Age-dependent Radiation Dose Rates from Canine Sn-117m Treatments

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Abstract—Tin-117m (Sn-117m) is used to treat dogs with osteoarthritic joints by radiosynoviorthesis. The decay process for Sn-117m is internal conversion wherein IC electrons and auger electrons provide the therapeutic effect. Additionally, the most prominent gamma emission is 158.6 keV. The effective dose rate received by a person interacting at close distances with a treated dog is needed to determine the person’s total dose and thus regulatory compliance. Simple measurement of the dose rate at a given distance does not provide an accurate measurement of the effective dose to a person due to the non-uniform nature of the radiation field at close distances. MNCP models of the interactions of five ages of humans at three distances were created to determine the effective dose rates using the methodology from NRC Regulatory Guide 8.40. Ratios of the effective dose rate to the person to the measured dose rate at 1 m from the same source were calculated.

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Key words: dogs; dose assessment; Monte Carlo; radiation protection

INTRODUCTION

RADIOSYNVIORTHESIS (RSO) is used to treat chronic pain and inflammation of osteoarthritis (OA) in dogs. Veterinarians turn to RSO in cases where the primary and secondary lines of treatment are found to be inadequate due to the lack of other treatment options. Synovetin OA® is a colloid containing tin-117m (Sn-117m) that can be used to treat osteoarthritic dog joints such as the elbow, stifle (the equivalent of the human knee), and hip. The internal conversion and Auger electrons emitted by the Sn-117m provide the therapeutic effect. Tin-117m also emits gamma rays, the most significant of which is 158.6 keV. The use of Sn-117m radiosynoviorthesis in veterinary medicine is relatively new. As a new therapy modality, there are multiple effectiveness and safety concerns that need to be addressed. The patient safety aspects have been addressed previously (Srivastava 2007; Doerr et al. 2015; Stevenson et al. 2015; Aashish 2018; Lattimer et al. 2019). As use of Sn-117m enters commercial use, radiation safety for members of the public must be addressed. The dose rate to people from a treated dog is of interest in order to limit the dose to the owners/caretakers of the dog.

One of the primary concerns with this treatment is ensuring that dose limits for members of the public will be met. The initial attempt to license Sn-117m using NCRP 148 methodology and what has been used for ¹³¹I therapy for cats was unsuccessful (US NRC 2018). The US Nuclear Regulatory Commission’s (NRC) main concerns revolved around Sn-117m’s relatively long effective half-life compared with ¹³¹I as used in hyperthyroid therapy in cats, the need for confidence in the characterization of pet-human interactions, and the adequacy and compliance with behavior modification instructions. Effectively, NRC’s position was that the behavior of cats and dogs and their interactions with their owners could be different and that dog-specific data was needed to demonstrate the ability to comply with public dose limits. Tin-117m colloid is different from many other unsealed radionuclides used due to its half-life, 14 d, and the lack of biological elimination.

To demonstrate compliance with the public dose limits, time and motion studies are needed to prospectively calculate the dose to members of the public, of which the people that share a household with the dog are the critical group. Earlier human dose assessments had used relatively simple assumptions regarding interactions and the geometry of those interactions (Wendt et al. 2020). Additional refinement of those assumptions, both with regard to dose rate and the geometry of those interactions, was needed to address NRC’s concerns. It should be noted that veterinary medicine is regulated under 10 CFR 30 rather than 10 CFR 35, and thus the public dose limits in 10 CFR 20, or the Agreement State...
equivalents, apply to veterinary medicine in all states except Texas, which regulates veterinary medicine under Title 25 Texas Administrative Code Chapter 289 Rule 256 (State of Texas 2018), the Texas equivalent of 10 CFR 35.

One of the inputs to the time and motion study is the dose rate at various distances from the dog at which an individual might be located. An individual in the same household may spend time in relatively close proximity to the dog, such as in contact with the dog, at a distance of approximately 30 cm, or at 1 m. It is common to refer to the distance between an individual and a radiation source based on the minimum separation. However, this “closest point of approach” method is not suitable for determining an overall dose rate. Simple geometric attenuation or point source approximations are not appropriate given the significant variations in distance that may occur. As an example, the treated joint of a dog standing beside its owner may be “in contact” with the owner’s leg yet half a meter removed from the individual’s torso and further still from the individual’s head. Thus the dose rate to the person’s leg, organs in the torso, and the head are all substantially different.

Deviation from the point source approximation for various geometries and distances is quantified in Gollnick (2000), which indicates that the deviation is substantial when the distance is less than 50% of the longest dimension of the source or receptor and can remain substantial until the distance is at least greater than 100% of the longest dimension. For a reference adult male that is 176 cm tall, a corresponding distance is needed to rely on the inverse square approximation.

Attempting to completely quantify the orientation of a person with respect to a dog for a time and motion study is not feasible. It is a simpler task to quantify time at a particular distance regardless of orientation. For determination of the dose rate, and ultimately the total dose to an individual, three distances are of significance: “contact,” 0.3 m, and 1.0 m. Various dog-individual interactions (feeding, petting, walking, etc.) can be categorized as occurring at one of these distances. Interactions at distances substantially greater than 1.0 m are dosimetrically insignificant. For any given distance, it can be assumed that a person will be in a variety of positions with respect to the dog. Therefore, an “average” dose rate at a particular distance becomes the relevant dose rate to use to calculate the individual’s dose. A previous study (Arno et al. 2021) evaluated the impact of the orientation of the dog upon the dose rate. This current study evaluates the receptor portion of the dose rate quantification.

**Background**

Due to the impracticality of quantifying the universe of possible orientations of an individual with respect to a dog, a conservative geometry has been chosen to narrow the focus of the study to calculation of the dose rate for the chosen conservative geometry. The size of the individual is also a factor to consider, and thus 5 ages were considered: 1, 5, 10, and 15-y old, and adult.

The most conservative interaction geometry occurs when the dog’s treated joint is in contact with the individual’s torso, such as when a person picks up and carries a dog, minimizing the distance from the radiation source to the center of mass, i.e., torso center. For greater distances, the highest dose is still obtained when the distance to the center of mass is minimized for a given distance from any part of the body. Therefore, a source located orthogonally from the center of the torso in the anterior direction is considered to be the most conservative orientation.

The US Nuclear Regulatory Commission provides guidance on how to measure a quantity described as the effective dose equivalent external (EDEX) in non-uniform radiation fields in their Regulatory Guide 8.40 (US NRC 2010). This can be thought of as the external equivalent to the committed effective dose equivalent where the dose to individual parts of the body is taken into account. This guidance was previously used to perform MicroShield (Grove Engineering, Lynchburg, VA) and simplified Monte Carlo N-Particle (MCNP; Los Alamos National Laboratory, Los Alamos, NM) calculations of the dose to an individual’s torso in this manner from a point source of radiation (Arno 2020; US NRC 2020b). MicroShield is limited in the geometries it can consider and especially cannot account for attenuation and buildup in more complex geometries. In order to accomplish this with MicroShield, super positioning was used to reverse the problem and calculate the dose to a point representing the treated dog joint from a volume source representing the torso (Arno 2020). However, this modeling does not take into account the geometry of the dog joint itself, and the attenuation and buildup methods used have their limitations.

The NRC conducted verification modeling using MCNP and a similar geometry, which noted that the MicroShield-based evaluation included substantial conservatism, especially at shorter distances (US NRC 2020b). That evaluation only considered the dose to the torso and did not calculate the dose to the head, upper arms, or upper legs. The present study was conducted to expand on the previous modeling efforts to more explicitly evaluate this more complicated geometry, taking into account both the geometry and materials of the source, the treated dog joint, and the human receptor.

**METHODOLOGY**

**Human phantoms**

US NRC Regulatory Guide 8.40 states that “If the body is not irradiated uniformly, a single-dose measurement cannot determine the dose to the various organs and tissues for an accurate determination of the EDEX.” Since a single
measurement is not representative, the body is divided into seven compartments, the doses to which can be calculated individually, and each of which has a weighting factor. The compartments and their respective weighting factors are provided in Table 1 and are based on the organ weighting factors for the organs in each compartment. The overall dose or dose rate to each of these compartments is evaluated rather than the dose or dose rate to individual organs. Each compartment’s dose is multiplied by its respective weighting factor to determine the overall EDEX. Note that these compartment weights do not correspond with the latest guidance in ANSI/HPS N13.41-2011 (HPS 2011), which uses the newer guidance from ICRP 103 (ICRP 2007). The older compartment weights based on ANSI/HPS N13.41-1997 (HPS 1996) and ICRP 26 (ICRP 1977) are used, as those correspond to the organ weights used in 10 CFR 20 (US NRC 1991) and thus are the ones that need to be used to determine regulatory compliance.

A phantom comprised of these seven compartments was created using the PIMAL (US NRC 2017) phantom as the starting point. The PIMAL phantom is an articulated phantom (movable arms and legs) with detailed internal anatomy. The advantage of the PIMAL phantom is that the arms are defined separately rather than being combined in an ellipsoid with the torso as in the older MIRD phantom (Snyder et al. 1969). The PIMAL phantom is also more readily resized than voxel phantoms or other phantoms with more detailed internal anatomy. For the purposes of this study, the articulation feature was not used, and the internal anatomy was simplified. The internal organs were removed from the PIMAL model along with the lower arms and legs, leaving the outer surface of the skin to define the shape of each compartment. This permits each compartment to be defined as a single volume. The torso was bisected on a horizontal plane into equal size compartments to represent the abdomen and thorax. Each compartment was modeled as ICRU soft tissue with a density of 1.04 g cc\(^{-1}\) (ICRP 2003). Fig. 1 shows a view of the resulting phantom.

PIMAL only provides phantom geometries for an adult male and an adult female. In order to create phantom geometries for the younger ages, the dimensions of the PIMAL adult male phantom were linearly scaled based on ICRP

| Compartment                  | Weighting factor |
|------------------------------|------------------|
| Head and neck                | 0.10             |
| Thorax, above the abdomen    | 0.38             |
| Abdomen, including the pelvis| 0.50             |
| Upper right arm              | 0.005            |
| Upper left arm               | 0.005            |
| Right thigh                  | 0.005            |
| Left thigh                   | 0.005            |

Fig. 1. Adult phantom.
89 anatomical data (ICRP 2003). ICRP 89 Section 4.1.2 provides reference values for body height at ages 1, 5, 10, and 15-y old, and adult. Section 4.2.4 of ICRP 89 further breaks this down into the height attributable to the legs, torso (trunk), and head/neck. Table 2 reproduces these values. The percentages attributable to the head/neck, torso, and legs are provided for ages 1, 8, 13, and 17-y in ICRP 89 Figure 4.5 rather than 1, 5, 10, and 15-y, and adult. The percentages at the ages of 5, 10, and 15-y were interpolated from the provided values, and those for an adult were assumed to be the same as for a 17-y-old.

The reference values for males were used to bound the values for females. The values for females are identical to those for males for ages 10 and under and are less at older ages. The sizes of the adolescent phantom heads were scaled using the calculated proportional dimension of the head and neck reference values as given in eqn (1):

\[
HN_C = HN_A \frac{H_C}{H_A} \frac{HN_{CP}}{HN_{AP}},
\]

(1)

where:

- \( HN_C \) = Child head/neck length;
- \( HN_A \) = Adult head/neck length;
- \( H_C \) = Child total height;
- \( H_A \) = Adult total height;
- \( HN_{CP} \) = Child head/neck percentage of overall height; and
- \( HN_{AP} \) = Adult head/neck percentage of overall height.

Due to differences between the ICRP 89 reference values and the PIMAL phantom dimensions, the ratios from the ICRP 89 reference values were used to scale the starting dimensions from the PIMAL adult male phantom model. The same approach was used for the upper legs based on the percentage of total height attributable to the legs and for the torso based on the percentage of total height attributable to the trunk. The arms of the PIMAL phantom place the elbows at the midpoint of the torso. Therefore, the arms were scaled based on the percentage of total height attributable to the trunk. In this manner, the five phantoms were created as shown in Fig. 2. Table 3 provides the scaled dimensions for each body compartment based on this approach.

### Table 2. ICRP 89 height proportions.

| Age, y | Adult | 15  | 10  | 5   | 1  |
|--------|-------|-----|-----|-----|----|
| Total height, cm | 176  | 167 | 139 | 109 | 76 |
| Head/neck length % | 20%  | 20% | 22% | 24% | 26%|
| Torso length %    | 33%  | 33% | 33% | 36% | 40%|
| Legs length %     | 49%  | 49% | 47% | 41% | 35%|

### Source characteristics

The mathematical model for a dog joint from Wendt et al. (2020) was used to model the radiation source. This model consists of a cartilage-lined bony ball-and-socket joint connected to cylindrical bone masses covered by an annular layer of skin as shown in Fig. 3. The space around the ball and socket simulates the synovial sac. The Wendt model was simplified by treating the cartilage as part of the bone. The ICRP 89 material compositions for human bone and skin were used for the corresponding canine anatomy. The synovial fluid was modeled as water and is the volume where the therapeutic dosage of Sn-117m is located. The gamma and x-ray energies and abundances for Sn-117m were obtained from Brookhaven National Laboratory’s NuDat 2.8 database (BNL 2020). All listed gamma and x rays were included in the model.

### MCNP modeling

Five phantoms were modeled at three source-to-receptor distances for a total of 15 scenarios with five calculated dose rates [head/neck, thorax, abdomen, upper arms (considered together), and thighs (considered together)] in each. The problem geometry is symmetric about the mid-sagittal plane, and thus the dose rates to the left and right upper arms and the left and right thigh are respectively the same. Additionally, the dose rate from the dog joint at a point 1.0 m away in air was modeled to simulate the measured dose-rate response of a radiation detector. This result was used to normalize the calculated EDEX rate in terms of
MCNP Version 6.2 (Werner 2017) was used for the calculations. The doses to the phantom compartments were calculated using “F6” cell volume energy deposition tallies, and the simulated detector was modeled using an “F5” point detector tally and MCNP’s built-in dose energy response function to determine Sv h\(^{-1}\) particle\(^{-1}\).

The dose rate is normalized by the measured dose rate at 1 m instead of using the injected activity due to the variation in dose rate per unit injected activity that has been observed. This variation is attributed to variation in joint size for dogs of the same mass. The injected activity is selected based on the dog’s total mass rather than a direct measurement of the joint size. Joint size can vary between an obese dog with slender legs and a muscular dog with larger legs, which changes the amount of attenuation that occurs within the joint. Use of the measured dose rate at 1 m inherently accounts for the attenuation that occurs within the joint.

RESULTS

Table 4 provides the calculated normalized dose rate in Sv Gy\(^{-1}\) for each compartment, age, and distance where the dose rate in Gy is measured at 1 m. Combining these values with the compartment weighting factors yields the EDEX values at the bottom of the table. Since the compartment definitions are the same in both the 1997 and 2011 versions of ANSI/HPS N13.41 (HPS 1996, 2011), this table can be

| Compartment       | Adult | 15   | 10   | 5    | 1    |
|-------------------|-------|------|------|------|------|
| Head/neck         | 0.11  | 0.15 | 0.33 | 0.66 | 1.73 |
| Upper torso       | 13.4  | 15.0 | 22.5 | 32.2 | 5.6  |
| Lower torso       | 13.3  | 14.9 | 22.4 | 32.0 | 55.4 |
| Upper arms        | 1.8   | 2.3  | 4.4  | 7.5  | 16.5 |
| Thighs            | 0.08  | 0.11 | 0.26 | 0.62 | 1.99 |

| 0.3 m dose rates, Sv Gy\(^{-1}\) |
|----------------------------------|
| Head/neck | 1.0   | 1.2   | 4.3   | 2.3   | 3.2       |
| Upper torso | 3.1   | 3.3   | 12.6  | 4.5   | 5.4       |
| Lower torso | 3.0   | 3.2   | 12.3  | 4.4   | 5.3       |
| Upper arms | 2.8   | 3.1   | 11.7  | 4.5   | 5.6       |
| Thighs     | 0.89  | 1.0   | 3.9   | 2.3   | 3.5       |

| 1 m dose rates, Sv Gy\(^{-1}\) |
|--------------------------------|
| Head/neck | 0.40  | 0.42  | 0.47  | 0.52  | 0.57     |
| Upper torso | 0.54  | 0.55  | 0.60  | 0.64  | 0.69     |
| Lower torso | 0.52  | 0.54  | 0.59  | 0.63  | 0.68     |
| Upper arms | 0.61  | 0.62  | 0.68  | 0.72  | 0.78     |
| Thighs     | 0.41  | 0.43  | 0.51  | 0.58  | 0.66     |

| EDEX, Sv Gy\(^{-1}\) |
|----------------------|
| Contact    | 11.8   | 13.2   | 19.8  | 28.4  | 30.2    |
| 0.3 m      | 2.8    | 3.0    | 11.5  | 4.2   | 5.1     |
| 1.0 m      | 0.52   | 0.53   | 0.58  | 0.62  | 0.68    |

Table 4. Normalized dose rates.

Fig. 3. Dog elbow joint.
used to calculate the EDEX based on the 2011 weighting factors if desired. As a practical matter, there is not much difference; the abdomen decreases by 0.04, and the thorax and head/neck increase by 0.02 each.

For an adult, the effective dose rate at 1 m is 52% of the measured dose rate at 1 m. For children, similar relationships are observed. The effective dose rate for a 1-y-old at 1 m is 68% of the measured dose rate at 1 m. These results are a decrease of between 27% and 54% compared to the earlier calculations performed with MicroShield. The higher decreases observed were for the closer distances and for the younger ages. A portion of that decrease is due to the more rigorous treatment of the geometry of the arms, legs, and head/neck. However, the weighting of those portions of the anatomy indicates that that difference is only a minor portion of the overall change. Another portion can be attributed to the different torso geometry, from a cylinder to a truncated ellipsoid. However, the overall magnitude of the decrease indicates it is driven more by accurate modeling of the radiation source, the self-shielding that occurs within the source, and better treatment of attenuation and buildup in the more complex geometry.

The increase in dose rates with the decrease in age/size can be attributed to two main factors. First, a smaller individual results in less self-shielding within the receptor since the needed penetration depth is less. Second, more of the body is closer to the source due to the decreased vertical distances involved; e.g., a 1-y-old’s head is physically closer to the source than that of an adult at the same lateral distance.

These results are greater than those calculated by the NRC in their MCNP modeling. While the details of the NRC model are not known, their model of the dog elbow contained the source within a sphere of bone covered by skin, whereas the modeling used in this study has the source exterior to the bone. This difference decreases the self-absorption in the source and is hypothesized to be the reason for the difference.

CONCLUSION

The actual dose rate to a person from what amounts to a point source differs significantly from the measured dose rate at a distance corresponding to the minimum distance between the person and the source. Conceptually, this makes sense since most of the body is further away than the minimum distance, and simple geometric attenuation would result in a lower dose rate. Where the inverse square law for a point source would indicate that the dose rate at 0.3 m should be 11 times higher than that at 1 m, the actual dose rate is less than 6 times higher. At “contact,” the inverse square law breaks down even further due to the finite dimensions involved. This modeling provides usable values at contact and other distances relevant to dose assessment.

The significance of these results lies in their use in calculating compliance with dose limits. The measured dose rate and simple inverse square law relationships should not be used in situations where such use introduces significant discrepancies and excessive conservatism. By using these still-conservative conversion factors, more accurate dose assessments can be performed.

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