V+ 2 Technical Manual Series: Wound Dosimetry Module

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ABSTRACT

VARSKIN+ is a U.S. Nuclear Regulatory Commission (NRC) computer code originally used by staff members and NRC licensees to calculate occupational dose to the skin resulting from exposure to radiation emitted from hot particles or other contamination on or near the skin. These assessments are required by Title 10 of the *Code of Federal Regulations* (10 CFR) 20.1201(c). NRC staff evaluates radioactive intakes through wounds pursuant to 10 CFR 20.1202(d). VARSKIN+ can be used to perform wound dose assessments by licensees if the metabolic modeling and dosimetry methods are consistent with NRC regulations (e.g., use of 10 cm^2 averaging area for skin dose assessments and tissue or organ weighting factors as defined in 10 CFR 20.1003). Wound dosimetry implements a new alpha dosimetry model for shallow skin assessments. The new VARSKIN+ user interface is written in Java with all scientific coding updated to Fortran 2018.

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ACKNOWLEDGMENTS

This report documents the work performed by Renaissance Code Development, LLC (RCD) for the U.S Nuclear Regulatory Commission (NRC) under Contract No31310022C0011. Staff at the Pacific Northwest National Laboratory authored initial versions of VARSKIN (US NRC 1987; US NRC 1989), with later versions amended at Colorado State University (US NRC 1992), the Center for Nuclear Waste Regulatory Analyses (US NRC 2006), and Oregon State University (US NRC 2011; US NRC 2014; US NRC 2018). The WoundDose module, based on NCRP 156 (2007), was added to VARSKIN+ in 2020. RCD performed the activities described herein on behalf of the NRC Office of Nuclear Regulatory Research, Division of Systems Analysis. This report is a product of RCD and does not necessarily reflect the views or regulatory position of the NRC.

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1.0 INTRODUCTION

WoundDose (Figure 1-1) is based on National Council on Radiological Protection and Measurement (NCRP) Report 156, “Development of a Biokinetic Model for Radionuclide-Contaminated Wounds and Procedures for Their Assessment, Dosimetry and Treatment” (NCRP 2007) and calculates shallow dose equivalent (SDE), local dose equivalent, and committed effective (and organ) dose equivalent from industrial or medical events resulting in the subdermal introduction of radioactivity following skin injury. The user will notice that many of the features of WoundDose are derived from the SkinDose module and their utilization is similar.

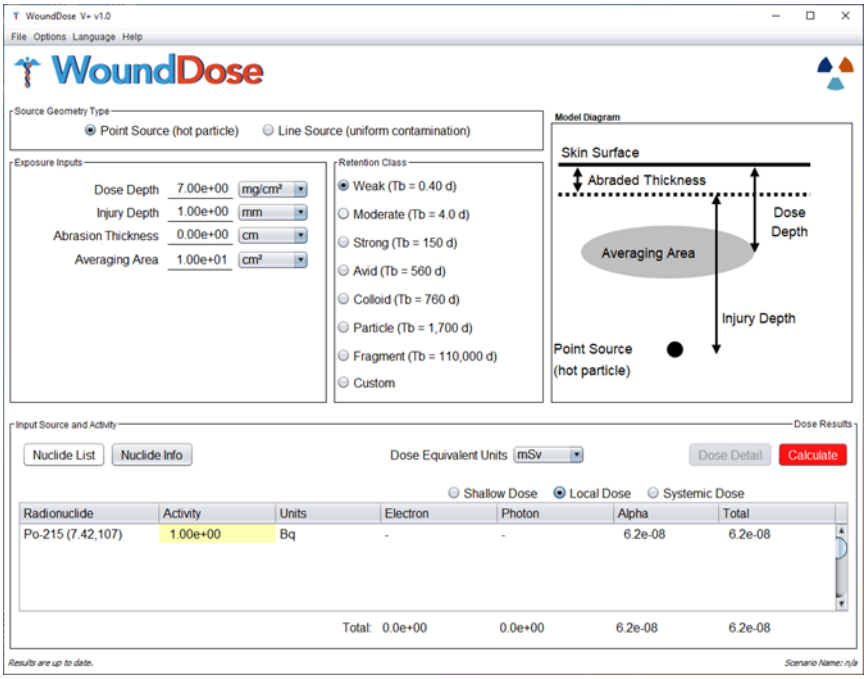

Figure 1-1. The WoundDose User Interface

2.0 WOUND DOSIMETRY MODEL

NCRP Report No. 156, "Development of a Biokinetic Model for Radionuclide-Contaminated Wounds and Procedures for Their Assessment, Dosimetry, and Treatment" (2007), provides most of the guidance on the wound model as it appears in WoundDose.

The wound model consists of three distinct dosimetry calculations: (1) SDE; (2) local dose equivalent; and (3) committed organ/effective dose equivalent. For converting absorbed dose to dose equivalent, the radiation weighting factor, w_r, is equal to unity (1) for photons and electrons, and 20 for alpha particles. Total dose is the sum of dose equivalent over the three radiation types.

2.1. Intact Skin, Abrasions and Non-severe Burns

For contamination events involving less-severe wounds where the skin remains intact, is lightly abraded, or has been lightly burned, dose assessments can be conducted using WoundDose to estimate the SDE calculations in a manner similar to that of SkinDose (i.e., no activity gets in the bloodstream). The shallow dose model is altered only by the removal of some or all the protective dead layer of skin. NCRP 156 (2007) states the following,

> "For contaminated wounds in which the skin is largely intact, [VARSKIN] dose calculations may be directly applicable. For embedded contamination, Berger's point kernels may be integrated over the depth of interest."

Previous versions of VARSKIN (before V5) for beta dosimetry were based on point kernels developed by Berger (1971). The more recent VARSKIN and SkinDose packages (V5.0 and later) have their foundation in Monte Carlo simulations using EGSnrc for electron dosimetry, but the methods are essentially the same. WoundDose draws on the shallow dose model of SkinDose.

In 10 CFR 20.1003, shallow skin dose is defined for external exposures and is to be determined at a basal-layer depth of 70 microns (7 mg/cm^2, 0.007 cm) beneath the surface of the skin. The basal layer depth varies in human tissue, as does the dead layer of skin, but this depth is assumed to be appropriate for the determination of risk. The regulation in 10 CFR 20.1201 also requires that shallow skin dose be "averaged over the contiguous 10 square centimeters of skin receiving the highest exposure". If an abrasion were to occur, in which a portion or all the dead layer of skin were removed, the depth at which shallow dose is determined would be altered by the thickness of removed tissue (alive or dead).

With this removal of a portion of the dead layer of skin, Co-60 dose for example to the shallow depth increases for electrons yet decreases for photons. The increase in electron dose is driven by the beta energy distribution and the characteristics of energy loss as a function of penetration depth. The decrease in photon dose is due to a reduction of charged particle buildup in 20 μm as opposed to 70 μm, which is ultimately a function of photon energy.

2.2. Severe Burns, Lacerations and Penetrating Wounds

For penetrating wounds where radioactive contamination has been forced under the skin surface, WoundDose will calculate dose for electrons, alpha particles, and photons for three different dose types: (1) shallow dose, which refers to a determination of the dose from the contaminated wound to the shallow basal-cell depth of 70 μm; (2) local dose, which refers to a determination of the dose to tissue surrounding the contaminated wound; and (3) committed systemic dose for uptakes to the bloodstream, which potentially affects all organs of the body.

Radiation dose to tissue from contaminated wounds is calculated using Eq. [2.1] for a user-specified, nuclide-specific dose factor (f), activity (Q), and the contamination residence time (τ).

$$D = fQ\tau \qquad [2.1]$$

The dose factor is dependent on the dose type being determined. Calculations of shallow and local dose in WoundDose are conducted for an estimated time that the radioactive contamination remains at the wound site (i.e., residence time). This residence time (τ) is calculated (Eq. [2.2]) by time-integrating the retention function

$$\tau = \int_0^\infty e^{-\lambda_e t}\, dt = \frac{1}{\lambda_e} \qquad [2.2]$$

where λ_e is the effective rate constant accounting for both biological and physical loss in Eq. [2.3]. Biological and radiological (physical) half-lives, $T_{1/2,b}$ & $T_{1/2,r}$ respectively, can be used to calculate the effective decay constant and effective half-life ($T_{1/2,e}$) or residence time in Eq. [2.4].

$$\lambda_e = \frac{\ln(2)}{T_{1/2,b}} + \frac{\ln(2)}{T_{1/2,r}} \qquad [2.3]$$

$$T_{1/2,e} = \frac{T_{1/2,b} \cdot T_{1/2,r}}{T_{1/2,b} + T_{1/2,r}} = \frac{\ln(2)}{\lambda_e} \quad or \quad \frac{1}{\lambda_e} = \frac{T_{1/2,e}}{\ln(2)} = \tau \qquad [2.4]$$

With the above definitions, Eq. [2.1] becomes Eq. [2.5] to directly determine dose for a specified nuclide.

$$D = f \cdot Q \cdot \tau = f \cdot Q \cdot \left(1.44 \cdot T_{1/2,e}\right) \qquad [2.5]$$

WoundDose employs the user-defined estimate of biological half-life from the user's selection of retention class. The "avid" retention class, for example, shows a biological half-life of 560 days. If the radionuclide contaminant in the wound has a radiological half-life of 2.5 years (912 days), the effective loss constant is shown by Eq. [2.6]:

$$\lambda_e = \frac{\ln(2)}{560\ [d]} + \frac{\ln(2)}{912\ [d]} = 0.0020\ [d^{-1}] \qquad [2.6]$$

with a wound residence time of 500 days. The residence time is used as the exposure time for calculating total dose at the shallow tissue depth and the local dose calculation. Additional information follows on the three dose calculations by type.

2.3. Shallow Dosimetry

To estimate total dose at the shallow depth (7 mg/cm^2) with an embedded wound source, the models of SkinDose (Hamby et al. 2024) are accessed and are identical but with modified backscatter correction. Air backscatter correction factors are enabled by the wound model when the injury depth is set exactly equal to zero. The user is cautioned that any depth greater than zero will disable full air backscatter correction. A future enhancement will include fractional backscatter correction for varying wound depths. Shallow dose calculations are allowed for a point source (hot particle at depth) or line source (uniform contamination with depth) geometries.

Point Source. In this case, the distance between source and skin averaging area is determined by the difference between source depth and the defined shallow depth (7 mg/cm^2). The user should still have the option to select the depth at which dose is calculated, but 7 mg/cm^2 would remain as the default.

Line Source. For a line source, it is assumed that a puncture has occurred (e.g., contaminated screwdriver) and any remnant of contamination is evenly distributed

as a line along the puncture route perpendicular to the skin surface. The shallow dose at 7 mg/cm^2 to a specified skin averaging area (10 cm^2) is calculated under the assumption that the line source begins at the surface, possibly penetrates the averaging area, and continues to the specified wound depth. Numerical integration of dose is performed over a series of point sources at depth, along the wound penetration line. The series of points are at fixed increments of 10 microns.

2.4. Local Dosimetry

Local dosimetry refers to estimating the dose equivalent to a tissue volume surrounding the contaminated wound. Contamination is modeled as a point source at the specified wound depth, or a line source uniformly distributed from the entry location along the entire length of the wound to the injury depth.

If a puncture wound results in a point source (hot particle) at some depth in tissue, local dose is calculated by assuming energy deposition occurs in a standardized 1 cm^3 sphere (radius of 0.62 cm) centered on the source. All electron and alpha (plus recoil) energy is assumed to be absorbed in that volume and a fraction of photon energy is calculated for absorption in the sphere. With the selection of line source, the volume in which energy is deposited is assumed to be a cylinder of radius 0.62 cm and a length equal to the wound depth, with hemispherical endcaps (NCRP 2007).

Electrons. For a point source beneath the skin surface, Eq. [2.7] is used to determine the local dose due to betas and electrons:

$$D_e = c\frac{Q\,\tau\,w_{r_e}}{\rho\,V_P}\left[\int Y_\beta E_\beta dE + \sum_i Y_i\,E_i\right] \qquad [2.7]$$

where c handles unit conversion, Q is the activity initially introduced into the wound, τ is residence time, w_{r_e} is unity for electrons, Y_β is the number of beta particles per decay per MeV, E_β represents the beta energy distribution, Y_i is the number of electrons emitted per decay, E_i is the kinetic energy per electron, ρ is tissue density (1.1 g/cm^3), and V_P is the absorption volume (e.g., 1 cm^3 for a point source). The first term in the brackets above accounts for beta emissions, and the second term accounts for conversion and Auger emissions.

Alphas. The local dose due to alpha emissions (including recoil energy) is calculated using Eq. [2.8]:

$$D_\alpha = c\frac{Q\ \tau\ w_{r_\alpha}}{\rho\ V_P}\sum_i Y_i\ E_i \qquad [2.8]$$

where w_{r_α} is 20 for alpha particles and E_i is the alpha and recoil energy of the ith alpha emission with yield Y_i.

Photons. The photon dose for an embedded point source shown in Eq. [2.9] is calculated for energy deposition in a surrounding 1 cm^3 sphere:

$$D_\gamma = c\frac{Q\ \tau\ w_{r_\gamma}}{\rho\ V_P}\sum_i Y_i\ E_i\ f_i \qquad [2.9]$$

where w_{r_γ} is unity for photons, and f_i shown in Eq. [2.10] is the fraction of ith photon energy deposited within a sphere of radius r (0.62 cm) surrounding the source (Piechowski and Chaptinel, 2004):

$$f_i = \frac{(\mu_{en})_i}{\mu_i}(1 - e^{-\mu_i r}) \qquad [2.10]$$

with μ_{en} and μ_i representing energy-specific linear absorption and attenuation coefficients in tissue, respectively.

A line source is handled in the same fashion with one exception. In this case, the volume of tissue in which energy is deposited is (Eq. [2.11]):

$$V_L = \pi r^2\ (L + 1.33r) \qquad [2.11]$$

where L is the length (i.e., depth of the wound) and r is the radius (0.62 cm) of the cylinder surrounding the line source, including two hemispherical end caps. Dose calculated for a point source can be converted to dose from a line source with a simple ratio of volumes. For example (Eq. [2.12]), with an injury depth of 5 mm (L = 0.5 cm and r = 0.62 cm) the dose ratio for line to point sources is:

$$\frac{D_L}{D_P} = \frac{V_P}{V_L} = \frac{1}{1.6} = 0.63 \qquad [2.12]$$

where subscripts P and L refer to the point source and line source, respectively.

2.5. Systemic Dosimetry

The biokinetic model for radiologically contaminated wounds considers four uptake categories: (1) radionuclides in soluble form; (2) particulates, aggregates, and bound states; (3) colloid and intermediate states; and (4) fragments. Movement of material from the wound and through the body to the bloodstream is characterized by the biokinetic model in Figure 2-1 (NCRP 2007).

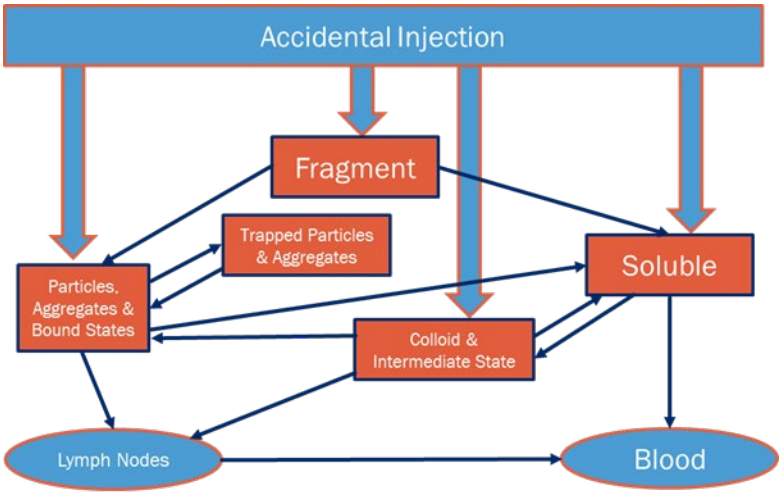

Figure 2-1. General Compartment Model of the Biokinetics of Radionuclides and/or Radioactive Materials Deposited in a Wound (taken from NCRP 156)

The Committed Effective Dose Equivalent (CEDE) and Committed Organ Dose Equivalent (CODE) are calculated. Organs include adrenals, bladder wall, bone surface, brain, breasts, esophagus, stomach wall, small intestine wall, upper large intestine wall, lower large intestine wall, colon, kidneys, liver, muscle, ovaries, pancreas, red marrow, extrathoracic airways, lungs, skin, spleen, testes, thymus, thyroid, and uterus (Toohey et al. 2014). Toohey et al. have tabulated internal dose coefficients for radionuclides reaching the bloodstream via penetrating wounds. WoundDose uses these dose coefficients to estimate internal dose equivalent via absorption following a skin wound. The coefficients vary based on nuclide and on the solubility of the molecular form in which the nuclide is incorporated. Dose coefficients account for a subcutaneous or intramuscular injection that may enter the bloodstream directly from the injection site. An examination of coefficients indicates that effective dose could vary by two orders of magnitude depending on the chemical/physical form of the compound containing the radioactivity. The user of WoundDose should refer to NCRP 156 (NCRP 2007) to determine the solubility characteristics of the chemical form in which the radionuclide is introduced. WoundDose estimates dose for all seven solubility characteristics provided by the NCRP 156 model. If the user selects the

“Custom” feature for biological half-life at the wound site, WoundDose chooses the retention class with the nearest biological half-life to that entered.

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