold time to zero with an occupancy factor of 100% provides the maximum potential dose, allowing a straightforward adjustment of dose for specific release times and occupancy durations as needed. Decay prior to a specific release time can be calculated utilizing the radioactive decay equation, and occupancy durations can be applied as a percentage of 24 hours spent in proximity to the contaminated animal.

Initial Scatter Simulation

Initially, a basic Monte Carlo simulation model was created using the MCNP6 software to quantify the effect of animal body material behind a modeled radioactive joint (e.g., elbow, knee). The simulation was designed to determine the importance of considering the animal's body as a contributor of additional dose to the caregiver due to secondary photon scatter. Four simulation geometries were tested using a combination of target distance and joint size as the variables. Uniform spheres of tissue were modeled with radii of 2 and 5 centimeters to represent small and large joints, respectively. Source-target distances of 50 and 100 centimeters were selected. For each combination of distance and joint size, the simulation was performed twice: once with scatter material (body mass of treated animal) and once without. The difference in dose was then compared to determine if secondary photon scatter is significant. Table 1 provides the results from the simulations, indicating that with body mass present, secondary scatter provides approximately 10% additional dose. Therefore, exposure scenarios that follow will include the whole animal to account for potential scatter contributions to external dose.

Table 1. Scatter contribution from the animal's body to human dose rates from radioactivity in a joint.

Receptor Distance	Joint Size	Scatter Material	# Tracks Entered	Dose (MeV/g) x 10^{-8}	Animal Scatter Contribution
50 cm	2 cm	No	822	7.15	7.7%
		Yes	921	7.70	
	5 cm	No	668	5.95	8.9%
		Yes	751	6.48	
100 cm	2 cm	No	2140	1.86	11.8%
		Yes	2500	2.08	
	5 cm	No	1655	1.47	12.2%
		Yes	1963	1.65	

Feline/Canine Geometries Considered

Nine different geometries were created to determine external dose rates for commonly encountered exposure scenarios. Three geometries were considered for each animal; examples are shown in Figure 1. Due to similarities in behavioral patterns, felines and canines were evaluated for the same exposure positions, but with consideration of different anatomical features, size, etc.

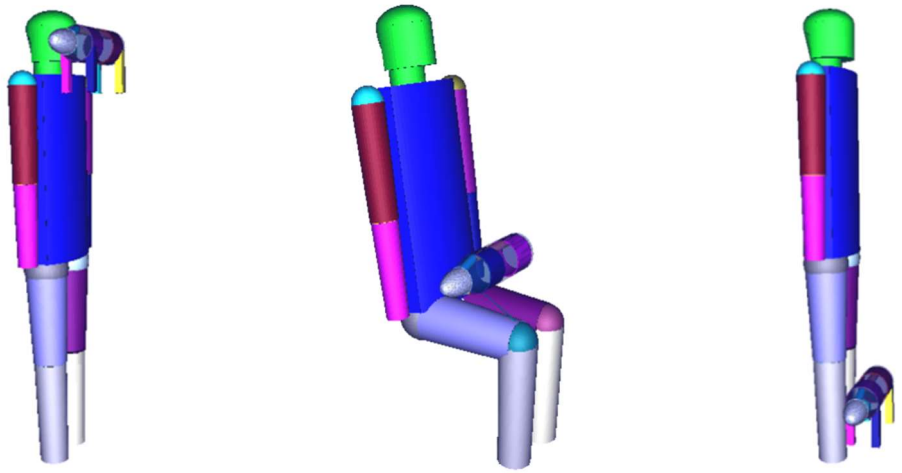

Figure 1. Exposure scenarios considered for both felines and canines.

Feline/Canine near owner's head

The basis of this model is to replicate a pet sleeping in an owner's bed. Many felines or smaller canines will sleep near their owner's head or chest. For this geometry, the animal was placed in close proximity to the PIMAL phantoms head. Both the feline and canine were positioned to produce a 20 cm on-center distance between the PIMAL phantom head and the animal's chest, resulting in an air gap of approximately 4 cm. This exposure scenario represents a realistic geometry in which extended exposure to a treated animal may occur. Additionally, there are many higher sensitivity target organs located within the upper torso.

Feline/Canine in owner's lap

Many pets will choose to rest on their owner's lap for prolonged periods of time. Felines commonly exhibit this behavior in a number of scenarios such as working at a desk, watching television on a couch, or sitting in bed reading a book, etc. This is also applicable to canines of all sizes with some limitations to the location for larger breeds. Small canines are assumed to follow similar time-spending habits of felines, as their size will not exclude them from locations such as a desk chair. For this analysis, a canine of medium size (50 lbs) was selected so that it will still fit in the model's lap while providing necessary changes in size for dosimetry. For both animals in this scenario, it is expected that the pet will be resting near the torso of the human. As such, an air gap of approximately 1 cm between human torso and animal skin is assumed.

Feline/Canine at owner's feet

The animal standing by the owner's feet is one of the most common scenarios in which pet owners find themselves. Examples include owners walking their dog, petting their dog, feeding their animal, or performing household chores with the animal in proximity. The PIMAL phantom is positioned to be standing with arms at its side with the animal in a standing position at their feet at a distance of 100 cm between the center chest of phantom and the animal.

Feline Simulations and Treatments

Tables 2 and 3 provide dimensions and organ masses, respectively, for an 11-pound feline. These parameter values were implemented in the MCNP6/PIMAL simulation.

Table 2. Dimensions of the simulated feline.

Parameter	Value
Weight	5.04 kg
Girth	6.5 cm
Body Length	28 cm
Height (at haunches)	22 cm
Back Spine Radius	1.5 cm
Cervical Spine Radius	1.4 cm
Leg Thickness	(average) 3 cm
Leg Length	12 cm
Pelvis Length	9 cm
Rib length	9 cm
Thyroid Volume	1.8 cm^3
Head Length	10 cm
Neck Length	9 cm

Iodine-131 (hyperthyroidism/thyroid cancer)

Radioiodine treatments modeled for felines included hyperthyroidism and cancer therapy. Iodine-131 was distributed uniformly in a sphere with a volume of 1.8 cm^3, representing the thyroid gland. For hyperthyroidism treatments 148 MBq of activity was used, and for cancer therapy 1,480 MBq was assumed. For these treatments within felines, hyperthyroidism is more common; however, cancer therapy presents a larger dosimetry concern.

Table 3. Organ masses for the simulated feline.

Tissue	Mass (kg)	%
Body	1.32	26.2
Neck	0.790	15.7
Head skin	0.0419	0.8
Brain	0.373	7.4
Lungs	0.265	5.3
Abdomen	0.980	19.4
Legs (soft tissue)	0.123	2.4
Bone	1.15	22.8
Total	**5.04**	

Technetium-99m (imaging)

Felines were modeled with a full-body technetium distribution. For veterinary procedures, skeletal scans in felines are generally uncommon. Additionally, after examining results from the canine model, it was determined that skeletal and full-body distributions of technetium for the same administered activity yielded comparable dose results. Thus, it was deemed unnecessary to create a feline skeletal distribution model. As with canines, 1,110 MBq was again the top range of administration activity for full-body distribution; this value was used for dosimetry calculations.

Canine Simulation and Treatments

Tables 4 and 5 provide dimensions and organ masses, respectively, for a 49-pound canine. These parameter values were implemented in the MCNP6/PIMAL simulation.

Table 4. Dimensions of the simulation canine.

Parameter	Value
Weight	22.3 kg
Girth	10.5 cm
Body Length	56 cm
Height (at haunches)	40 cm
Back Spine Radius	2 cm
Cervical Spine Radius	1.8 cm
Leg Thickness	(average) 3.5 cm
Leg Length	35 cm
Pelvis Length	19 cm
Rib length	19 cm
Knee implant radius	1 cm
Head Length	20 cm
Neck Length	10 cm

Iodine-131 (hyperthyroidism/thyroid cancer)

Radioiodine treatments modeled for canines included hyperthyroidism and cancer therapy. Iodine-131 was distributed uniformly through a sphere with a volume of 1.8 cm^3, representing the thyroid gland. For hyperthyroidism treatments, 148 MBq of activity was used; for cancer therapy, 4,440 MBq was assumed.

Table 5. Organ masses for the simulated canine.

Tissue	Mass (kg)	%
Body	5.95	26.7
Neck	2.21	9.9
C-spine	0.14	0.6
Head skin	0.35	1.6
Skull	0.44	2.0
Brain	1.67	7.5
Lungs	1.61	7.2
Ribs	0.34	1.5
Abdomen	5.43	24.4
Pelvis	1.65	7.4
Spine	0.99	4.4
Leg (soft tissue)	0.50	2.3
Leg (bone)	0.97	4.4
Total	**22.3**	

Technetium-99m (imaging)

Canines were modeled with two separate distributions for technetium-99m. Canines frequently undergo entire body imaging, as well as more advanced skeletal imaging as older canines tend to become prone to osteosarcomas. For both administrations, an activity of 1,110 MBq was assumed. Full body imaging assumed even distribution of the technetium throughout all tissues of the canine model. The skeletal targeted distribution used the same principle, however, restricted to the bones within the model; dimensions are given below.

Sn-117m (radiosynovectomy)

Radiosynovectomy treatments are unique in that 98% of all administered radiocolloid remains within the targeted joint. Due to this retention, this scenario was modeled with all radiation being emitted from a singular knee joint. For these purposes, the knee was represented by a sphere with a radius of 1 cm, resulting in a total volume of 4.19 cm^3. For the MCNP simulation, the joint itself was given the density of soft tissue since the Sn-117m radiocolloid is injected into the synovial fluid of the joint capsule. A total activity of 222 MBq was used in the dosimetry calculations to match the maximum published administration (Smith and Krimins 2022; Arno et al. 2021). The maximum activity is based on two joints being treated because the current maximum prescribed per joint is 111 MBq (Arno et al. 2021).

Equine Scenario Geometries

Standing at the horse's shoulder

The first equine model (see Figure 2) was created with geometry that would be common when caring for a horse. The horse model is positioned standing with head upright and facing out, the PIMAL phantom is positioned standing to the side and facing the horse at its shoulder. A distance of 50 cm is assumed between the center of the phantom's trunk and the center of the horse's chest. Such positioning could be found while performing maintenance of the animal such as grooming, cleaning of stall, feeding, and other standard tasks. The selected orientation is closest to that of grooming, as this is a fairly long task which requires the owner to be within arm's reach of the horse. Like the previous simulations, this geometry was selected to provide conservatism and an increased safety for owners.

Leading the horse

A second common scenario involves one in which a person is leading their horse with the use of a rope. One meter was selected as the length of the lead rope, as that falls within recommendations made by many companies which produce these ropes. In the leading position, the male's center is positioned 270 cm from the center of the horse body. This amounts to an air gap from the tip of the horse's nose to the back of the male phantom of approximately 70 cm. The horse model was oriented with head pointing at the back of the PIMAL phantom in a neutral relaxed position.

Riding the horse

The final equine geometry has the owner placed on top of the horse in a riding position. For riding, there is a distance of 95 cm from the PIMAL heart to the center of the horse's chest. The air gap at its largest is between the testes and back of horse at approximately 11 cm. The PIMAL phantom was manipulated with legs around the horse and with the phantom's torso positioned at the mid-point of the back where a saddle would be placed. The saddle itself was not included in the simulation.

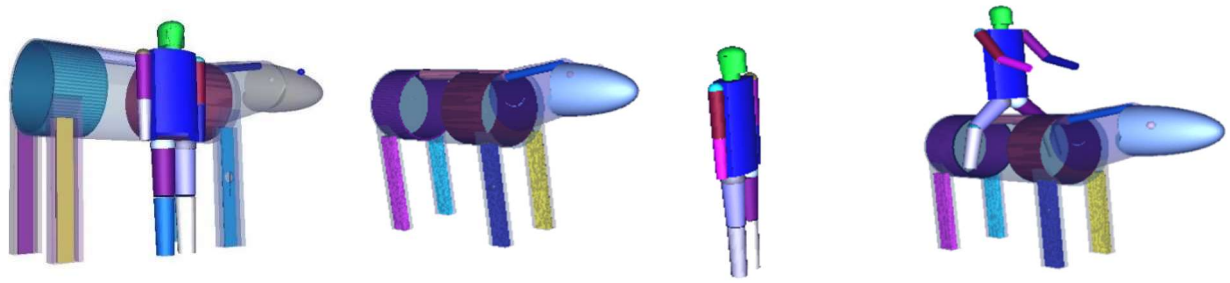

Figure 2. Exposure scenarios considered for equines.

Equine Simulation and Treatments

Tables 6 and 7 provide dimensions and organ masses, respectively, for a 426-pound equine. These parameter values were implemented in the MCNP6/PIMAL simulation.

Technetium-99m (imaging)

Contrary to the previous animals modeled, only skeletal distribution was tested for equines. This was done simply due to the administration activities at the time of the scan. Skeletal administrations in equines require several times more activity than a full-body scan. With skeletal and full-body distributions resulting in similar dose levels at the same administration, this indicates that skeletal imaging will be the treatment of concern for equines. As with the canine model, distribution was assumed to be uniform in the entirety of the equine skeletal system. A total administration of 8,880 MBq was used for dosimetry.

Sn-117m (radiosynovectomy)

All radioactive material is assumed to remain within the joint capsule for the entirety of the treatment. For equines, the knee joint was represented by a sphere with a radius of 4.5 cm, resulting in a total volume of approximately 381 cm^3. Soft tissue density was assumed as the administration occurs into synovial fluid. As there are currently no approved uses of Sn-117m for radiosynovectomy in equines in the United States, the maximum permissible activity of 222 MBq for canines (Smith and Krimins 2022; Arno et al. 2021) was used. The maximum activity is based on two joints being treated because the current maximum prescribed per joint is 111 MBq (Arno et al. 2021). It should be noted that if approved for use with equines,

this treatment will likely require a higher administration value. Performing a simulation at these values will still give an indication of whether it is likely to be problematic.

Table 6. Dimensions of the simulated equine.

Parameter	Value
Weight	938 kg
Girth	35 cm
Height (at withers)	165 cm
Back Spine Radius	5 cm
Cervical Spine Radius	3.5 cm
Leg Thickness	10 cm
Leg Length	94 cm
Pelvis Length	34 cm
Rib length	45 cm
Knee implant radius	4.5 cm
Head Length	60 cm
Neck Length	60 cm
Eye Radius	3 cm

Table 7. Organ masses for the simulated equine.

Tissue	Mass (kg)	%
Body	292.8	31.22
Neck	122.2	13.03
C-spine	3.2	0.34
Head skin	100.1	10.67
Skull	4.2	0.45
Brain	58.3	6.21
Lungs	119.5	12.74
Ribs	9.8	1.05
Abdomen	112.7	12.01
Pelvis	19.7	2.10
Spine	11.5	1.23
Leg (soft tissue)	41.3	4.40
Leg (bone)	34.0	3.63
Leg (bone marrow)	7.8	0.83
Eyes	0.2	0.02
Knee Implant	0.4	0.04
Total	**938**	

Ir-192/I-125 (brachytherapy)

Equines were determined to be recipients of skin depth brachytherapy implants often enough to warrant investigation. The primary ailment requiring treatment with brachytherapy are sarcomas located in the eyelid. Two different radionuclides, Ir-192 and I-125, were found to be the most common to this veterinary procedure. Both were modeled in the same manner, a point source located atop the model equine's eye. Because sources are sealed, typically in the form of seeds, it was deemed appropriate to

simplify the model for this source distribution with a total of 45,000 MBq for Ir-192 or 1,665 MBq for I-125.

3.2 Internal Dose Assessment

Potential internal dose to humans from veterinary uses of radioactive material is assessed based on available information from the literature. While internal dose requires the transfer of radioactive material to humans, the type of information that typically supports internal dose assessments varies greatly among individual radionuclides and veterinary procedures. Nonetheless, an assessment of potential internal dose is performed to determine if additional investigation into internal pathways is warranted. From a general perspective, internal human doses may arise from inhalation, ingestion, dermal absorption, or radioactive material entry into open wounds. This internal dose assessment for veterinary uses of radioactive material considers inhalation and ingestion because those two pathways have a greater potential for human uptake of radionuclides, compared to more limited potential for uptakes from dermal absorption or wound pathways in veterinary release scenarios.

The internal dose assessment specifically considers inhalation dose from resuspension of cat litter as well as ingestion dose from contact with the animal itself, surfaces in the animal's living environment, animal saliva, and animal excreta. Engineered confinement for permanent and temporary implants is assumed to be reliable for preventing internal dose to humans. Therefore, the internal dose assessment does not include potential radionuclides associated with veterinary implants. In addition, radiosynovectomy compounds for medical uses in human patients may also consider the application of ^{32}P, ^{186}Re, and ^{169}Er; these radionuclides have not been used in veterinary medicine and are not considered further.

For each pathway, the committed effective dose equivalent (CEDE) for internal intake is calculated with effective dose coefficients from federal guidance (EPA 1988). EPA (1988) remarks that the dose coefficients for committed effective dose equivalent are "intended for general use in assessing average individual committed doses in any population that can be characterized adequately by the Reference Man," as defined by the International Commission on Radiological Protection (ICRP 1975). The Reference Man is a well-defined characterization in terms of anatomical and physiological parameters for an adult, which is necessary to establish intake and concentration guides (EPA 1988). 10 CFR Part 20 (App. B) is based on this characterization and federal guidance (EPA 1988). In this assessment, doses to specific organs are not calculated for members of the public, and thus, dose coefficients for committed dose equivalent to individual organs are not utilized.

In its simplest form, internal dose to the human can be calculated from the product of two parameters:

$$CEDE = I \cdot C$$

where $CEDE$ is the committed effective dose equivalent, I is the total intake activity of the radionuclide, and C is the internal dose coefficient for the radionuclide and intake pathway. Internal doses arise from the intake of radioactive material. In many cases, a fraction of the total mass (or activity) of the original source of radioactive material is available for intake. For example, a hyperthyroid cat treated with ^{131}I can represent a source of radioactive material. For internal human dose, the intake activity equals a fraction of the total activity

$$I = A^* \cdot F_T$$

where A^* is the total activity either retained in the veterinary patient or present as contamination and F_T is the fraction of total activity that the human ingests or inhales. When human intake occurs from contacting animal body fluids (e.g., saliva) or waste (e.g., urine or feces) with a known radionuclide activity concentration, the calculation for intake activity can be rewritten as

$$I = A_m^* \cdot m$$

where A_m^* is the radionuclide activity per unit mass and m is the intake mass of ingested fluids or inhaled particulates. The intake mass can be a fraction of the total mass available for contact. This implies additional terms can be added in the determination of these parameters. Values for each term incorporated into the internal dose assessment are presented in the following sections. For repeated contacts and intakes, the intake activity for calculating internal dose becomes the cumulative intake of radioactive material.

In this internal assessment, no credit is taken for the reduction in the amount of radionuclide activity remaining in the veterinary patient after administration. This approach allows specific veterinary procedures that may warrant precautions to be identified for future consideration, e.g., calculations that account for reduced radionuclide activity due to biological loss and radioactive decay for typical hold times of the animal in veterinary facility prior to release. Results presented in this report do not include hold times in the veterinary facility.

Potential Inhalation of Radioactive Material

Internal dose calculations were performed for the airborne resuspension of accumulated excreta during litter box cleaning. This scenario was investigated as a bounding scenario for potential inhalation sources because urine-soaked cat litter and fecal particulate intakes were calculated assuming undiluted ^{131}I concentrations per unit mass for feline urine and feces, respectively.

Inhalation dose calculations were not performed for radionuclide concentrations in air exhaled by the pet, because Nishizawa et al. (1980) reported maximum ^{131}I exhalated activity fractions from human patients ranging between 2.8×10^{-7} and 1.4×10^{-5} per hour, relative to the administered activity shortly after sodium iodide administration. Although analogous data for veterinary patients were not available, these fractions are insufficient to represent internal dose concerns for human interaction over short-term (hours to days) or long-term (days to weeks) time periods. Internal dose calculations were also not performed for human inhalation of pet sneezes because they are severely mass constrained (i.e., both contaminated liquid volumes available for intake and total activities entrained in the sneeze are very small) and bounded by other pathways (e.g., saliva ingestion). In summary, feline litter-box cleaning was the only scenario for which potential inhalation doses were calculated, and assessments of potential inhalation doses were not performed for canines and equines because (1) radionuclide concentrations in canine and equine excreta are not well documented and (2) inhalation dose estimates based on bounding assumptions for feline excreta were low enough to not represent a concern in terms of radiological health.

For hyperthyroid feline patients administered ^{131}I, a bounding inhalation intake is calculated for the airborne resuspension of urine-soaked litter during domestic cleaning of a litterbox. Depending on the size distribution of airborne particulates, inhaled particles would be deposited in different regions of the human respiratory tract. In lieu of detailed characterizations of resuspended litter dust and deposition fractions in the nasopharyngeal, tracheobronchial, and pulmonary lung regions, a conservative approach applies a single effective dose coefficient to overestimate dose from radioactive material intake. This

simplification prevents separate accounting for inhaled particulates not reaching the lungs as these particulates can be mobilized by biological clearance, swallowed, and contribute internal dose via ingestion. Instead of modeling these complex processes, the largest effective dose coefficient for various retention models and chemical forms is applied to all inhaled material to yield a bounding dose.

Dose coefficients for the calculation were evaluated from major sources spanning three decades: (1) Federal Guidance Report No. 11 (EPA 1988); (2) DCFPAK 3.02 (Eckerman and Leggett 2013) based on biokinetic and dosimetric models in Federal Guidance Report No. 13 (EPA, 1999); and (3) updated dosimetry in International Commission on Radiological Protection Publication 137 (ICRP, 2017). Considering published chemical forms and pathways for radioactive material uptake by the human body, the largest potential for effective dose arises from the exposure of a 1-year-old child because the product of breathing rate (EPA, 1999, Table 3.1) and maximum effective dose coefficient (from the sources above) was larger for a 1-year-old child compared to other age groups including adults. From the compiled information, a 1-year-old child could receive an effective dose that is approximately twice that of an adult for the same environmental exposure conditions and duration if the child is held by the adult, secured to the adult in a child carrier, or placed near the adult during the cleaning. For radiological protection, the child could be exposed to the same air space while the adult cleans the litterbox. Therefore, the highly simplified and conservative calculation proceeds with a maximum effective dose coefficient of 1.79×10^{-4} mSv/Bq and a breathing rate of 0.0047 m^3/min. In this calculation, an adult breathing rate of 0.02 m^3/min for light work (EPA, 1988) is scaled down for a 1-year-old child breathing 23% as much air as an adult [i.e., 5.2 / 22.2 = 0.23 from Table 3.1 of EPA (1999)].

The effective dose coefficient allows CEDE to be calculated directly from the intake activity of the radionuclide. The intake activity is estimated by multiplying a conservative airborne mass load with the ^{131}I activity concentration in urine-soaked litter. Lamb et al. (2013, Table 3) quantified ^{131}I activity concentrations in urine-soaked litter at 20.4 Bq/mg for a cohort of hyperthyroid felines in the first week after radionuclide administration. By using this maximum urine concentration in the inhalation calculation, resuspended litter is assumed to be completely soaked so that all particulates from the litter have the same concentration. To account for the unlikely potential that cat feces represent all airborne particulates at their maximum concentration instead of urine-soaked litter, the ^{131}I activity concentration of 20.4 Bq/mg can be replaced with 43.6 Bq/mg for feces as quantified by Lamb et al. (2013).

As a highly conservative upper bound for cleaning a litterbox, an airborne mass load of 10 mg/m^3 is combined with an assumed exposure period of 10 min. This selection is informed by airborne particle concentrations measured in the breathing zone from human-induced resuspension activities on a variety of outdoor surface deposits (Benke et al. 2009). The conservatism of this airborne mass loading is further supported by limits set by the Occupational Safety and Health Administration for airborne particulates and mineral dusts: 15 mg/m^3 for total dust and 5 mg/m^3 for respirable fraction in 29 CFR Part 1910, "Occupational safety and health standards," Chapter XVII, "Labor." Although 10 minutes represents a much longer duration than would be expected to empty, clean, and refill a litterbox, this duration accounts for the possibility that the individual performs the task indoors in a space with limited air circulation and remains in the vicinity while airborne litterbox particulates disperse and settle.

Potential Ingestion of Radioactive Material

Potential intakes from inadvertent ingestion were assessed for a variety of radionuclides according to the three pathways shown in Figure 3. Data gaps and methods for the ingestion calculations are described below.

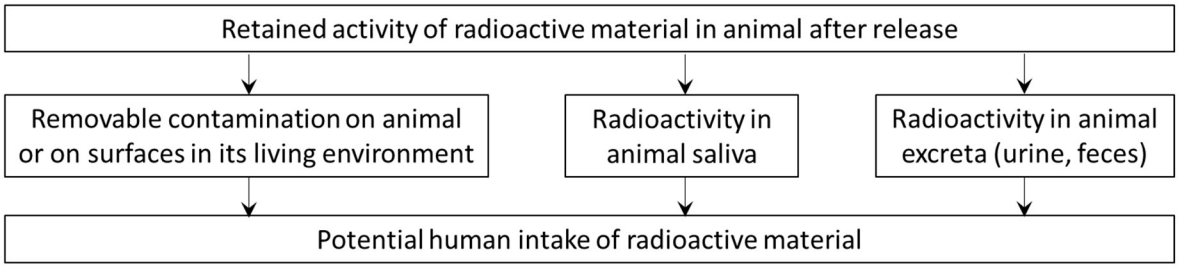

Figure 3. Internal pathways and potential data gaps for hypothetical ingestion intakes.

Table 8 summarizes source-term data availability and describes how the source term was approximated when directly relevant data were unavailable.

Beyond ^{131}I administrations to felines, there is a lack of source term data relevant to internal dose pathways for other veterinary administrations. In the absence of case-specific information for other radionuclides, removable contamination fractions from feline case studies are applied to other veterinary administrations and radionuclides. The presence of ^{131}I in body fluids and excreta is well known following sodium-iodide administrations. While this may not be the case for other nuclides, applying the same removable fraction to all radionuclides will overestimate potential internal-dose source terms. For this reason, the hypothetical removable activity fraction of 5×10^{-7} is applied throughout this assessment to determine a conservative amount of radioactive material available for inadvertent human ingestion. Table 9 provides information on ^{131}I data from felines used to derive the 5×10^{-7} fraction that allows ingestion doses for non-iodine radionuclides to be calculated.

Table 8. Data availability for human ingestion source terms and approaches to address data gaps.

Ingestion Source Term	*Available Data*	*Data Gap*	*Approach to Address Data Gap*
Removable contamination found on the animal or on surfaces in its living environment	^{131}I data for hyperthyroid felines	Lack of data for radionuclides other than ^{131}I	Calculate the fraction of administered activity found as removable contamination for ^{131}I; Use this removable contamination fraction to approximate source terms for other radionuclides, including ^{99m}Tc and emerging radionuclides
Radionuclide concentrations in animal saliva	None found	Lack of data for all veterinary radionuclides	Use ^{131}I saliva data from human patients; Calculate administered activity fraction found in saliva; Apply this fraction to canines and felines for veterinary cancer therapy to bound other procedures and radionuclides
Radionuclide concentrations in animal excreta	^{131}I data for felines (hyperthyroidism & thyroid cancer)	Lack of data for radionuclides other than ^{131}I	Perform calculations with ^{131}I administered activities for thyroid cancer and hyperthyroid treatments; Perform calculations for Sn-117m colloids with activity not retained in the injected joint unrealistically assumed to be available for human intake to yield a bounding dose

Table 9. Radioiodine removable activity fraction for hyperthyroid felines establishes a hypothetical fraction of 5×10^{-7} to address data gaps associated with other radionuclides.

Radionuclide Administered & Veterinary Patient	Fraction of Administered Activity Resulting in Removable Activity	Source
^{131}I as NaI to Feline	70 Bq / 154 MBq = 5×10^{-7}	Chalmers et al. (2006)
^{131}I as NaI to Feline	30 Bq / 79 MBq = 4×10^{-7}	Davila (2019)
Other radionuclides	Hypothetical 5×10^{-7}	No source

As shown in Figure 3, potential ingestion doses were investigated for (i) removable contamination, (ii) animal saliva, and (iii) animal excreta. Methods and specific terms for these pathway calculations are described below.

Potential Ingestion of ^{131}I from Removable Contamination

To determine the maximum ^{131}I internal dose to an adult, a bounding calculation was performed for complete intake of removable contamination found on hyperthyroid felines. Although felines are sometimes held at the veterinary facility before release, no reduction in removable activity is assumed from typical facility hold times in this calculation. Table 10 presents removable contamination levels found on hyperthyroid felines. Removable contamination found on surfaces in the animal's living environment is shown in Table 11. The calculation for contamination on the animal proceeds with a total intake of 70 Bq. This represents complete intake of the median daily removable activity for 14 consecutive days. The effective dose coefficient for ^{131}I ingestion is $1.44 \times 10^{-5}\ \frac{mSv}{Bq}$ (EPA 1988). As previously described, the effective dose coefficient allows CEDE to be calculated directly from the intake activity. The maximum activity of removable contamination observed by Davila (2019) in the feline's living environment was approximately 185 Bq.

Table 10. Removable ^{131}I contamination found on hyperthyroid felines.

Removable ^{131}I Activity on the Feline	Administered ^{131}I Activity	Source
Median daily activity ≈ 5 Bq	148 MBq to each of five (5) felines	Chalmers et al. (2006) for 6 felines
Maximum observed ≈ 70 Bq	185 MBq to one feline	
Maximum observed ≈ 30 Bq	60 – 94 MBq to each feline with an average of 79 MBq	Davila (2019) for 6 felines

Table 11. Removable ^{131}I contamination in the living environment of hyperthyroid felines.

Removable ^{131}I Activity in Living Environment	Administered ^{131}I Activity	Source
Maximum observed ≈ 185 Bq	60 – 94 MBq to each feline with an average of 79 MBq	Davila (2019) for 6 felines

Because higher activities are administered for cancer therapy compared to hyperthyroidism, the maximum hypothetical CEDE for removable contamination due to a veterinary cancer therapy patient was calculated by multiplying the maximum CEDE for a hyperthyroid veterinary patient with an activity ratio to account for the larger cancer-therapy administration. One ratio was calculated for removable contamination on the animal and another ratio was determined for removable contamination on surfaces. For removable contamination on the animal, the ratio equals 1.48 GBq for felines (or 4.44 GBq for canines) divided by an average administered activity of 154 MBq. For removable contamination on surfaces in the animal's living environment, the average administered activity of 154 MBq is replaced by 79 MBq.

Potential Ingestion of ^{131}I from Animal Saliva

The maximum ^{131}I internal dose to humans calculated from the ingestion of animal saliva is described in this subsection. Feline and canine patients are treated with ^{131}I. Unfortunately, post-treatment source term data pertaining to animal saliva are severely lacking. In lieu of measured radioiodine concentrations in feline or canine saliva following veterinary cancer treatments, ^{131}I saliva concentrations in human patients are used as analogs for the veterinary patient. The maximum fraction of administered activity found in human saliva ranged from 0.0013 per mL to 0.012 per mL for patients treated with ^{131}I (Nishizawa et al. 1980). Following a maximum reached within the first day, saliva concentrations of ^{131}I in human patients were found to decrease rapidly with time. For example, the concentration of ^{131}I in human saliva at 4 days after administration was a factor of 1,000 lower than its maximum value (Nishizawa et al. 1980, Figure 7). Because this assessment addresses maximum potential internal doses to humans, no credit is taken for any reduction in ^{131}I saliva concentration over time.

Human ingestion of 1 mL of animal saliva is selected to represent licking of the face, mouth, and possible kissing. The 1-mL volume of saliva was intentionally selected to address the upper bound for inadvertent human ingestion. For felines, the higher saliva concentration of 0.012 per mL was coupled with an administered activity of 1.1 GBq for thyroid carcinoma (Hibbert et al. 2009). For canines, the administered activity of ^{131}I increased to 4.44 GBq (NCRP 2004, Table 8.1).

Potential Ingestion of ^{131}I from Animal Excreta

The internal dose potential from contact with animal excreta following veterinary release is estimated with an upper-bound ^{131}I activity of 1.48 GBq or 4.44 GBq for the cancer therapy of felines or canines, respectively (NCRP 2004, Table 8.1). From a radiological half-life of 192 h and an effective half-life of 55 h (2.3 d) for elemental ^{131}I consistent with felines (Miles 2004), a biological removal half-time for all excreta is approximated to be 77 h. In other words, the daily biological excretion rate is 0.22 per day. Under bounding circumstances, inadvertent intake of 0.01% of animal excreta for the day immediately after release is assumed to result in a maximum internal dose. This percentage of intake approximates contact of waste by the hands and transfer to the skin as smeared material before inadvertent ingestion. Although a reduction in the amount of contamination from normal hygiene (i.e., washing of hands) is not explicitly implemented, larger amounts of ingested waste were not adopted because they would be more noticeable and subsequently removed by scraping, hand wiping, or washing.

To provide additional information, a second calculation incorporated published data on ^{131}I concentrations in excreta. According to Lamb et al. (2013), a feline patient administered 1 GBq of ^{131}I to treat thyroid carcinoma was found to excrete feces and urine with radioiodine concentrations up to 43,600 Bq per gram (feces) to 20,400 Bq per gram (urine-soaked litter) during the first week after administration while still in isolation. These levels were substantially higher than second-week excreta concentrations that rarely exceeded 1,000 Bq per gram from feline hyperthyroidism patients administered lower activities of ^{131}I (120 – 200 MBq). For the higher concentration range of 20,400 – 43,600 Bq per gram, inadvertent ingestion of 1 gram yields a conservative hypothetical ^{131}I intake range of 20,400 – 43,600 Bq. One gram approximates the maximum amount of excrement transferred to the hands and inadvertently ingested.

It is important to note that canines with cancer have been administered larger ^{131}I activities compared to the 1-GBq activity used in the calculation above for a feline cancer patient. However, appreciable size differences among domestic felines and canines preclude simple linearized scaling (i.e., using a ratio based on administered activity) to approximate excreta concentrations, which are already reported on a per-gram basis. In other words, greater activities administered to more massive animals may yield excreta concentrations on a per-gram basis that are comparable to excreta from less massive veterinary cancer

patients. Better inferences could be made if measured excreta concentrations (Bq/g) were coupled to radioiodine dosage administrations reported in terms of activity per unit animal mass (MBq/kg). Unfortunately, data for performing this comparison are lacking. For these reasons, radioiodine concentrations in the excreta of canines after cancer treatments remain unknown, and thus, separate prospective calculations on hypothetical internal doses to humans from contacting canine excreta following treatment with radioiodine were not performed.

Potential Ingestion of ^{117m}Sn following Veterinary Radiosynoviorthesis Injections

Bounding calculations were performed for a ^{117m}Sn colloidal injection into canine and equine joints. Lattimer et al. (2019) studied ^{117m}Sn radiosynoviorthesis agent injections into normal canine elbows and reported 99.1% of the 92.5-MBq injected activity was retained in the joint for 45 to 47 days when tissue samples were obtained to determine radionuclide retention. Analysis of blood, urine, and feces from the canines, indicated much higher relative Sn-117m activities in urine compared to blood and feces. Considering prolonged excretion with measured reductions in activity over time (Lattimer et al. 2019, Table 4), the maximum amount of excreted activity in any day was estimated in this assessment to be less than 20% of the cumulative activity excreted over time. The first day after treatment exhibited the largest concentrations in canine excreta. Neglecting radioactive decay, biodistributions of Sn-117m within the canine prior to excretion, and other plausible activity reductions prior to human exposure, a bounding calculation was performed with 20% of the 0.83-MBq activity outside joint assumed to be immediately available for human ingestion.

Potential Ingestion of ^{99m}Tc following Veterinary Diagnostic Imaging

For ^{99m}Tc, 8.88-GBq is applied as the maximum administered activity to equines (NCRP 2004, Table 8.1). The removable contamination fraction derived for radioiodine is applied to estimate a maximum internal dose. Neither radiological decay nor biological removal is included in the calculation. In essence, 5×10^{-7} of the administered activity is immediately available as removable contamination and completely ingested by a human in contact with the animal. The ^{99m}Tc calculation for felines utilized a maximum administered activity of 1.11 GBq (NCRP 2004, Table 8.1), and the same maximum activity was applied to canines for diagnostic imaging. Maximum ^{99m}Tc activities administered to felines and canines are lower than the maximum activity administered to equines because of substantial differences in animal mass.

4 FELINE ADMINISTRATIONS

Veterinary treatments for cats include the following procedures:

- Imaging with ^{99m}Tc
- Hyperthyroid therapy with ^{131}I
- Cancer therapy with ^{131}I

Radioiodine activities required for successful cancer treatment are quite substantial and cause the feline to generate contamination for over a week. For both the hyperthyroidism and cancer simulations, iodine was assumed to concentrate within the thyroid, and thus it was modeled as a small volumetric source at the location where the thyroid would be present. For technetium administrations, a full-body distribution of the pharmaceutical was assumed because the highest administration values are used for this type of scan. The assessment of hypothetical internal dose from feline veterinary procedures benefited from fewer data gaps compared to other animals. Therefore, a larger number of internal dose calculations were performed for feline patients.

4.1 External Dose Assessment for Felines

External dose to humans from felines was calculated for three veterinary procedures: ^{99m}Tc imaging, ^{131}I hyperthyroid treatment, and ^{131}I thyroid cancer treatment. As shown in Table 12, the greatest potential for exceeding 10 CFR Part 20 regulatory limits occurs when the pet is in the owner's lap after cancer treatment. The same procedure generates a significantly reduced external EDE when the pet is at the owner's feet, emphasizing the importance of distance as a dose control variable.

Technetium-99m will be removed quickly from the animal due to its short effective half-life of 4.8 h. While initial dose rates exceeding 0.02 mSv/h are possible when the pet is close to or in contact with a person's torso, the initial dose rate will have lessened to negligible levels within a single day. Table 12 indicates that ^{99m}Tc would not deliver more than 1 mSv even under the most conservative assumptions.

In contrast to ^{99m}Tc, retention of radioiodine ^{131}I in the pet continues for long periods. For both hyperthyroidism and cancer treatments, there is a potential to exceed public dose guidance following administration. For cancer treatments, the higher administration activities provide a substantially increased potential dose to humans.

Table 12. External dose rate and total dose for human exposure to felines.

Procedure	Tc-99m Full Body	I-131 Hyperthyroidism	I-131 Thyroid Cancer
Administration (MBq)	1,110	148	1,480
Feline at Owner's Head			
Dose Rate (mSv/h)	0.11	0.031	0.31
Total Dose (mSv)	0.75	2.7	27
Feline in Owner's Lap			
Dose Rate (mSv/h)	0.15	0.041	0.42
Total Dose (mSv)	1.1	3.6	36
Feline at Owner's Feet			
Dose Rate (mSv/h)	0.0083	0.0019	0.019
Total Dose (mSv)	0.058	0.17	1.7

4.2 Internal Dose Assessment for Felines

Current feline veterinary procedures utilize ^{131}I and ^{99m}Tc. The internal dose assessment considers

- potential inhalation intake of ^{131}I following feline hyperthyroid treatment
- potential ingestion intake of ^{131}I following a feline hyperthyroid treatment
- potential ingestion intake of ^{131}I following feline cancer treatment
- potential ingestion intake of ^{99m}Tc following feline diagnostic imaging

Potential Inhalation Dose from Urine-Soaked Litter and Fecal Particulates with ^{131}I

The worst-case inhalation CEDE for litterbox cleaning is presented in Table 13. Even without precautions to lower radiation exposure to humans, doses are more than a factor of 270 below 1 mSv. Neither inhalation of urine-soaked litter nor inhalation of airborne fecal particulates appears to be a viable pathway for significant internal dose.

Table 13. Maximum hypothetical inhalation dose from a feline patient treated with 1-Gq ^{131}I.

Radionuclide	Inhalation of Contaminated Litter	Maximum CEDE
^{131}I urine	$\left(1.79 \times 10^{-4}\ \frac{mSv}{Bq}\right)\left(20.4\ \frac{Bq}{mg}\right)\left(10\ \frac{mg}{m^3}\right)\left(0.0047\ \frac{m^3}{min}\right)(10\ min) = \ 0.0017\ mSv$	
^{131}I feces	$\left(1.79 \times 10^{-4}\ \frac{mSv}{Bq}\right)\left(43.6\ \frac{Bq}{mg}\right)\left(10\ \frac{mg}{m^3}\right)\left(0.0047\ \frac{m^3}{min}\right)(10\ min) = \ 0.0037\ mSv$	

Potential Ingestion Doses

Potential internal dose to humans from removable ^{131}I contamination on the animal itself or in its living environment are not expected to exceed current regulatory limits for feline veterinary patients. However, more research is recommended to strengthen the basis for internal dose calculations.

For inadvertent human ingestion of ^{131}I in feline saliva at the time of maximum radioiodine concentration, a maximum ingestion dose of 190 mSv for feline cancer therapy treatments is obtained, based on human saliva data neglecting substantial reductions in the ^{131}I concentration over time. Inadvertent ingestion of feline saliva shortly after hyperthyroid treatments could exceed the 1-mSv limit without precautions. Assessment of recommended hold times for specific veterinary procedures is left for future work. Information on ^{131}I saliva concentrations in felines would improve these calculations.

Diagnostic imaging administrations of ^{99m}Tc to felines are associated with very low internal doses to humans and are not a concern from the perspective of radiological protection.

Maximum ingestion CEDEs from feline veterinary procedures are presented in Table 14.

Table 14. Maximum ^{131}I ingestion doses to humans following feline veterinary procedures.

Radionuclde & Intake Source	Ingestion Calculation	Maximum CEDE
^{131}I removable contamination on animal (hyperthyroidism)	$70\ Bq \cdot \left(1.44x10^{-5}\ \frac{mSv}{Bq}\right) =$	$0.0010\ mSv$
^{131}I removable contamination on surface (hyperthyroidism)	$185\ Bq \cdot \left(1.44x10^{-5}\ \frac{mSv}{Bq}\right) =$	$0.0027\ mSv$
^{131}I removable contamination on animal (cancer therapy)	$1.0x10^{-3}\ mSv \cdot \frac{1480\ MBq}{154\ MBq} =$	$0.01\ mSv$
^{131}I removable contamination on surfaces (cancer therapy)	$2.7x10^{-3}\ mSv \cdot \frac{1480\ MBq}{79\ MBq} =$	$0.05\ mSv$
^{131}I animal saliva (cancer therapy)	$0.012 \cdot 1.1x10^{9}Bq \cdot \left(1.44x10^{-5}\ \frac{mSv}{Bq}\right) =$	$190\ mSv$
^{131}I animal saliva (hyperthyroidism)	$0.012 \cdot 0.148x10^{9}Bq \cdot \left(1.44x10^{-5}\ \frac{mSv}{Bq}\right) =$	$26\ mSv$
^{131}I animal excreta fraction (cancer therapy)	$1.48\ x10^{9}\ Bq\ \cdot 0.22\ \cdot 0.0001 \cdot \left(1.44x10^{-5}\ \frac{mSv}{Bq}\right) = 0.47\ mSv$	
^{131}I animal excreta concentration (cancer therapy)	$4.36x10^{4}\ Bq \cdot \left(1.44x10^{-5}\ \frac{mSv}{Bq}\right) =$	$0.63\ mSv$
^{99m}Tc removable contamination (full body imaging)	$5 \times 10^{-7} \cdot (1.11x10^{9}Bq) \cdot \left(1.68x10^{-8}\ \frac{mSv}{Bq}\right) =$	$0.000009\ mSv$

5 CANINE ADMINISTRATIONS

Veterinary treatments for dogs include the following procedures:

- Imaging with ^{99m}Tc
- Synovectomy therapy with ^{117m}Sn
- Hyperthyroid therapy with ^{131}I
- Cancer therapy with ^{131}I

Dose calculations for canines considered two additional simulations beyond the three procedures analyzed for felines. Canines suffer from bone cancers more commonly than felines and as such have a higher prevalence of technetium administrations designed to target the skeletal system. Therefore, bone distribution of ^{99m}Tc was added for canines to complement the simulation of full-body distribution of ^{99m}Tc. The second additional simulation models a procedure performed on canines, a ^{117m}Sn radioligand administration directly to the knee joints.

5.1 External Dose Assessment for Canines

Conservative external dose to humans following administration to canines was estimated for five veterinary procedures: imaging with a full-body distribution of ^{99m}Tc, imaging with ^{99m}Tc in bone, ^{117m}Sn synovectomy treatment in knee joints of canines, ^{131}I hyperthyroid treatment, and ^{131}I thyroid cancer treatment. Table 15 shows that radioiodine cancer therapy generates a very large external dose rate and external dose potential, which can reach more than an order of magnitude above the limits in 10 CFR Part 20. Because of the higher activities associated with the cancer treatment of canines compared to felines, large external dose rates can be expected for about two weeks following administration. As with felines, hyperthyroidism treatments utilizing ^{131}I have potential to exceed regulatory guidance. Additionally, ^{117m}Sn synovectomy treatment can exceed regulatory limits when the pet is in proximity to the owner's head. Other irradiation geometries and veterinary procedures are less important from the perspective of external EDE.

Table 15. External dose rate and total dose for human exposure to canines.

Procedure	Tc-99m Full Body	Tc-99m Bone Distribution	Sn-117m Synovectomy	I-131 Hyperthyroidism	I-131 Cancer
Administration (MBq)	1,110	1,110	222	148	4,440
Canine at Owner's Head					
Dose Rate (mSv/h)	0.089	0.090	0.088	0.038	1.1
Total Dose (mSv)	0.77	0.78	43	3.3	99
Canine in Owner's Lap					
Dose Rate (mSv/h)	0.11	0.11	0.017	0.021	0.62
Total Dose (mSv)	0.93	0.94	8.7	1.8	53
Canine at Owner's Feet					
Dose Rate (mSv/h)	0.0092	0.011	0.00030	0.0018	0.053
Total Dose (mSv)	0.080	0.092	0.15	0.15	4.6

5.2 Internal Dose Assessment for Canines

Internal dose calculations for canine veterinary procedures are carried out considering potential human intakes of ^{117m}Sn and ^{131}I according to conservative assumptions. Dose calculations are performed for the potential ingestion intake of ^{117m}Sn following injections into canine elbows and potential ingestion intake of ^{131}I. Maximum ingestion CEDEs from canine veterinary procedures are presented in Table 16.

Table 16. Maximum internal dose to humans for canine veterinary procedures.

Radionuclide & Intake Pathway	Ingestion Calculation	Maximum CEDE
^{99m}Tc removable contamination (full body imaging)	$5\text{x}10^{-7} \cdot (1.11\text{x}10^{9} Bq) \cdot \left(1.68x10^{-8}\ \frac{mSv}{Bq}\right) =$	$0.000009\ mSv$
^{117m}Sn animal excreta (joint injections)	$0.2 \cdot (0.83\ \text{x}10^{6}\ Bq) \cdot \left(7.97x10^{-7}\ \frac{mSv}{Bq}\right) =$	$0.13\ mSv$
^{131}I removable animal contamination (cancer therapy)	$1.0\text{x}10^{-3}\ mSv \cdot \frac{4440\ MBq}{154\ MBq} =$	$0.03\ mSv$
^{131}I removable surface contamination (cancer therapy)	$2.7\text{x}10^{-3}\ mSv \cdot \frac{4440\ MBq}{79\ MBq} =$	$0.15\ mSv$
^{131}I animal saliva (cancer therapy)	$0.012 \cdot 4.44x10^{9} Bq \cdot \left(1.44x10^{-5}\ \frac{mSv}{Bq}\right) =$	$770\ mSv$
^{131}I animal excreta	No data were found on ^{131}I concentrations in canine excreta	

Diagnostic imaging administrations of ^{99m}Tc to canines are associated with very low internal doses to humans and are not of concern from the perspective of radiological protection.

Inadvertent contact with canine excreta and potential ingestion of ^{117m}Sn are not expected to be a concern provided that administering facilities confirm ^{117m}Sn colloids were correctly injected and retained in the joint.

Removable ^{131}I contamination on the animal itself or in its living environment are not expected to exceed current regulatory limits. However, more research is recommended to strengthen the basis for veterinary cancer patients. Unrealistically conservative calculations for canines indicate worst-case ^{131}I doses from inadvertent saliva ingestion following canine cancer therapy have the potential to exceed regulatory limits when no precautions are followed. Human saliva data were used because canine saliva data were not found in the published literature. Information on ^{131}I saliva concentrations in canines would improve the calculation. Due to a lack of supporting data on ^{131}I concentrations in canine excreta, no calculations were performed for this potential pathway.

6 EQUINE ADMINISTRATIONS

Veterinary uses for radioactive material administered to horses include the following procedures:

- Imaging with ^{99m}Tc
- Synovectomy therapy with ^{117m}Sn
- Eyelid cancer therapy with ^{192}Ir or ^{125}I (as sealed sources)

For horses, ^{99m}Tc administrations can range from 1,110 MBq for a full-body distribution to 8,880 MBq for bone imaging. In this report, emphasis is given to the higher activity administration in horses. Although Synovetin (^{117m}Sn) treatment is currently not licensed within the United States for equines, it was included in the external dose analysis as a potential emerging technology. From the variety of brachytherapy procedures performed on horses, two eyelid cancer therapy treatments were selected for external dose calculations. These procedures involve source positioning at external locations on the body and therefore are more likely to impart dose to humans. Both treatments involve surgically implanting brachytherapy seeds within the animal's eyelid for irradiation of common sarcomas.

6.1 External Dose Assessment for Equines

External dose rate to humans from equine administrations were determined for four veterinary procedures: imaging with ^{99m}Tc in bone, ^{117m}Sn synovectomy treatment in knee joints, eyelid cancer therapy with ^{192}Ir or ^{125}I as a sealed source. Table 17 demonstrates that the very high activity ^{192}Ir source generates external dose rates to a nearby individual that can exceed limits by more than an order of magnitude. Additionally, ^{99m}Tc imaging in bone can generate external doses in excess of 0.02 mSv/h when the individual is in close proximity to the horse immediately after administration. Dose rates in excess of 0.02 mSv/h can be expected to persist for about half a day. Even when 100% occupancy is assumed, Table 17 indicates none of the equine procedures are expected to deliver an external EDE to humans of more than 0.5 mSv. The total dose to humans from sealed sources were not included in these calculations as the source is assumed to be removed prior to release of the animal. With sealed sources, there is no potential environmental contamination, and the external radiation hazard ceases immediately upon removal of the source.

Table 17. External dose rate and total dose for human exposure to equines.

Procedure	Tc-99m Bone Distribution	Sn-117m Synovectomy	Ir-192 (sealed) Eyelid	I-125 (sealed) Eyelid
Administration (MBq)	8,880	222	45,000	1,665
Standing at Horse's Shoulder				
Dose Rate (mSv/h)	0.063	0.00085	0.16	0.0015
Total Dose (mSv)	0.44	0.41	(Source removed prior to release)	
Riding Horse				
Dose Rate (mSv/h)	0.069	5.1E-7	0.43	0.0016
Total Dose (mSv)	0.48	0.00025	(Source removed prior to release)	
Leading the Horse				
Dose Rate (mSv/h)	0.0074	0.00028	0.65	0.0019
Total Dose (mSv)	0.051	0.14	(Source removed prior to release)	

6.2 Internal Dose Assessment for Equines

Removeable radionuclide contamination on equines, radionuclide concentrations in equine saliva, and radionuclide concentrations in equine excreta have not been found in the available literature. Tables 15 and 17 indicate the same activity of ^{117m}Sn is administered to the joints of canines and equines. However, a lack of data on equine joint retention prevents calculation of potential ^{117m}Sn ingestion doses. Table 18 shows that the maximum internal dose following equine diagnostic imaging is negligible.

Table 18. Maximum internal dose to humans for an equine veterinary procedure.

Radionuclide	Ingestion of Removable Contamination	Maximum CEDE
^{99m}Tc	$5\text{x}10^{-7} \cdot (8.88\text{x}10^{9} Bq) \cdot \left(1.68x10^{-8}\ \frac{mSv}{Bq}\right) =$	$0.00007\ mSv$

7 EMERGING TECHNOLOGIES

The administered activity for emerging veterinary technologies is currently in various phases of research. Emerging technologies are therefore evaluated by comparing dose coefficients to those of ^{131}I (Table 19), because details on administered activities for emerging radionuclides are not known at this time.

Four emerging radionuclides are considered: ^{18}F, ^{166}Ho, ^{153}Sm, and ^{90}Y as supported by a least one cited publication on its veterinary use.

- For ^{18}F, a 285-MBq (7.7-mCi) administration is assumed for a large canine of 45 kg according to an administration protocol of 0.17 mCi/kg (Griffin et al. 2019). Radioactive decay of this short-lived radionuclide is not credited in the assessment, which effectively implies that removable contamination is immediately available for human intake.
- For ^{166}Ho, an average activity of 1 GBq administered to a horse (Mäkelä et al. 2004) is applied.
- For ^{153}Sm, a 3.3-GBq administration was selected as the upper bound from 37–74 MBq/kg (Wendt et al. 2020) for a large dog of 45 kg. This administered activity exceeds the single administration dosage range of 36–57 MBq/kg reported by Coomer et al. (2009).
- For ^{90}Y, the calculation proceeds with a 1.6-GBq maximum activity for a dog (Wendt et al. 2020).

Table 19. Comparison of external and internal dose coefficients relative to those of ^{131}I.

Radionuclide (Veterinary Use)	External Dose Coefficient[a] Relative to ^{131}I	Internal Dose Coefficient[b] Relative to ^{131}I
^{18}F (canine imaging)	3x greater	430x less
^{90}Y (canine skeletal treatments)	37x less	5x less
^{153}Sm (canine palliative care)	5x less	18x less
^{166}Ho (equine synovectomy)	11x less	10x less
Alpha emitters (none proposed)	Approximately equal for ^{223}Ra	Up to 12x greater for ^{223}Ra

[a]Dose-rate constant at 1 m for point-to-point irradiation in units of mSv per GBq-h from Table A-1 of Draft Revision 2 of Regulatory Guide 8.39 (NRC, 2021).
[b]Ingestion dose coefficients for CEDE (EPA, 1988, Table 2.2)

Table 19 highlights two situations with greater dose coefficients for emerging radionuclides compared to ^{131}I. These are discussed separately.

- Combined with its relatively short physical half-life (110 min), veterinary use of ^{18}F for diagnostic imaging requires significantly lower administered activities compared to radioiodine therapies. These factors more than offset the modest 3x larger external dose coefficient of ^{18}F on a per-activity basis. In other words, ^{18}F is not expected to be a concern from the perspective of external and internal doses to humans following veterinary release.
- Regarding internal doses following veterinary procedures with emerging radionuclides, Table 19 indicates that alpha-emitting radionuclides have a greater internal dose potential compared to ^{131}I for the same intake activity. For these reasons, additional considerations pertaining to internal doses are described for emerging radionuclides.

Results of the assessment are presented in Table 20 with a description of each calculation.

Table 20. Maximum internal dose to humans for veterinary procedures with emerging radionuclides based on a generic ingestion fraction of $5x10^{-7}$ for the total removable contamination available for intake following administration.

Radionuclide	Ingestion of Removable Contamination	Maximum CEDE
^{18}F	$5x10^{-7} \cdot (285x10^{6}Bq) \cdot \left(3.31x10^{-8}\ \frac{mSv}{Bq}\right) =$	$0.000005\ mSv$
^{166}Ho	$5x10^{-7} \cdot (1x10^{9}Bq) \cdot \left(1.51x10^{-6}\ \frac{mSv}{Bq}\right) =$	$0.0008\ mSv$
^{153}Sm	$5x10^{-7} \cdot (3.3x10^{9}Bq) \cdot \left(8.07x10^{-7}\ \frac{mSv}{Bq}\right) =$	$0.0013\ mSv$
^{90}Y	$5x10^{-7} \cdot (1.6x10^{9}Bq) \cdot \left(2.91x10^{-6}\ \frac{mSv}{Bq}\right) =$	$0.0023\ mSv$

Radionuclides considered in this assessment are based on the published literature for current and proposed veterinary uses. As technology advances, additional radionuclides may be considered for veterinary procedures. No speculation or analysis has been performed on specific, yet-to-emerge radionuclides, however, qualitative impacts on internal dose are discussed for main considerations along with semi-quantitative reference points for human intakes of radioactive material.

Three main considerations for internal dose to humans are administered quantities, transfer potential, and internal dose potential:

- Radioactivity is quantified by administered activity and retained activity in the animal after release. Retained activity is either equal to the administered activity or, more likely, less than the administered activity due to radiological and biological loss following administration. Low-activity administrations of radionuclides for veterinary diagnostic imaging have not been shown to be a concern for potential human internal dose following release. For example, short-lived radionuclides may result in greatly reduced or negligible retained activities several hours after administration. In contrast, long-lived radionuclides with slow biological clearance can persist for several weeks, or longer, following the procedure.
- Transfer potential relates to how retained activity in the animal is made available for human contact and potential intake. Colloidal injections that remain in the joint of the treated animal have no transfer potential for human intake under most circumstances. If the same animal suffers an unrelated serious traumatic injury to the treatment area following release, the natural confinement provided by the animal's body could be compromised. For this rare situation, the transfer potential for exposed or oozing radioactive material would be substantially greater.
- Internal dose potential for a specific radionuclide is quantified by internal dose coefficients for relevant human intake pathways (e.g., inhalation, ingestion, or transfer of radioactive material into human wounds). Radionuclides with smaller internal dose coefficients require a larger intake activity to result in the same committed effective dose equivalent (CEDE). Radionuclides that emit alpha particles tend to have larger internal dose coefficients compared to radionuclides that emit electrons and photons.

From the assessments of electron- and photon-emitting radionuclides in Sections 4, 5, and 6, the largest internal dose coefficient of 1.44×10^{-5} mSv/Bq pertains to the ingestion of ^{131}I. This implies human intakes of approximately 0.1 MBq could result in committed effective dose equivalents (CEDE) greater than 1 mSv. No calculations were performed on alpha-emitting radionuclides because current and proposed veterinary uses of radionuclide materials have not included alpha-emitting radionuclides. Nevertheless, alpha-emitting radionuclides and decay series, such as ^{211}At, $^{225}Ac/^{213}Bi$, $^{227}Th/^{223}Ra$, and $^{224}Ra/^{212}Bi$, are characterized by effective dose coefficients for human ingestion that range from roughly comparable to more than a factor of 10 greater than the largest internal dose coefficient for previously assessed radionuclides. This additional "effectiveness" translates into reduced activities for the same committed effective dose equivalent. In other words, human intake of about 0.01 MBq of an alpha-emitting radionuclide may approach or exceed 1 mSv. Furthermore, radiopharmaceutical behavior in the veterinary patient, including excretion rates, is very important to the transfer potential of the radionuclide and assessment of potential human intakes.

Several highly conservative assumptions made in this report regarding the transfer potential of radioactive material for human intake should be reevaluated for alpha-emitting radionuclides that could be retained in the veterinary patient for longer time periods compared to ^{131}I or ^{99m}Tc. Maximum and bounding internal doses estimated in this report were found to be below or far below 1 mSv. Applying the same highly conservative assumptions to the transfer potential for alpha-emitting radionuclides could result in higher hypothetical internal doses and, thus, may warrant additional effort to determine more realistic transfer parameter values. When the transfer potential of radioactive material is reduced, higher activities retained in the veterinary patient translate into lower potential human intakes and internal doses. As one of the important parameters in the calculation of internal dose, the transfer potential of alpha-emitting radionuclides should be assessed for expected scenarios if alpha-emitting radionuclides are ultimately proposed for use in veterinary procedures.

8 SUMMARY & CONCLUSIONS

8.1 External Dosimetry

The external effective dose equivalent (EDE) to humans was estimated from radionuclides in their pets, using conservative exposure assumptions to generate maximum dose rates for a variety of possible exposure geometries, as well as maximum external doses accumulated over time. External dose was estimated assuming 100% occupancy, close contact, and fully integrated dose to the human through the residence time in the animal's body. A summary (Table 21) is provided below in which the highest values obtained for each administration procedure are presented in mSv/h for dose rates and mSv for total dose.

Table 21. Summary of potential human external dose for 100% occupancy listed by radionuclide.

External Exposure Description	*Maximum Dose Rate (mSv/h)*	*Maximum Dose (mSv)*
I-131 (feline hyperthyroidism)	0.041	3.6
I-131 (canine hyperthyroidism)	0.038	3.3
I-131 (feline thyroid cancer)	0.42	36
I-131 (canine thyroid cancer)	1.1	99
Sn-117m (canine joint)	0.088	43
Sn-117m (equine joint)	0.00085	0.41
Tc-99m (feline body imaging)	0.15	1.1
Tc-99m (canine body imaging)	0.089	0.77
Tc-99m (equine body imaging)	0.014	0.097
Tc-99m (canine bone imaging)	0.090	0.78
Tc-99m (equine bone imaging)	0.069	0.48
Ir-192 (equine eyelid)	0.65	Not calculated, source removed
I-125 (equine eyelid)	0.0019	Not calculated, source removed

For administrations of Tc-99m, the highest potential dose rate of 0.15 mSv/h can be attributed to felines sitting in their owner's lap when biological and radiological loss are neglected. This dose rate is more than 7 times higher than the limitation specified in 10 CFR Part 20.

Radiosynovectomy (Sn-117m) in canines can exceed 0.02 mSv/h for up to one month after administration if the animal sleeps with a family member. Additionally, a total dose of more than 1 mSv can be received if the animal is allowed to sleep with the family member during consecutive nights or sit in their lap for several hours a day.

External doses and dose rates to humans are important to consider following radioiodine (I-131) administrations in felines and canines for cancer and hyperthyroid treatments. For nearly all representative irradiation geometries, I-131 administrations can yield dose rates greater than 0.02 mSv/h and a total dose greater than 1 mSv.

And finally, brachytherapy with Ir-192 in equines can generate large dose rates above 0.2 mSv/h. In contrast, brachytherapy with I-125 results in very small external dose rates to humans of less than 0.002 mSv/h. Due to their high activities, Ir-192 implants can exceed 0.02 mSv within a few minutes.

8.2 Internal Dosimetry

Table 22 provides a summary of estimated internal doses to humans with highly conservative assumptions. Inadvertent ingestion of ^{131}I in animal saliva and animal excreta were the only two internal dose pathways capable of exceeding 1 mSv. Uncertainties and conservatism could be reduced in the animal saliva calculation if data become available on radionuclide activities or concentrations in animal saliva during cancer therapy. Because no such data for animals were found in the literature, the assessment utilized analog saliva data from human patients to estimate potential internal doses from ingesting animal saliva.

Scenarios with bounding internal doses that approached 1 mSv involved ^{117m}Sn colloidal injections into canine joints—with an assumed human intake of all radioactivity not retained in the joint—and potential ingestion of removable contamination on surfaces in the animal's living environment following ^{131}I cancer treatments of canines. A separate calculation for ^{117m}Sn colloidal injections into equine joints could not be performed due to a lack of data on activity not retained in the joint.

Internal doses from alpha-emitting radionuclides were not assessed. If alpha-emitting radionuclides at specific administered activities are proposed for future veterinary procedures, additional work is recommended to estimate potential human intakes for animal exposure scenarios.

Table 22. Summary of internal dose potential for highly conservative assumptions.

Pathway	*Description*	*Maximum Dose Potential (mSv)*
Airborne resuspension and inhalation	I-131 in kitty litter (hyperthyroidism)	0.0017 (urine as source) 0.0037 (feces as source)
Ingestion of removable contamination based on radioiodine transfer data	I-131 on animal (hyperthyroidism)	0.0010
	I-131 on surfaces (hyperthyroidism)	0.0027
	I-131 on animal (cancer therapy)	0.03
	I-131 on surfaces (cancer therapy)	0.15
Ingestion of animal saliva at maximum concentration	I-131 (feline cancer therapy)	190
	I-131 (canine cancer therapy)	770
	I-131 (feline or canine hyperthyroidism)	26
Ingestion of animal excreta	I-131 (assumed excretion fraction)	1.4
	I-131 (measured concentration)	0.63
	Sn-117m (100% activity not in joint)	0.13

9 RECOMMENDATIONS

Potential doses received by maximally exposed individuals (human) resulting from veterinary nuclear medicine administrations were investigated. Without protective measures such as limiting time spent in close contact with the veterinary patient, radioiodine procedures for cancer therapy in felines and canines have the greatest potential of resulting in external dose rates exceeding 0.02 mSv (2 mrem) in any one hour or external doses exceeding 1 mSv (100 mrem). Radiosynovectomy via ^{117m}Sn colloidal injections in canines can also result in external dose rates in excess of 0.02 mSv/h. Without protective measures, radioiodine procedures for cancer therapy in felines and canines have the greatest potential of resulting in internal doses exceeding 1 mSv. With similar conservative assumptions, hyperthyroid treatments of felines with ^{131}I could also result in internal doses exceeding 1 mSv. Inadvertent ingestion of animal saliva could be associated with a larger potential for internal doses compared to excreta ingestion. However, animal-specific data on saliva concentration are needed to reduce uncertainties.

Exposure geometry and time spent close to the pet are important factors for external exposure. Future guidance for pet release could provide activity thresholds by radionuclide that would be protective of humans coming into close contact with veterinary patients. For radioiodine administrations for cancer therapy, biokinetics and facility hold times will be especially important to developing behavioral restrictions and release instructions. For other procedures, such as long-lived ^{117m}Sn colloidal injections into animal joints with negligible biological elimination, a greater reliance may be placed on behavioral restrictions to justify pet release. If a limit on dose-rate is applied, measurement thresholds in pet release guidance may be redefined for external effective dose equivalent to humans at close distances and, thus, could become independent of the administered radionuclide.

Radiation safety considerations and instructions should include a systematic evaluation of hold times for ^{131}I treatments of felines and canines, as well as behavioral restrictions for ^{117m}Sn radiosynovectomy, because dose rates in proximity to the animal can be quite high following these procedures. Additionally, biokinetic elimination of ^{99m}Tc in equines could be quantified to determine if a one-day hold or shorter time-period would be protective for release without behavioral restrictions. For brachytherapy, a no-release condition can be recommended as long as the source remains on or in the animal.

Maximally exposed humans are likely the animals' owners and may spend considerable time near their pets. A dosimetric method could be developed to address future radiopharmaceuticals, such as alpha-emitting radionuclides, that have a greater potential to deliver internal dose. With additional information, guidelines could be developed for radioactive contamination resulting from anticipated pet activities, such as licking, grooming, transfer to bedding, sickness, or urination and defecation in the home.

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