

THESIS

SAVE THE PANGOLINS! COBALT-60 AS A RADIOACTIVE DETERRENT FOR PANGOLIN
PRESERVATION

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2026

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ABSTRACT

SAVE THE PANGOLINS! COBALT-60 AS A RADIOACTIVE DETERRENT FOR PANGOLIN PRESERVATION

Pangolins are the most trafficked mammal in the world; nearly 2.7 million African pangolins are illegally poached each year. Placement of Cobalt-60 on pangolins as a radioactive deterrent is intended to alarm existing radiation portal monitor networks at border crossings and eventually protect pangolin populations from illegal poaching. Dimethyl sulfoxide was proposed as a carrier to embed the radioactive Cobalt-60 tracer into a pangolin's keratinous scales. The goal of the study was to estimate the radiation dose to the pangolin via first-principles calculations and computer modeling to ascertain the viability of the proposed deterrent. Calculation of dose to the pangolin's body and potentially radiosensitive organs was required to prevent any potential radiation injury to the pangolin. Monte Carlo N-Particle (MCNP) simulation and first-principles calculations demonstrated that pangolin scales are thick enough to absorb the maximum energy beta particles emitted as Cobalt-60 decays and the resultant bremsstrahlung is negligible. Placement of 0.01 MBq of Cobalt-60 over an area of 200 cm² produced an MCNP calculated whole-body photon dose of $11.6 \pm 0.1 \text{ mGy y}^{-1}$ ($1.33 \pm 0.01 \text{ } \mu\text{Gy h}^{-1}$) and a basal layer of the skin dose of $22.7 \pm 0.1 \text{ mGy y}^{-1}$ ($2.59 \pm 0.01 \text{ } \mu\text{Gy h}^{-1}$). Any agency intending to use the radioactive deterrent method for the pangolin must consider the radioactivity level that would optimize both detection and deterrence and meet the organization's established, acceptable risk to the pangolin, the public, and the environment.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to everyone who has supported me throughout this journey. Completing this Master's thesis would not have been possible without the guidance and encouragement of many incredible individuals and organizations. This research was made possible by funding from the United States Navy.

First, I want to thank Colorado State University for providing a stimulating academic environment and the resources necessary to pursue this research. To my advisor, Dr. Tom Johnson, and to my committee members, Dr. Alex Brandl and Dr. Vinnie Paglioni, thank you for your invaluable feedback, your high standards, and your commitment to my growth as a researcher. Your expertise was instrumental in shaping this work.

I am deeply grateful to Dr. James Larkin of the University of Witwatersrand and The Rhisotope Project. Your pioneering work in using nuclear science for conservation is an inspiration, and I am honored to have contributed to an initiative with such profound global impact. Thank you for your mentorship and for the opportunity to collaborate on this groundbreaking project.

To my peers and colleagues, thank you for the many hours of collaboration, the camaraderie, and the shared discussions that helped me through the most challenging parts of this program. Your friendship made this experience far more rewarding.

Finally, I want to thank my family, whose belief in me has never wavered. To my husband, Pablo, you have been my rock through every long night and every moment of doubt. Your unwavering support, patience, and love are the reasons I am standing here today. This achievement belongs to you as much as it does to me.

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INTRODUCTION

Pangolins, the only living organisms in the order Pholidota and family Manidae, are myrmecophagous mammals found throughout Asia and Africa which are easily recognized by their most note-worthy feature: a suit of “armor” made of individual, overlapping keratinous scales. Pangolins will roll into a ball when threatened, so only hard scales are exposed to protect their soft, non-scaled underbellies (Gaudin et al. 2020). The etymology of the word pangolin is derived from the Malay word “peng-goling”, meaning “one that rolls up” (Kingdon 2015). There are three genera of pangolin: *Maninae*, Asian pangolins; *Smutsiinae*, large and terrestrial African pangolins; and *Phatagininae*, small and arboreal African pangolins. There are eight total species of pangolin within the three genera. In Asia, there are *Manis crassicaudata*, the Indian pangolin; *Manis culionensis*, the Philippine pangolin; *Manis javanica*, the Sunda pangolin; and *Manis pentadactyla*, the Chinese pangolin. Among African large and ground-dwelling pangolins, there are *Smutsia gigantea*, the giant pangolin and *Smutsia temminckii*, ground pangolin. The African small and tree-dwelling species are the *Phataginus tricuspis*, the white-bellied pangolin and *Phataginus tetradactyla*, the long-tailed pangolin (Gaubert et al. 2020).

Illegal Pangolin Trade

Pangolins are the most trafficked mammal in the world with an estimated 0.4 – 2.7 million pangolins poached each year (Gaubert et al. 2020; Ingram et al. 2018). All eight species of pangolin were listed in Appendix I by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) as “Critically Endangered” in 2017 with some species being listed in other CITES appendices as “Vulnerable” or “Endangered” since 1975. In the modern era, each species is threatened with extinction and the effect is greatly exacerbated by

trade (“CITES Appendices I, II, and III” 2025). Trade in animals listed in CITES Appendix I is highly controlled and authorized only in rare circumstances. Pangolins are hunted and killed for bushmeat as subsistence and their body parts and scales are used for traditional medicine, ritual, art, and tribal magic (Baiyewu et al. 2018; Soewu et al. 2020; Xing et al. 2020). Pangolins do not breed well and have high mortality rates when kept and raised in captivity, leaving harvest from the wild as the only method for procuring pangolins (Korenblit et al. 2016).

Throughout South Asia, Southeast Asia, and East Asia, the meat and scales are believed to treat medical conditions such as reproductive health difficulties, gastrointestinal distress, skin rashes, blood disease, and mental health disorders. The pangolin trade was legal in China until 2020, with the Chinese government restricting the manufacture and sale of medicine containing pangolin scales to government certified stockpiles of scales in 2007. Between 2009 and 2015, an average of 26.6 metric tons of scales were released annually from the government stockpiles for use in traditional Chinese medicine (Xing et al. 2020). In 2020, the People’s Republic of China removed raw pangolin scales as a prescribable ingredient from the Chinese Pharmacopoeia’s volume dedicated to Traditional Chinese Medicine (The Chinese Pharmacopoeia Commission 2020). Even though raw pangolin scales were removed from official use, some formulations involving processed pangolin scales or other pangolin parts were still prescribable and in use. It was not until the 2025 update to the Chinese Pharmacopoeia that all remaining formulas with any pangolin byproducts were completely removed from use in traditional Chinese medicine (The Chinese Pharmacopoeia Commission 2025). Similarly, pangolin scales and other body parts are used throughout Africa and are regarded as a powerful medicine to treat body pain, gastrointestinal upset, blood disease, and reproductive health concerns. Rural Africans still rely heavily on traditional healers to meet their healthcare needs, further endangering pangolin

populations (Soewu et al. 2020). Research shows that traditional uses for pangolins in both Asia and Africa are rapidly being replaced with harvest and export of scales for their use in the traditional Eastern medicine trade. Export of pangolins to buyers in Asian markets can earn tribal hunters up to four months' salary from one animal, further incentivizing the illegal poaching and trading of sensitive pangolin populations (D'Cruze et al. 2018; Ingram et al. 2019; Trageser et al. 2017; Zanvo et al. 2021).

Current Preservation Efforts

Though pangolins are listed as critically endangered in CITES Appendix I, the United Nations Office on Drugs and Crime (UNODC) reports that protected species are still illegally traded in bulk. The UNODC also notes that some crime rings ship multiple species in the same shipments with pangolin byproducts being seized alongside rhino horns, lion teeth, and elephant ivory (Korenblit et al. 2016). There are 185 member nations in CITES, and it is the responsibility of individual nations to enforce and prosecute international trade bans and sanctions (Harrop 2020). The legislation exists to protect pangolins, and many CITES member nations have imposed legislative punishments for violating the trade agreements with heavy fines or imprisonment although it is unclear if enforcement is adequate. Pangolin populations of all species continue to decline; populations of the Chinese pangolin are down 94% in China and associated border regions (Challender and Waterman 2017). Traditional conservation methods are not adequate to protect pangolin populations.

Radioactive Material as a Tool for Conservation

Application of radioactive material to a pangolin's body was proposed to detect and deter the illegal smuggling of pangolins or their scales using existing radiation detector networks at border crossing stations, maritime shipping ports, rail freight transport stations, and air cargo

terminals. The use of radioactive material in conservation is not unprecedented with The Rhisotope Project established in 2021 to insert radioactive material into rhinoceros' horns. The radioactive material serves to deter illegal poaching, increase detection of smuggled horns, increase the successful prosecution of poachers, identify methods and routes for smuggling, and reduce end-user demand (Hillis et al. 2025).

Radioactive material emits radiation regardless of environmental conditions or animal behavior and seamlessly integrates with established radiation detection equipment to efficiently and discreetly find smuggled material. The physical characteristics of radioactive material are more attractive than using traditional tracking devices, which require installed transmitters, specialized receivers, and satellite devices which are sensitive to changes in weather and terrain. The tracking devices are obvious to poachers and can be non-lethally removed by poachers, predators, or even through the pangolin's natural burrowing actions (Carroll et al. 2024). The delivery method for radioactive material onto a pangolin must differ from the rhinoceros as the pangolin's anatomy differs. The pangolin's keratinous scales were investigated for the deposition of radioactive material.

Hypothesis

Radioactive material in a quantity high enough to alarm existing radiation detectors can be applied to a pangolin's scales without short- or long-term harm to pangolin populations.

BACKGROUND

This study focuses on the African ground pangolin species: Temminck's pangolin, *Smutsia temminckii*. Temminck's pangolin was named after the Dutch zoologist Professor C. J. Temminck but is also known as the ground pangolin or the cape pangolin (Richer et al. 1997). The Temminck's pangolin habitat includes the savannas and woodlands of southern and east Africa with the northern range limits in southern Sudan and southern Chad (Swart 2013). The adult Temminck's pangolin averages a body weight between 9-10 kg and a total body length of up to 140 cm with some variation in size across the occupation range with some samples as light as 2.5 kg and as heavy as 21 kg (Darren W. Pietersen et al. 2020). For the study, the lower average male adult weight of 6 kg was used to assess a more conservative radiation dose.

Temminck's pangolin longevity in the wild is unknown, but is estimated to be between 20-30 years. The Temminck's pangolin population density of reproductively active individuals is between 0.12 – 0.16 individuals km⁻¹ with the absolute density of all individuals estimated at 0.23 – 0.31 individuals km⁻¹ (Darren W. Pietersen et al. 2020). The area of occupancy for the Temminck's pangolin ranges from 58,354 km² to 200,846 km², but is decreasing with dwindling areas of natural vegetation. Thus, the mature pangolin population is estimated to be between 7,002 – 32,135 individuals.

The Temminck's pangolin is greatly impacted by the illegal pangolin trade, but also faces other anthropomorphic threats such as electrocution by electrified fence to which 377-1,028 animals y⁻¹ are lost, road collisions that kill on average 280 animals y⁻¹, and incidental losses in gin traps or jaw-traps set for other animals that can lead to severe pangolin injury and death (D. W. Pietersen et al. 2016).

Pangolin Scales

Pangolins are the only known mammal with overlapping, keratinous scales covering the dorsal part of the body, the entire tail, and the outside of the legs to protect the pangolin from predators (B. Wang, Yang, Sherman, et al. 2016). Temminck's pangolins are covered with roughly 380 of these scales (Darren W. Pietersen et al. 2020). While rhinoceros horns are made of only α -keratin like other mammalian wools, claws, and hooves, pangolin scales are made of both α - and β -keratin and are more homologous with primate nails (Gaudin et al. 2020; B. Wang, Yang, Sherman, et al. 2016; Zhang et al. 2018). Pangolin scales do not contain blood vessel infrastructure, but are grown from the epidermis (Liu et al. 2016). This study assumes the pangolin scale matrix originates in the basal layer of the skin, the deepest layer of the epidermis, which is analogous to primate nails that originate in the nail matrix from the basal layer of the epidermis. Pangolin scales themselves are not living tissue, and are thus an ideal candidate to embed radioactive material. Pangolin scales are continuously worn down through burrowing and abrasive action throughout the pangolin's lifetime (B. Wang, Yang, Sherman, et al. 2016). Pangolin scales do not molt if damaged but rather continuously grow from the scale matrix (Liu et al. 2016). The wear and growth rates of pangolin scales are unknown. Fig. 1 below is a diagram of pangolin scale histology.

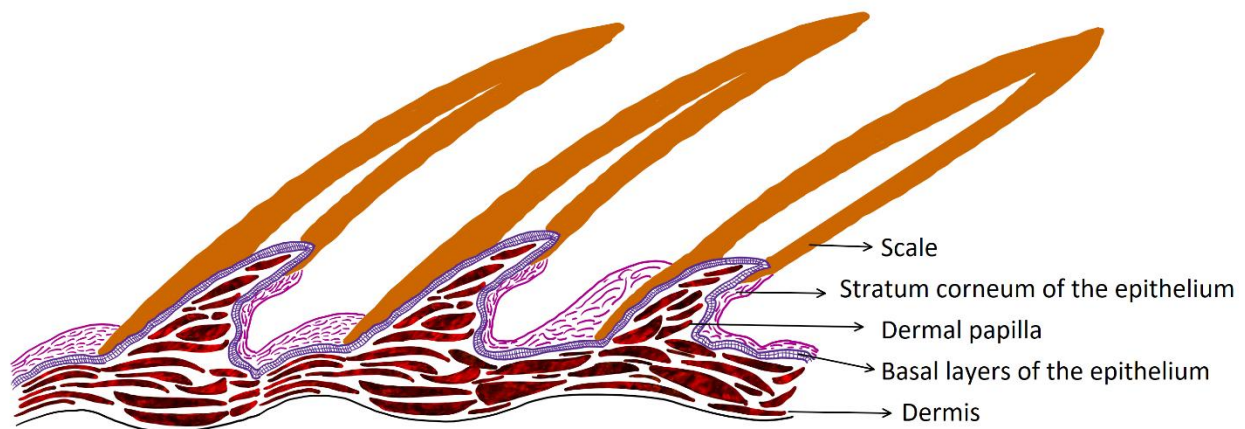
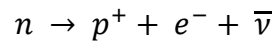


Fig. 1: Diagram of pangolin scale histology created by the author based on Gaudin et al. 2020

Types of ^{60}Co Radiation

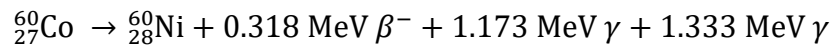
Cobalt-60 (^{60}Co) was proposed as a radionuclide for application onto a pangolin's scales. ^{60}Co undergoes beta-minus decay 100% of the time, which is an isobaric transition in atomic nuclei with a high neutron to proton ratio. In high neutron to proton ratio nuclei, a neutron will convert to a proton which will release an electron, called a beta particle, and the correlating electron antineutrino.



A neutron is slightly more massive than a proton, with the mass of a neutron at $1.674927357 \times 10^{-27}$ kg and the mass of a proton at $1.672621777 \times 10^{-27}$ kg. The mass of an electron is orders of magnitude less than either a neutron or proton at only $9.10938291 \times 10^{-31}$ kg with the antineutrino essentially massless. The remaining mass energy difference, or the transformation energy, is converted to kinetic energy. A very small amount is transferred to the recoil nucleus, but the vast majority is shared between the electron and the antineutrino. Hence, beta particles are emitted in a spectrum of energies with the average beta energy about one-third that of the maximum possible beta energy. Beta radiation can penetrate tissue to a depth dependent on the energy of the beta particle. Beta particles are charged particles and undergo charged particle interactions: direct ionization, excitation, and bremsstrahlung emission. Ionization breaks atomic bonds, which can cause chemical and biological changes to the organism and can potentially generate more charged particles that can go on to produce a cluster of their own charged particle interactions. Bremsstrahlung occurs when a beta particle interacts with the electronic field of an atom; any change in velocity will cause a release of electromagnetic photon energy in the form of x-rays. This is especially important when

considering shielding materials for beta-emitting radionuclides as the bremsstrahlung radiation can be highly penetrating depending on the initial energy of the beta particle (Johnson 2017).

Beta emission alone could possibly contribute to the pangolin's dose, but not to detection. However, if beta/gamma emitters are applied to the outside of the scales, the scales may block all the beta particles in the inert keratin and prevent chemical and biological damage to the living cells of the animal. Once ^{60}Co converts a neutron to a proton during beta decay, 99.88% of the time it emits a 0.318 MeV maximum energy beta particle and the atom is now $^{60}\text{Ni}^{4+}$. The resulting nucleus is in an exceptionally excited state, and $^{60}\text{Ni}^{4+}$ will emit a 1.1732 MeV gamma ray to become $^{60}\text{Ni}^{2+}$. To become stable, $^{60}\text{Ni}^{2+}$ emits a 1.3325 MeV gamma ray to become ^{60}Ni . An alternative decay path is where the initial beta maximum particle emission is 1.48 MeV for ^{60}Co and the atom decays directly to the $^{60}\text{Ni}^{2+}$ energy state, but this decay pathway only occurs 0.12% of the time. To become stable, $^{60}\text{Ni}^{2+}$ emits a 1.3325 MeV gamma ray to become ^{60}Ni . For first-principles calculations, only the most abundant beta particle maximum energy of 0.318 MeV and the subsequent 1.1732 MeV and 1.3325 MeV photons were considered for determining radiation dose to the pangolin (Browne and Tuli 2013). For the MCNP model, both potential beta particle energies of 0.318 MeV and 1.48 MeV with their corresponding probabilities were used to determine beta particle penetration depth into the pangolin's scales. The simplified decay formula for ^{60}Co to ^{60}Ni is:



It is the two highly energetic photons that make ^{60}Co both ideal and concerning for use on the pangolin scales. The desired type of radioactive material to detect pangolin scales will emit gamma radiation at a high enough energy to penetrate potential shielding materials and still be detected in existing portal monitors. Potential shielding material could include palletized crates,

55-gallon steel drums, steel shipping containers, or the exterior of a vehicle, train, or airplane.

Gamma radiation is an isomeric transition in the nucleus where both the atomic number and the atomic mass number of the daughter atom is the same as the parent atom. Particle emission or nuclear excitation leaves the nucleus of the atom unstable. Gamma emission in the form of a photon generally follows to release excess energy and promote nuclear stability. Gamma emissions are always predictably monoenergetic, which is ideal for maximizing detection efficiency.

Internal conversion is a competing process to gamma emission, in which case an inner shell electron absorbs the excitation energy from the nucleus and is ejected from the atom. The ejected conversion electrons are monoenergetic with the kinetic energy of the would-be gamma emission minus the binding energy of the electron. To fill the hole in the energetically favorable lower electron shell left by the conversion electron, either electrons in higher shells will move to the lower shell and emit a monoenergetic characteristic x-ray of the difference in energy between the two shells or the excess energy will be transferred to another electron in the same shell and that electron will eject, called Auger electrons. (Johnson 2017). Internal conversion is negligible in ^{60}Co decay, only occurring 0.03% of the time, and is not considered for this study (International Atomic Energy Agency 2026).

Gamma rays are indirectly ionizing radiation; they do not break chemical bonds themselves but interact with atomic nuclei to free electrons, which become secondary directly ionizing particles. Gamma rays interact with the environment by photoelectric absorption, Compton scattering, or pair production. In photoelectric absorption, the photon collides with an electron. The electron is ejected as a photoelectron, and the photon's full energy is transferred to the electron and the photon disappears. For more energetic photons, Compton scattering is the

more prevalent interaction mechanism. In Compton scattering, the photon collides with an electron, the electron is ejected, but the photon continues in a lower energy state to either continue further Compton scattering events or to undergo photoelectric absorption. If the gamma ray's kinetic energy exceeds 1.022 MeV, the rest-mass energy of an electron and a positron pair, pair production can occur. The photon interacts with the electrostatic Coulomb field surrounding an atomic nucleus, and 1.022 MeV of the photon's energy is converted to mass to produce a positron and an electron. The remaining energy is transferred as kinetic energy to the positron and the electron. The photoelectron, the Compton electrons, and the positron/electron pair are all directly ionizing particles that will go on to lose energy by ionization or excitation. Once the positron loses any excess kinetic energy, it will annihilate with an electron and produce two 0.511 MeV annihilation photons (ibid.).

There are many radionuclides that produce gamma radiation, but half-life is another important factor when choosing a radionuclide for deposition onto the pangolin's scales. The time required for any radionuclide to decrease to one-half of its original quantity is called its half-life and is a physical characteristic of that radionuclide. Half-life is a measure of a radionuclide's transformation or decay rate and no known physical or chemical interferences are known that can change a radionuclide's half-life (ibid.). ^{60}Co has a half-life of 5.27 years, which is relatively short compared to other gamma emitters, but is long enough to not require reapplication during the pangolin's life span and to not persist in the environment for greater than a generation. Wild Temminck's pangolin life spans are not well known, but some reports of pangolins in captivity suggest a 20 year life span (Panaino 2021; Swart 2013).

Additionally, ^{60}Co is not naturally occurring and must be produced either by particle accelerator or far more frequently by fission neutron bombardment in a nuclear reactor of ^{59}Co

targets (Artun 2017; Howard et al. 2021). Since it is not naturally occurring, there would be no natural interference if ^{60}Co is detected. ^{60}Co is produced at a commercial level for industrial, medical, and research applications; hence, ^{60}Co is relatively inexpensive to acquire (Howard et al. 2021).

Radiation Dose

The basis of dosimetric quantities for external radiation relies on the physical quantities of fluence (ϕ), KERMA (K), or absorbed dose (D). These quantities are directly measurable either by the physical properties of the radioactive material, as with fluence, or via instrument as with KERMA or absorbed dose. Photon fluence rate, also called photon flux density, is the number of photons incident on a cross-sectional area per unit time and is expressed in terms of photons $\text{cm}^{-2} \text{s}^{-1}$. The energy transported by these particles is known as the energy fluence rate. Fluence is a non-stochastic expectation value based on the radiation field's innate physical properties (Johnson 2017).

The Kinetic Energy Released per unit MAss is known as KERMA. As the name suggests, KERMA is a measure of the kinetic energy of secondary charged particles from an initial transfer of energy. The secondary charged particles are liberated by uncharged primary particles, such as photons or neutrons. Thus, KERMA is a non-stochastic quantity that measures the amount of energy transferred to secondary charged particles from a single incident particle and is expressed in terms of joules per kilogram (J kg^{-1}), which is also known as a Gray (Gy). The binding energy of the secondary charged particles are not transferred as kinetic energy and is not accounted for by KERMA. KERMA can approximate absorbed dose if charged particle equilibrium assumptions are met, if radiative losses are negligible, and the binding energies are small (ibid.).

Not all energy transferred to a material in a volume may be absorbed by that volume. Some of the energy transferred may leave that volume and be deposited elsewhere. The energy imparted (ϵ) in a target for any given interaction is the sum of the incident particle energy minus the sum of the particle energies leaving the interaction plus the change in rest mass energy and is expressed in units of joules. Energy deposition is a stochastic quantity for any given interaction and can vary in magnitude.

Absorbed dose is the basic physical dose quantity, is derived as the mean energy imparted in energy per unit mass, and is expressed in terms of J kg^{-1} or Gy. Absorbed dose relies not only on incident radiation, but is also impacted by charged particles created outside of the target volume that deposit energy into the target volume. Conversely, charged particles created in the target volume could travel and deposit energy outside of the target volume. Electronic equilibrium exists when the amount of energy that leaves target volume equals the amount of energy that deposits in the target volume. If electronic equilibrium is established, KERMA is a good approximation for absorbed dose as the amount of energy transferred is equal to the amount of energy deposited (ibid.). Absorbed dose is the internationally recognized dosimetric quantity for non-human biota as other forms of radiation dose, either protection quantities or operational quantities, are only defined for humans (ICRP 2017).

Radiation Portal Monitor Response

The International Atomic Energy Agency (IAEA) recommends that fixed, installed instruments at border stations be sensitive enough to detect a $0.1 \mu\text{Sv h}^{-1}$ dose rate increase within one second of exposure to the source at 1 meter with a 99.9% precision (IAEA 2002). Most of these requirements such as within one second of exposure, at 1 meter, and with a 99.9% precision are situation dependent. These parameters can change depending on the detector's size,

sensitivity, the portal width, and the vehicle speed. This study assumed the $0.1 \mu\text{Sv h}^{-1}$ dose rate increase as the detection goal for the pangolin to determine the needed ^{60}Co activity for application onto the pangolin. In practice, any agency that intends to use this technique to preserve pangolin populations must determine the appropriate ^{60}Co activity based on specific equipment limitations.

Another point to consider is that pangolins are rarely smuggled individually but rather in large shipments. The average, seized shipment of African pangolin scales is approximately 2200 kg (Nethavhani et al. 2025). The wet scale weight is estimated to be $\sim 35\%$ of the body weight of a Temminck's pangolin, which is about 2.1 kg (Darren W. Pietersen et al. 2020). Thus, an average shipment of pangolin scales would represent approximately 1047 individual Temminck's pangolins. Considering that the pangolin scales are shipped in such large numbers, the amount of radioactivity that is deposited onto an individual pangolin may be reduced by a factor of 10 or even 100 to reduce the radiation dose to an individual pangolin and still maintain relative confidence that illegal shipments of scales or individuals will be adequately identified at radiation portal monitoring stations. Since the illegal pangolin trade is exceptionally robust, shipments are successfully smuggled without being seized. However, no data exists to quantify the extent to which undetected smuggling occurs; thus, this study is limited by the available data to only quantify risk to the pangolin and potential detection methods from scale seizure data.

Dimethyl Sulfoxide (DMSO)

The proposed delivery method of radioactive material into the scales is via dimethyl sulfoxide (DMSO). DMSO is a colorless, liquid organosulfur produced as a byproduct of wood pulp from paper manufacturing. DMSO is unique in that it is a polar, aprotic solvent that can dissolve both polar and non-polar substances and can act as a carrying mechanism for smaller

molecules to penetrate different types of barriers (Capriotti and Capriotti 2012). DMSO is used as a penetration enhancer to deliver antifungal medications to the nailbed for the treatment of fungal infections under and around human fingernails and toenails (Angelo et al. 2017; Capriotti and Capriotti 2015). In human fingernails, DMSO penetrates into the nail about 50 μm after 24 hours (Chiu et al. 2015). It is unknown if the DMSO blend will continue to penetrate after 24 hours or if washing the pangolin after application will stop the DMSO penetrating action without removal of ^{60}Co . Pangolin scales are made up of both α - and β -keratin, similar to human fingernails (B. Wang, Yang, McKittrick, et al. 2016). DMSO has been shown to dissolve and complex with both the +2 and +3 oxidation states of cobalt (Cupertino et al. 2001; Duggan et al. 2013; Neuman et al. 2021). These traits make DMSO the most likely candidate to deliver radioactive ^{60}Co approximately 50 μm into the pangolin's scales.

Dose Rate Goal

The International Commission on Radiological Protection (ICRP) Publication 136, Dose Coefficients for Non-Human Biota Environmentally Exposed to Radiation, was published by the ICRP in September 2017 to address an increasing concern among radiation protection professionals: to recommend standards to protect the environment and non-human biota from harm from anthropogenic sources of radiation. ICRP 136 is an update to ICRP Publication 108, Environmental Protection: the Concept and Use of Reference Animals and Plants, that was published in October 2008. ICRP 136 provides updated dose coefficients for a Reference Animal or Plant (RAP) that related the absorbed dose rate to the organism to the radionuclide's activity concentration either internal to the organism or external in the environment to facilitate ecological assessment of radiation exposure. Derived Consideration Reference Levels (DCRLs) are defined in ICRP 136 as a range of dose rates in fractions of Gy d^{-1} or $\mu\text{Gy h}^{-1}$ for a particular

Reference Animal or Plant (RAP). Chronic exposure to a RAP above the DCRL increases probability of population-level deleterious effects on a species. These detrimental effects are defined at the population level, not at the individual level and include early mortality, forms of morbidity that decrease reproductive capability, impairment of reproductive capacity, and chromosomal damage.

Several RAPs are defined in ICRP 136 for many different radionuclides. The defined RAPs for ^{60}Co are the bee, wild grass (spike), earthworm, frog, rat, duck, deer, pine tree (trunk), brown seaweed, crab, trout, and flatfish. The most appropriate RAP analogue for the pangolin is the rat. The rat is a small, terrestrial mammal that lives close to the ground and burrows into the ground like the pangolin. Although the pangolin is generally much longer lived than the rat and can be much larger, the only other RAP mammal is a deer, which is far larger and stands much further from the ground than either the pangolin or the rat. Both the rat and the deer RAP use the same DCRL bands, so the difference is inconsequential.

Assuming that the pangolin is analogous to a rat for dosimetry size and shape purposes, the DCRL band recommended for exposure to the pangolin is $0.1\text{-}1\text{ mGy d}^{-1}$ ($4\text{-}40\text{ }\mu\text{Gy h}^{-1}$) to maintain a very low probability of population-level effects. Since the endpoint of concern is harmful tissue effects at the population-level, the ICRP does not specify a different DCRL for skin-dose to non-human biota. This study assumed that harmful tissue effects to the basal layer of the skin would negatively impact pangolin populations, and thus assumed the DCRL to also be $0.1\text{-}1\text{ mGy d}^{-1}$ ($4\text{-}40\text{ }\mu\text{Gy h}^{-1}$) for the pangolin's basal layer of the skin (ICRP 2017). An annual dose of 350 mGy y^{-1} ($40\text{ }\mu\text{Gy h}^{-1}$), roughly equivalent to 1 mGy d^{-1} for the whole body and the basal layer of the skin, were the radiation dose rate goals assumed to minimize potential detriment to pangolin populations.

Any organization that wishes to use the applied radioactivity technique to deter pangolin poaching and preserve pangolin populations may define different dose rate goals that are specific to the organization's needs, acceptable risks, and limitations. For example, an organization may want to maintain whole-body radiation dose to the pangolin below the recommended human effective dose limits. ICRP Publication 103, the 2007 Recommendations of the International Commission on Radiological Protection, recommends human effective dose limits of 20 mSv y⁻¹, averaged over 5 years, with no single year exceeding 50 mSv and an equivalent dose to the skin recommended limit of 500 mSv y⁻¹ (ICRP 2008b). In this scenario, the human whole-body radiation dose limit is based on stochastic outcomes such as cancer and heritable diseases using a total detriment approach that combines the probability of fatal cancer, non-fatal cancer, and hereditary effects and keeps risk to an acceptable level. Radiation-induced leukemia is likely to be noted in humans after a five to seven year latency period. Radiation-induced solid tumors have at least a ten year latency period in humans (Fraser 2011). The human stochastic outcomes that the ICRP 103 recommended dose limits were established to prevent may not be appropriate for a mammal with a lifespan of twenty to thirty years like the pangolin. Only one instance of cancer in a pangolin, an infantile hemangioma in the subcutaneous tissue of the right dorsum, was noted in the literature (X. Wang et al. 2024) although incidence may be more abundant but unknown based on the pangolin's reclusive nature. This study focused primarily on harmful tissue effects that could potentially impact pangolin populations and used the ICRP 136 DCRLs as a baseline.

Biological Effects of Radiation

The technical basis for the DCRL is found in ICRP Publication 108, Environmental Protection: the Concept and Use of Reference Animals and Plants. The rate of energy transferred

as a charged particle moves through a medium is known as the linear energy transfer (LET); this measurement is used to assume the rate of energy absorption in that medium and type of radiation exposure. For radiation biologists, the rate of energy absorption also correlates to the likelihood of damage to subcellular components. Radiation can produce damage to a cell either with direct action or indirect action. The mechanism for radiation damage by direct action is when inbound radiation transfers enough energy to a target to directly ionize and disassociate molecules. The direct action mechanism of damage is especially troublesome in the sensitive nucleus of the cell where genetic material is maintained. Indirect action occurs when inbound radiation interacts with the water in the cell and produces highly oxidizing free radicals that then produce secondary damage. Since water is much more abundant in living tissue than any other target material, the mechanism of damage by indirect action is especially likely. As with direct action, the free radicals produced by indirect action are most negatively impactful when occurring near the DNA in the nucleus of the cell (Johnson 2017).

Radiation induced DNA damage presents differently than naturally occurring oxidative injuries, which are randomly distributed and chemically simple in the damage mechanism. DNA lesions from radiation are found in complex clusters and account for 60% of total DNA damage after exposure to low-LET radiation and up to 90% of total DNA damage following exposure to high-LET radiation. These complex clusters of DNA lesions are more difficult for a cell's DNA repair mechanisms, and can lead to the induction of chromosomal aberrations, gene mutations, and cell death (ICRP 2008a).

Observed biological effects of radiation can be classified as either stochastic or deterministic effects. Stochastic effects, also called delayed effects, occur randomly with the probability of occurrence increasing in relation to the amount of radiation dose received. The

most common stochastic effect in humans is the development of cancer. Cancer has a natural background rate in the population, but the probability of occurrence increases with additional radiation exposure. Deterministic effects, also called non-stochastic, threshold, or harmful tissue effects, are effects that will appear if an individual is exposed to or above a certain threshold of radiation dose with the severity of the effect increasing in relation to radiation dose received. Different deterministic effects of radiation can be observed in humans from minor changes in whole blood counts, escalating to erythema and depilation, and further eventually to increased vascular porosity and death (Johnson 2017).

The difference in damage potential by whether inbound radiation is high- or low-LET leads to the concept of relative biological effectiveness (RBE), which is the ratio of low-LET reference radiation to any other type of radiation that produces the same biological endpoint. The RBE depends on the biological endpoint of interest, the tissue or cell type being irradiated, the radiation dose and radiation dose rate, and the dose fractionation. For human dosimetry, this difference in RBE is the basis for assigning radiation weighting factors (w_r). Unfortunately, there is no such equivalent in non-human biota. Additionally, the goal for protection of human beings from exposure to ionizing radiation is controlled individually so that the risks of stochastic and deterministic effects to the individual are minimized to as low as reasonably achievable (ALARA). For non-human biota, this individual-level concern with biological endpoints is neither useful nor practical. Rather, it is the deterministic effect to populations that is the primary indicator of concern for exposure to ionizing radiation. The population-level concerns include increased death rate, decreased population density, and early mortality. Some forms of morbidity or “fitness” to survive and reproduce in the wild are also of concern such as impairment of reproductive capacity, which would lead to decreased birth rate, changes in population age

distribution, decreased population number, decreased population density, and chromosomal damage (ICRP 2008a).

MATERIALS AND METHODS

Cobalt-60

Cobalt-60 (^{60}Co) was investigated for application onto pangolin scales. The specific gamma-ray dose constant for ^{60}Co is given as $0.3062 \mu\text{Sv h}^{-1} \text{MBq}^{-1}$ at 1 meter (Peplow 2020). The activity of ^{60}Co required to trigger the alarm set at the IAEA's recommended goal dose-rate detection capability of $0.1 \mu\text{Sv h}^{-1}$ is found by dividing the goal dose-rate detection by the gamma-ray dose constant.

$$\frac{0.1 \frac{\mu\text{Sv}}{\text{h}}}{0.3062 \frac{\mu\text{Sv}}{\text{h} \cdot \text{MBq}}} = 0.3266 \text{ MBq or } 8.83 \mu\text{Ci}.$$

The activity of ^{60}Co required to alarm a portal monitor based on the IAEA dose rate goal is 0.3266 MBq or $8.83 \mu\text{Ci}$. This study utilized 0.37 MBq or $10 \mu\text{Ci}$ as the baseline for dose calculations as this quantity of ^{60}Co is more commercially convenient for acquisition.

Organs of Concern

It is assumed that keeping the radiation dose to the pangolin below the ICRP 136 recommended DCRL will prevent detriment to pangolin populations. However, specific radiosensitive organs must be identified to understand the potential effects of the dose on the organ of concern to prevent damage to an individual pangolin that would negatively impact the population. The Law of Bergonié and Tribondeau states that cells are more sensitive to cell death as a result of radiation exposure if the cell is undifferentiated and rapidly dividing (Vogin and Foray 2013). The undifferentiated cells in the basal layer of the skin are among the most radiosensitive cells in human skin (Johnson 2017), and thus the basal layer of the epidermis was assumed as among the most radiosensitive cells of the pangolin. The basal layer of the

pangolin's skin is the deepest layer of the epidermis where the pangolin scales originate and will be closest in proximity to the proposed ^{60}Co application site.

The impact of reproductive capability by radiation exposure must also be considered in addition to mortality and morbidity. Pangolins are placental mammals with internal ovaries. Some research shows that the left ovary is often more developed than the right ovary and may be the primary female sex organ (Ofusori 2007). Male Temminck's pangolins are ascrotal mammals with internal testes located in the inguinal region (Tink et al. 2024). Radiation dose to both the female ovaries and the male testes are of concern to maintain breeding effectiveness. It is assumed that maintaining the radiation dose to the pangolin below the ICRP 136 recommended DCRL for the whole body will prevent damage at the population level as the pangolin's reproductive organs are internal organs. First-principles calculations were performed for potential radiation dose to the pangolin's reproductive organs to demonstrate if this assumption holds true.

A close biological analogue to the composition of pangolin scales is primate nails (Spearman 1967). Human fingernails express several types of keratins with differing molecular weights (Bragulla and Homberger 2009). The average molecular weight of the most common keratins found in human fingernails is 54,000 g/mol. The average density of healthy human fingernails is 1.34 g/cm³ (Baraldi et al. 2015). Pangolin scales are highly export-controlled materials; no actual pangolin scales could be obtained to ascertain the elemental composition of the scales. No studies have detailed the exact nature of Temminck's pangolin scales, so human fingernail composition was utilized as a substitute. Table 1 below calculates the average molecular weight of the most common keratin types found in human fingernails.

Table 1, Calculated average molecular weights of keratins in human fingernails

Keratin Type	Molecular Weight (g/mol)
K5	56,000
K6	56,000
K14	50,000
K16	46,000
K31	47,200
K32	50,300
K33	46,000
K34	49,400
K81	54,800
Average	54,000

Temminck's pangolins give birth to pups every year or every other year with an aseasonal breeding cycle. Pups are born in burrows and one-week old juvenile pangolins are moved from the birthing burrow to another burrow by clinging to the mother's tail scales. Juvenile pangolins will ride on the mother's tail while learning to feed until reaching independence around 3-6 months old, although some reports have noted juveniles up to one-year old riding on their mothers' tails (Darren W. Pietersen et al. 2020). Because of this, radiation dose to the pangolin pups must also be considered in future studies.

Pangolin Measurements

A computed tomography (CT) scan digital imaging and communications in medicine (DICOM) file of an adult male Temminck's pangolin was used to obtain pangolin measurements for radiation dose calculations. CT file analysis was accomplished using 3D Slicer computer software. 3D Slicer is free, open-source software to visualize and analyze DICOM files (Pieper et al. 2004). 3D Slicer was used to measure the thickness of the pangolin scale, obtain dimensions for radiation transport modeling, and calculate volume of the pangolin. Figs. 2 and 3 below are examples of images created using 3D Slicer. Full images and measurements are in Appendix A.

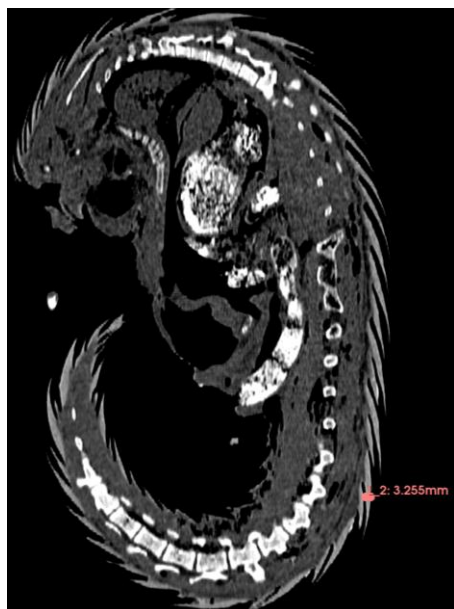


Fig. 2, Measurement of pangolin tail scale thickness in 3D Slicer

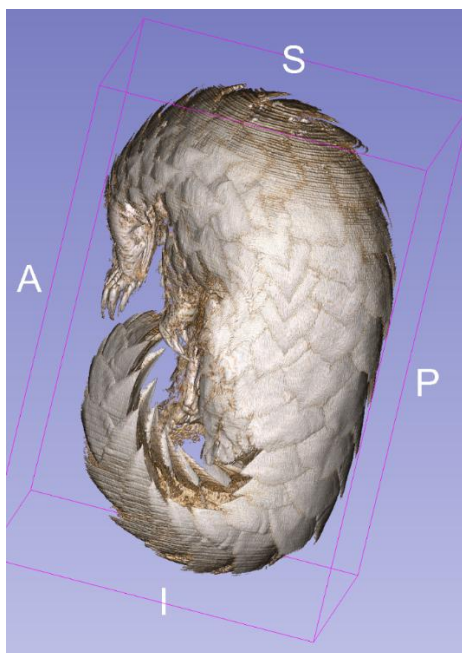


Fig. 3, 3D rendering of pangolin sample from 3D Slicer

The pangolin tail scale thickness was measured to be approximately 3 mm thick, which closely matched literature values on the Chinese ground pangolin (B. Wang, Yang, Sherman, et al. 2016).

The width of the pangolin was measured at 21.22 cm using an anterior view and measuring the widest distance of the pangolin from side-to-side. The thickness of the pangolin was measured at 23.97 cm using a lateral view and measuring the widest distance from the pangolin anterior to posterior. The height of the pangolin was measured at 39.04 cm using an anterior view and measuring the largest distance vertical axis. The pangolin was imaged in a relaxed posture, but the posture with the most risk of radiation exposure to the pangolin is in the fully rolled defensive position since this would bring the radioactive tail sections closer to the main body of the pangolin. To mimic the distance of the tail to a pangolin fully rolled into the defensive position, the empty space in the image was measured using a lateral view and removed from the total height. The empty space was initially measured at 5 cm, which led to a corrected pangolin full height of 34.04 cm. The initial pangolin model approximation resembled a prolate spheroid like a rugby ball. After comparing model volume to the CT volume of the pangolin from the 3D slicer software, the prolate spheroid approximation was nearly twice the volume of the pangolin. The empty space was remeasured and approximated at 15 cm after closer inspection of how the pangolin rolls up and where the snout touches the inside of the tail. The corrected pangolin full height of 24.04 cm was found to be a more conservative estimate for radiation exposure. The 3D Slicer software calculated the volume of the pangolin sample at 6362.86 cm³.

To simplify modeling, the width, height, and thickness of the pangolin was averaged to 23.08 cm to build a reference pangolin as a sphere to model radiation dose. The dimensions of the pangolin were established as 23.08 cm wide, 23.08 cm high, and 23.08 cm thick for modeling purposes. The thickness of the average Temminck's pangolin scale was measured at 0.3 cm or 3 mm. Therefore, the dimensions of the inner soft tissue of the pangolin without the scales is 22.48

cm wide, 22.48 cm high, and 22.48 cm thick. The formula for the volume of a sphere is $V = \frac{4}{3}\pi r^3$, where r is the radius for the sphere. For the simplified pangolin model, $r = 11.54$ cm for the scale sphere and $r = 11.24$ for the inner, soft tissue sphere. The volume for the pangolin model including the scale layer was found as $V = \frac{4}{3}\pi(11.54^3) = 6437.33 \text{ cm}^3$ and the volume for the inner, soft tissue sphere for the pangolin model is $V = \frac{4}{3}\pi(11.24^3) = 5948.23 \text{ cm}^3$. The percentage difference between the model volume and expected volume for the pangolin was calculated by:

$$\left| \frac{(\text{Expected Volume} - \text{Model Volume})}{\left(\frac{\text{Expected Volume} + \text{Model Volume}}{2}\right)} \right| * 100 = \text{Percentage Difference}$$

$$\left| \frac{(6362.86 \text{ cm}^3 - 6437.33 \text{ cm}^3)}{\left(\frac{6362.86 \text{ cm}^3 + 6437.33 \text{ cm}^3}{2}\right)} \right| * 100 = 1.16 \% \text{ Difference}$$

The very low percentage difference of 1.16% between the software calculated volume based on the CT scan of the pangolin and the simplified model volume indicates that the model is an appropriate substitute for the anatomical values.

Figs. 4 and 5 below images show the difference between the anatomical pangolin measurements and the simplified pangolin measurements for modeling.

Assuming the pangolin's reproductive organs are in the lower abdomen, the closest point of approach from a tail scale to where the assumed reproductive organs would be is approximately 5.91 cm. The closest point of approach from the proposed ^{60}Co application area and the assumed reproductive organs, after subtracting the empty space to mimic the rolled posture, is 8.82 cm. The 5.91 cm distance will be used as the most conservative value until the

pangolin's reproductive organs are positively identified. Reference Appendix A for full pangolin images and measurements.

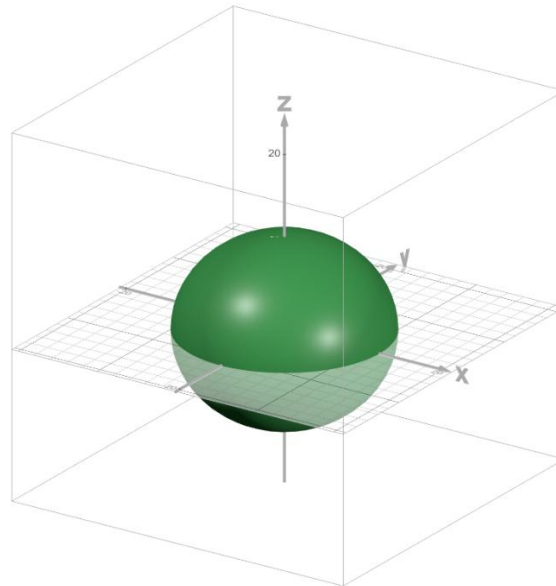


Fig. 4, Exact pangolin measurements for modeling

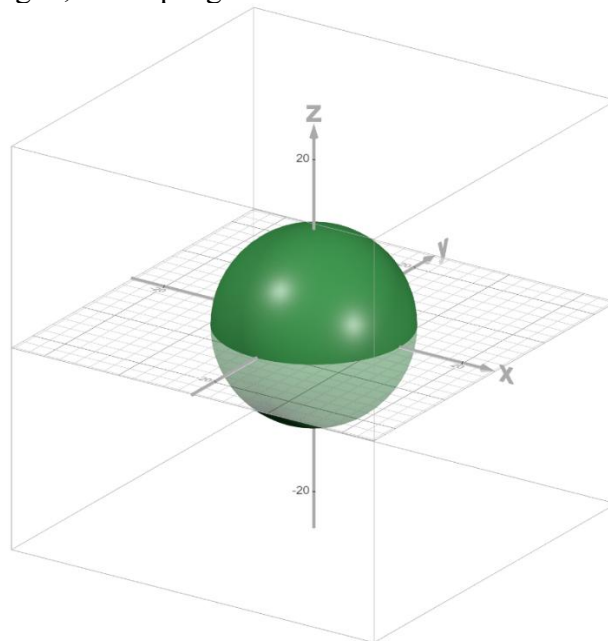


Fig. 5, Simplified pangolin measurements for modeling

First-Principles Calculations

Calculations for the radiation dose to the pangolin from ^{60}Co application to the scales must consider both the radiation dose from the beta particles and the gamma rays. Two different

methods were investigated for the radiation dose from the beta particles: using the Bethe-Bloch equation and the empirical range formula. Additionally, the anticipated dose from bremsstrahlung production was calculated. Two methods were also used to investigate the radiation dose from the gamma rays: using a point source geometry and using a planar source geometry.

All calculations assume 0.37 MBq as the deposited activity of ^{60}Co . For planar sources, the activity concentration is assumed to be homogeneously distributed. The effective thickness of the pangolin scale is 2.95 mm or 0.295 cm, which is the difference between the measured 3 mm thickness of the scale and the 0.050 mm assumed penetration depth of DMSO.

Calculating dose to the pangolin's whole body and the basal layer of the skin must consider the different density of the scales compared to human dosimetry. ICRP Publication 116, Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures, recommends a depth for equivalent dose to human skin at 0.007 g cm^{-2} and recommends a depth of 1 g cm^{-2} for assessing human effective dose to the whole body. The density thickness of the pangolin scale and the soft tissue were added to find the appropriate depth to calculate dose to the basal layer of the skin and the whole body of the pangolin.

The density of the pangolin scale is assumed to be the density of human fingernails at 1.34 g cm^{-3} (Baraldi et al. 2015). The density thickness for the pangolin scale is thus $0.295 \text{ cm} \times \frac{1.34 \text{ g}}{\text{cm}^3} = 0.395 \text{ g cm}^{-2}$. The calculated dosimetric depth for the basal layer of the skin adds both the density thickness of skin used in human dosimetry, 0.007 g cm^{-2} , and the density thickness of the pangolin scale, 0.395 g cm^{-2} , which gives 0.402 g cm^{-2} . Assuming that tissue density is 1 g cm^{-3} , the calculation depth for radiation dose to the basal layer of the skin is 0.402 cm. The calculated dosimetric depth for dose to the whole body adds both the density thickness

for effective dose to the whole body used in human dosimetry, 1 g cm^{-2} , to the density thickness of the pangolin scale, 0.395 g cm^{-2} , which gives 1.395 g cm^{-2} . Assuming that tissue density is 1 g cm^{-3} , the calculation depth for radiation dose to the whole body is 1.395 cm .

All calculations assume no radiological decay, which is not realistic and will overestimate the radiation dose to the pangolin. Since the radiological half-life is a constant, physical property of the radionuclide, the number of atoms at any point in time, t , can be found by multiplying the initial number of atoms by the number of half-lives that have elapsed. The number of half-lives is represented in the equation below by raising one-half to the quotient of the amount of time that has passed, t , relative to the radiological half-life, $t_{1/2}$.

$$N(t) = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

To find the ratio of the original activity remaining after one year, the values of one year for time elapsed and 5.27 years for the radiological half-life of ^{60}Co are substituted into the formula and results in 0.877.

$$\frac{N(1)}{N_0} = \left(\frac{1}{2}\right)^{\frac{1 \text{ y}}{5.27 \text{ y}}} = 0.877$$

After one year, the remaining radioactivity on the pangolin will be 87.7% of the original activity and the radiation dose to the pangolin will subsequently decrease by 12.3%. However, this trade-off in radiological consequence to the pangolin also means that the pangolins may be harder to detect as the ^{60}Co decays. The dose overestimation made by disregarding radiological decay is considered conservative and maintained for simplicity in this study.

Dose from Beta Particles

Bethe-Bloch Equation

The Bethe-Bloch equation provides the linear rate of energy loss $\left(\frac{dE}{dx}\right)$ due to both excitation and ionization of beta particles in media. The use of this equation is most appropriate for beta particle energies greater than 0.5 MeV, but is used to approximate the 0.31 MeV beta particles from ^{60}Co . Calculations for the linear rate of energy loss are compared both in soft tissue and in keratin using the composition of human fingernails as an analogue for the composition of pangolin scales. Full calculations using the Bethe-Bloch equation are provided in Appendix B.

$$\frac{dE}{dx} = \frac{2\pi q^4 N Z \cdot (3 \times 10^9)^4}{E_m \beta^2 (1 \times 10^{-6})^2} \left(\ln \left(\frac{E_m E_k \beta^2}{I^2 (1 - \beta^2)} \right) - \beta^2 \right) \text{MeV cm}^{-1}$$

Where:

q = charge of the electron

N = number of absorber atoms cm^{-3}

Z = atomic number of the absorber

E_m = electron mass energy

E_k = kinetic energy of β particles

$\beta = v/c$ = ratio of particle's velocity to the speed of light

I = mean ionization and excitation potential

Empirical Range Formula

The experimentally derived formula for beta-particle range (R) for particles with a maximum energy less than 0.8 MeV is calculated using human fingernails as the density analogue for pangolin scales. This empirical range formula also estimates beta-particle range in

air at standard temperature and pressure to estimate potential beta-particle range to pangolin pups. Full calculations using the empirical range formula are provided in Appendix B.

$$R = \frac{0.407E^{1.38}}{\rho}$$

Where:

E = energy of the beta particle

ρ = material density

Bremsstrahlung Dose

The maximum beta particle energy of 0.318 MeV was used to calculate bremsstrahlung production to overestimate the dose since the mean beta particle energy for ^{60}Co is 0.09577 MeV (Eckert & Ziegler 2010). For ^{60}Co exposure, the vast majority of photon dose comes from the two, high-energy photons produced per decay rather than from bremsstrahlung produced from beta particle interactions. However potentially minimal, the bremsstrahlung dose is a non-zero quantity and was investigated. The radiation dose to dosimetric depth in the pangolin for both the whole body and the basal layer of the skin were calculated using the following equation (Johnson 2017). Full bremsstrahlung dose rate ($\dot{D}$) calculations are provided in Appendix B.

$$\dot{D} = \frac{f_{\beta} \cdot A \cdot E_m \cdot \mu_l}{\rho \cdot 4\pi d^2}$$

Where:

f_{β} = fraction of beta particle energy converted to bremsstrahlung

A = source activity

E_m = maximum beta energy of the beta particle

μ_l = linear energy absorption coefficient

ρ = material density

d = dosimetric depth

Dose from Gamma Rays

Point Source

The point source equation will result in the highest dose estimate to the pangolin. The point source model assumes 0.37 MBq is deposited in an infinitesimally small area and calculated via distance correction to the dosimetric depth of 1.395 cm for the whole body. The mass absorption coefficient is the amount of energy that is absorbed in a material at a given photon energy. The 1.25 MeV average energy of the ^{60}Co gamma emissions in soft tissue was used for this equation (Johnson 2017). The use of soft tissue rather than keratin in these calculations results in the most conservative dose to the pangolin as some gammas will interact and deposit energy in the scaly keratin layer. Reference Appendix B for full point source dose rate ($\dot{D}$) calculations.

$$\dot{D} = \phi E \frac{\mu_{en}}{\rho}$$

Where:

ϕ = particle fluence rate in particles $\text{s}^{-1} \text{cm}^{-1}$

E = energy photon $^{-1}$ in MeV photon $^{-1}$

$\frac{\mu_{en}}{\rho}$ = the mass attenuation coefficient

This equation is truly an energy transfer or collision KERMA equation rather than an energy absorbed or dose equation as it assumes charged particle equilibrium. In charged particle equilibrium, the charged particle energy escaping a volume equals the charged particle energy entering that same volume. The maximum dose depth (d_{max}) for ^{60}Co photons is 0.5 cm (Leung et al. 1976). For whole body dose calculated at 1.395 cm, charged particle equilibrium is assumed, and it is appropriate to use energy transferred as an approximation for energy absorbed. Any depth less than 0.5 cm into the soft tissue is known as the electronic build-up region where

secondary electrons created by the photon interactions leave the interaction area and deposit the energy deeper into the tissue. In this region, the energy transferred can be much higher than the energy absorbed and the resulting collision KERMA calculations are much larger than actual energy absorbed calculations. The point source equation for the shallow dose was calculated via distance correction to the dosimetric depth for the basal layer of the skin of 0.402 cm, which is still within the electronic buildup region. Additionally, shallow dose calculations are recommended to be averaged over a 1 cm² area (ICRP 2008b). The calculated particle fluence rate in this equation is defined as the number of particles cm⁻² s⁻¹, so further correction is not needed to meet the averaging area. The calculated collision KERMA from the point source formula must be corrected for electronic disequilibrium at depths less than the d_{max} using the below fraction of charged particle equilibrium equation as a function of secondary particle energy and depth (f_{cpe}).

$$f_{\text{cpe}}(E, d) = \frac{D}{K}$$

Where:

D = absorbed dose

K = collision KERMA

For the dose to the basal layer of the skin from a point source, the calculated, fluence-based collision KERMA dose was also corrected for the fraction of charged particle equilibrium attained.

The potential radiation dose to the reproductive organs from a point source was also calculated using the first-principles approach using a 5.91 cm distance correction. Reference Appendix B for full calculations.

Planar Source

Calculations were performed for an assumed 0.37 MBq deposited uniformly over a circular 200 cm² area. The dosimetric depths of 1.395 cm for the whole body and 0.402 cm for the basal layer of the skin were used for distance values. Planar source calculations are less sensitive to charged particle equilibrium concerns, which had a greater effect on the basal layer of the skin calculations for the point source. A planar source can be visualized as an array of point sources so that secondary electrons may be lost from one volume but are simultaneously replaced in that volume by secondary electrons originating from an adjacent point source in the planar array. This lateral electron overlap even in a state of charged particle disequilibrium creates a more uniform radiation field. The potential radiation dose to the reproductive organs from a planar source was also calculated using the first-principles approach using a 5.91 cm distance correction. Reference Appendix B for full planar source dose rate ($\dot{D}$) calculations.

$$\dot{D} = \pi \Gamma_{Co-60} C_a \ln \left(\frac{R^2 + h^2}{h^2} \right)$$

Where:

R = radius

h = dosimetry depth

Γ_{Co-60} = gamma constant for ⁶⁰Co

C_a = concentration area

Modeling Calculations

NRC V+

NRC V+, formerly VARSKIN+, is a free software tool developed, maintained, and distributed by the United States Nuclear Regulatory Commission widely accepted by radiation safety professionals to calculate radiation dose for skin, wound, and eye contamination. The

module of NRC V+ used in the study is SkinDose. SkinDose is a comprehensive suite that calculates doses to the skin and to the whole body from skin contamination either as a point source or planar source and either with or without a cover. For planar sources, the source concentration and area can be defined by the user. Cover densities and thicknesses can also be specified by the user to model any potential inference materials.

To model the pangolin, a 0.37 MBq source of ^{60}Co and a 2.95 mm cover with 1.34 g cm^{-3} density and 0.395 g cm^{-2} density thickness were used to represent the source activity, the human fingernail density analogue, and the effective thickness of the pangolin scale at 3 mm minus the 0.050 mm penetration depth of DMSO, respectively. First, a point source was modeled with a one-year exposure time at a depth of both 7 mg cm^{-2} and 1000 mg cm^{-2} to represent the skin dose and the whole-body dose to the pangolin, respectively. The skin dose depth of 7 mg cm^{-2} was averaged over 1 cm^2 , as recommended by ICRP 103 (ICRP 2008b). The whole-body dose at a depth of 1000 mg cm^{-2} is not recommended to be averaged over an area, but rather is calculated at a point in space; however, constraints of the SkinDose software required an averaging area be specified. The whole body dose was averaged over 1 mm^2 to mimic a point detector and meet the software requirements.

A circular disc source was used to model the planar source. Different disc source radii were input into SkinDose to better understand what area of ^{60}Co is both practical for use on a pangolin's tail scales and could potentially produce a dose below the radiation dose goals for the study. The disc areas used were: 50 cm^2 , 100 cm^2 , 150 cm^2 , 200 cm^2 , and 250 cm^2 and their respective radii were: 7.98 cm, 11.28 cm, 13.82 cm, 15.96 cm, and 17.84 cm. The one-year exposures to the 0.37 MBq ^{60}Co disc source were calculated at a depth of both 7 mg cm^{-2} and 1000 mg cm^{-2} to represent the skin dose and the whole-body dose to the pangolin, respectively.

The output of NRC V+ is in the unit of Sievert (Sv), which is only defined for humans and inappropriate for use in nonhuman biota. Thus, the NRC V+ data cannot be used directly to estimate radiation dose to the pangolin. This study used the SkinDose software as a starting point to determine a desirable concentration area for application with the assumption that 1 Sievert is equivalent to 1 Gray for photons and beta particles as recommended by ICRP 103 (ibid.). From the V+ output, an application area of 200 cm² produced results that were close to the dose rate goal of 350 mGy y⁻¹ (40 µGy h⁻¹) for the whole body and for the skin and is convenient for practical application purposes. The 200 cm² area is used throughout this study for baseline calculations. Reference Appendix C for full model inputs and outputs.

ICRP 136

The pangolin is assumed to be analogous to the rat for RAP dosimetric purposes using methods defined in ICRP 136. The applicable dose coefficients given for the rat are either in soil or on ground external contamination conditions. ICRP 136 defines “in soil” as the organism being exposed in the middle of a 50-cm-thick uniform volume source in the soil. The “in soil” dose coefficient is most appropriate for burrowing organisms that could live surrounded by contaminated soil. The “in soil” dose coefficient assumes the organism is essentially immersed in the contamination source and receives radiation dose from all directions, which produces a higher, more conservative dose coefficient. ICRP 136 defines “on ground” as the organism being exposed on or above a 10-cm-thick uniform volume source in soil. The organism is exposed only from its lower half and both the air and soil provide some attenuation.

The “in soil” depth allows for better representation for burrowing animals that may live in the soil, which the pangolin does part of the time and may be the most representative of the radiation dose to the pangolin from a surface contamination source on the scale. The dose

coefficient for a rat RAP externally exposed in soil to a ^{60}Co source is $1.2 \times 10^{-3} \mu\text{Gy kg h}^{-1} \text{Bq}^{-1}$. Reference Appendix C for full calculations.

BiotaDC

BiotaDC is an open-access web-based annex to ICRP 136 to generate dose coefficients for both terrestrial and aquatic animals and plants to many different radionuclides in different internal and external contamination conditions. BiotaDC's contamination conditions for external pathways include: an above soil planar source, an above soil 10-cm-thick source, an above soil infinitely deep source, an above soil submersion in contaminated air, and in-soil. Like using ICRP 136 directly, the most appropriate dose coefficient for the pangolin would be in-soil. From the user-defined inputs, the produced dose coefficient is $9.63 \times 10^{-4} \mu\text{Gy kg h}^{-1} \text{Bq}^{-1}$. Reference Appendix C for full model inputs and outputs.

MIRD

Radiation absorbed dose is defined as the energy deposited per unit mass in units of J kg^{-1} or Gy. For the scenario of surface contamination on the pangolin's scales, it is incorrect to assume that the highest energy absorbed can be averaged throughout the entire mass of the animal. The radiation source being placed directly on the surface of the pangolin creates a gradient that is higher closer to the source and lower further away from the source based on how likely the photons are to interact with the soft tissue. Volume-averaging over the entire mass of the pangolin will cause the radiation absorbed dose to be drastically underestimated and potentially lead to not identifying deleterious effects. The Medical Internal Radiation Dose Committee (MIRD) method and a point source will illustrate this dosimetry difference.

MIRD is part of the Society of Nuclear Medicine and Molecular Imaging (SNMMI) and publishes standard terminology, formulas, and reference data for calculating absorbed radiation

doses to organs, tissues, and cells from radiopharmaceutical administration in nuclear medicine applications and is widely considered the standard in medical physics applications (Zanzonico 2024). One of the foundational documents in the MIRD Method is Pamphlet 3: Absorbed Fractions for Photon Dosimetry (Brownell et al. 1968). This provides the absorbed fractions for photons of differing energies in tissues of differing masses. The radiation absorbed dose using the MIRD method is found by using the gamma emission rate, the average photon energy for ^{60}Co emissions, the absorbed fraction, and the total mass of the animal. Reference Appendix C for full calculations.

$$\dot{D} = \frac{\dot{\gamma} \cdot E \cdot \phi}{m}$$

Where:

$\dot{\gamma}$ = photon emission rate

E = average photon energy

ϕ = photon absorbed fraction

m = mass of the organism

MCNP

Monte Carlo N-Particle (MCNP) code was developed by Los Alamos National Laboratory and uses stochastic Monte Carlo methods to simulate particle interactions with matter. By using random numbers to model the probabilities of particles' trajectories, it can calculate numeric values for dose, fluence, and detector responses in three-dimensional environments. MCNP is widely used for health physics, nuclear physics, and other areas of interest. MCNP uses text-based constructive solid geometry (CSG) to define the geometry of the simulated world using Boolean operators. This methodology is widely accepted, but can become burdensome for complex geometries.

The MCNP input deck is divided into three blocks: cell cards, surface cards, and data cards. Cell cards reference surface cards and define the geometry region of interest using Boolean operators, the material composition and material density that comprise the specified geometry, and define the tracking importance of particles in that defined region. An inner sphere of soft tissue, an outer sphere of keratin, and a bounding box of dry air near sea level were all defined. All volumes beyond this bounding box were labeled as void space with zero importance to terminate tracking of particles.

Surface cards define the physical measurements and placement of each object in the simulation, which can either be in simple geometries using Cartesian coordinates or predefined macrobodies that also use Cartesian coordinates. Macrobodies were more convenient for this project when using the CSG simplified geometry. Two nested sphere macrobodies (SPH) were used in the CSG text for the internal soft tissue and the external keratin scales. A right parallelepiped (RPP) filled with dry air, near sea level was used to bound the pangolin to account for potential backscatter in the environment that could contribute additional radiation dose to the pangolin.

Data cards define the materials, the source, and what type of particles are to be counted and from where in the simulation universe. First, materials are specified. The density and weight fractions for dry air, near sea level were defined from Pacific Northwest National Laboratory's Compendium of Material Composition Data for Radiation Transport Modeling (Pacific Northwest National Laboratory 2021). The density and weight fractions for soft tissue were defined from the International Commission on Radiation Units and Measurements Report 44, which specifies a four-component model for human tissue for use in dosimetry modeling (International Commission on Radiation Units and Measurements 1989). The density of keratin

for this study was previously defined, but the weight fraction was derived from a study of men and women's index and little fingernails. The 24 male and 25 female control measurements for both index and little fingers were averaged and the weight fraction calculated. (Schumacher et al. 2009). The sum of these weight fractions only accounts for 68.6% of the nail weight. The remaining mass was assumed as water as the nail samples were dehydrated prior to elemental analysis. Water content in human fingernails varies due to humidity, environmental exposures, and hydration status but can range from 10 – 30% (Baden et al. 1973). There are several trace elements and minerals found in human fingernails such as Mn, Fe, Cu, Cr, As, Br, Ca, Zn, Se, and Pb that were not considered for this study (Van Nguyen et al. 2025). Reference Appendix E for mass fractions used for the keratin scales.

Point Source

A source was positioned at cartesian coordinates (0, -11.535, 0) to model the point source dose to the pangolin. Since the radius of the model pangolin scale sphere was 11.54 cm, and the DMSO is assumed to penetrate to 0.050 cm, 11.535 cm was used. The source energy was defined as discrete using source information (SI) and source probability (SP) cards to further define the source. The source parameter was defined as “2” for photons. The source energy was defined as 1.173 MeV and 1.332 MeV to indicate the two gamma energies released during ^{60}Co decay, and both probabilities of emission were defined as 1, with each equally probable to emit during a single decay.

The F5 tally was used for the point source geometry to measure the photon fluence to the dosimetric depths specified at 1.395 cm and 0.402 cm for the whole-body and the basal layer of the skin, respectively, to verify the first principles calculations. The F5 tally uses a point detector to calculate particle fluence at a specific location. The MCNP software utilizes a “next-event

estimator” to calculate the probability of a particle scattering towards the detector from each collision point, source point, or termination. The F5 point source detector for the whole-body dose was placed at cartesian coordinates (0 cm, -10.145 cm, 0 cm), which was 1.395 cm inside of the 11.54 cm radius of the outer keratin scale layer and directly inside the sphere from the point source.

The F5 point source detector for the basal layer of the skin dose was placed at cartesian coordinates (0 cm, -11.138 cm, 0 cm); 0.402 cm inside of the 11.54 cm radius of the outer keratin scale layer and directly inside the sphere from the point source. Since the point detector was placed so close to the point source, an exclusion area with a radius of 0.25 cm was placed around the source detector to prevent large energy deposits from creating a singularity error near the detector. Importance biasing was used to promote statistical convergence for the F5 tally. As the source particles moved closer to the detector cell, the cell importance increased to prompt particle splitting and generate more particles to potentially enter the detector. Additionally, source biasing was used so that particles were only emitted in the positive y-direction to maximize computational efficiency and further encourage statistical convergence. Each simulation ran 500 million particle histories. Reference Appendix E for full MCNP tallies and dose calculations.

General pangolin geometry and source positions were the same for the +F6 tally as the F5 tally. The +F6 tally was used for both primary photons and secondary electrons. The +F6 tally calculates the volume averaged total energy deposition for all particles in a specified cell and is recommended in situations when the geometry is thin relative to the mean free path of generated secondary particles. The mean free path, or relaxation length, is the average distance a particle will travel before it interacts. For charged particles, the continuous slowing down

approximation (CSDA) estimates the total path length the charged particle will travel before it stops. The highest potential energy of a ^{60}Co secondary electron is averaged at 1.25 MeV. The CSDA range for 1.25 MeV electrons in water as a tissue substitute is 0.5717 g cm^{-2} . Assuming a density of soft tissue at 1 g cm^{-3} , the average range for a 1.25 MeV electron in soft tissue is approximately 0.5717 cm or 5.717 mm (International Commission on Radiation Units and Measurements 1984). Although the whole body dose is measured at a depth beyond the CSDA of the secondary electrons, the basal layer of the skin dose is within the CSDA range making the +F6 tally the most appropriate.

The +F6 tally requires a volume in which to measure energy deposition, so a right circular cylinder macrobody (RCC) was used as a detector cell in the soft tissue inner sphere of the pangolin model with the same density and material definition as the soft tissue. The whole-body dosimetry method placed the origin of the RCC at cartesian coordinates (0 cm, -10.145 cm, 0 cm), which is 1.395 cm inside of the 11.54 cm radius of the outer keratin scale layer and directly inside the sphere from the point source. The RCC was assigned a height in the y-direction of 0.001 cm to represent an infinitesimally thin layer and a radius of 0.05642 cm to represent the 1 mm^2 radius used in the V+ simulation to approximate a point detector. The resulting mass of this RCC in soft tissue with a density of 1 g cm^{-3} is $10.004 \text{ }\mu\text{g}$.

The basal layer of the skin dosimetry method placed the origin of the detector RCC at cartesian coordinates (0 cm, -11.138 cm, 0 cm); 0.402 cm inside of the 11.54 cm radius of the outer keratin scale layer and directly inside the sphere from the point source. The detector RCC was assigned a height in the y-direction of 0.001 cm to represent an infinitesimally thin layer and a radius of 0.5642 cm to represent the 1 cm^2 radius used in human dosimetry methods and in the V+ simulation. The resulting mass of this RCC in soft tissue with a density of 1 g cm^{-3} is

1000.04 μg . Each +F6 simulation was programmed for both photon and secondary electron tracking and ran 500 million particle histories. Reference Appendix E for full MCNP tallies and dose calculations.

Figs. 6 and 7 below show a 3D rendering of the outer scale sphere geometry and a visual representation of the point source location.

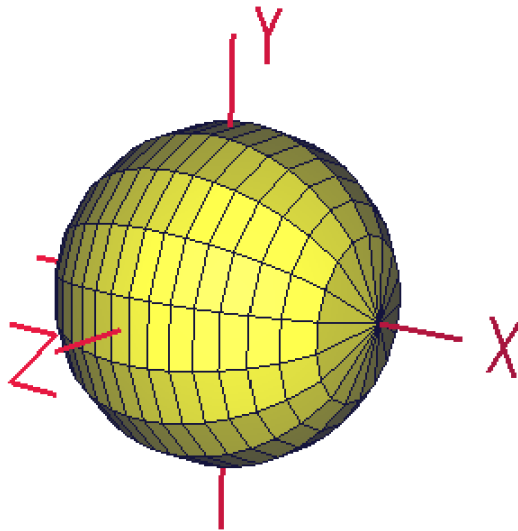


Fig. 6, Dynamic 3-dimensional display of MCNP geometry input for the pangolin using MCNPX Visual Editor Version 2.7.E of April 2011

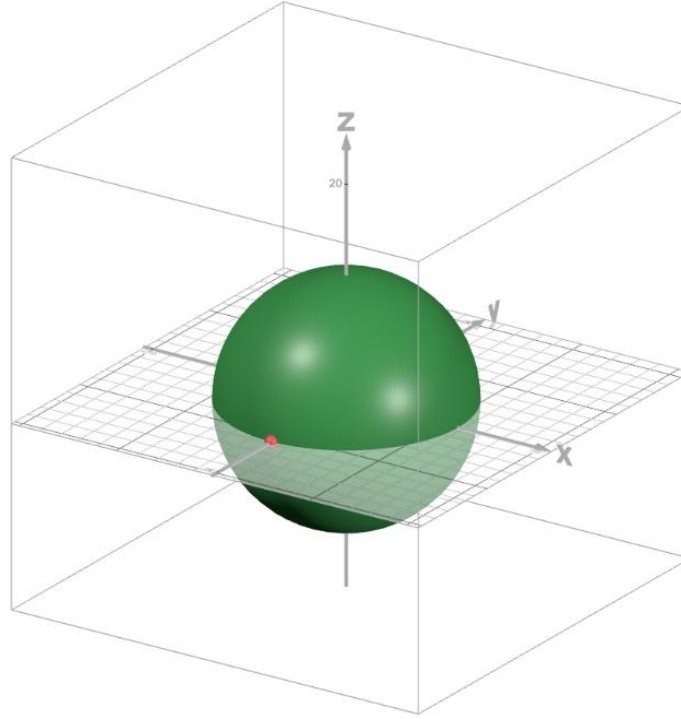


Fig. 7, 3D rendering of the pangolin scale sphere with point source

Planar Source

To model the planar source, the general pangolin geometry was the same as for the +F6 tally and the F5 tally. To represent the planar application area, two hundred point sources were plotted onto the surface of the sphere in a $20\text{ cm} \times 10\text{ cm}$ grid pattern on a phantom sphere for the sources at a radius of 11.535 cm to account for the 0.05 cm DMSO penetration depth from the 11.54 cm radius of the keratin shell layer of the pangolin. Figs. 8 – 10 below are 3D renderings of the point source locations on the surface of the pangolin sphere. Reference Appendix E for full point source location calculations.

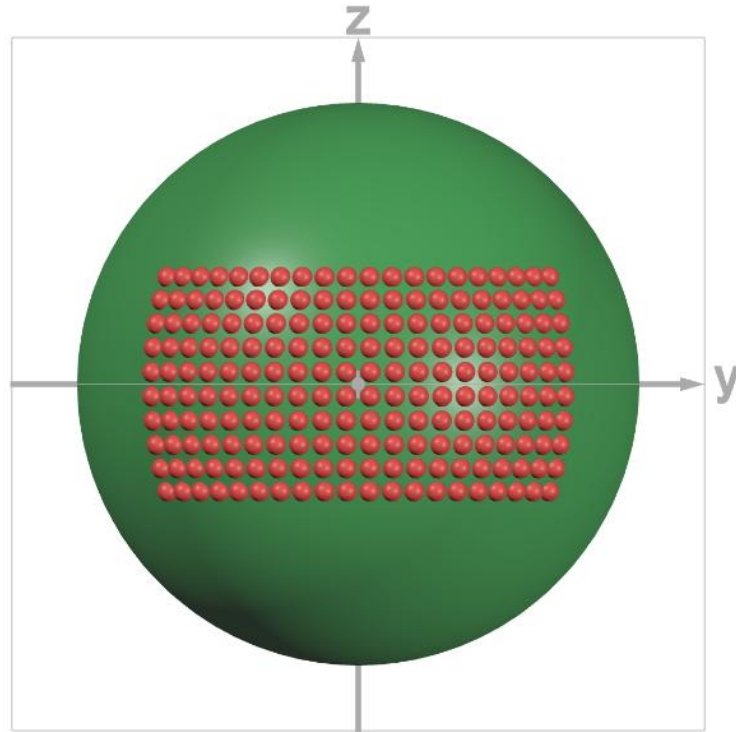


Fig. 8, 3D rendering of the pangolin scale sphere with 200-point source grid

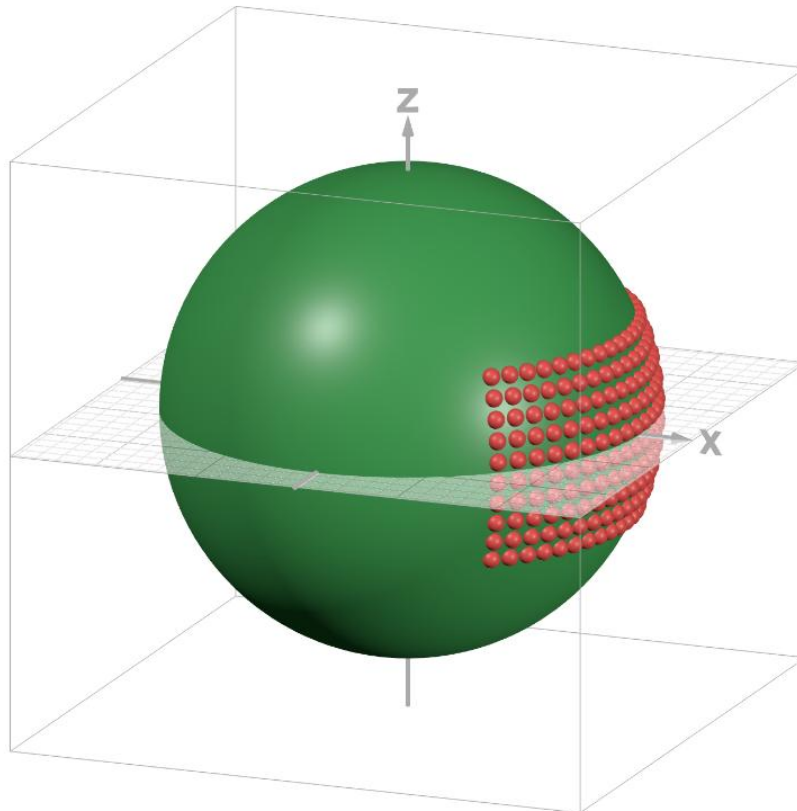


Fig. 9, 3D rendering of the pangolin scale sphere with 200-point source grid

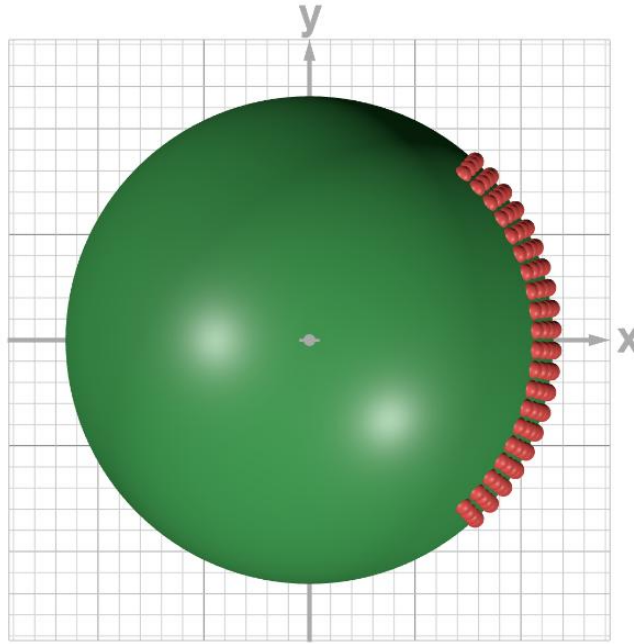


Fig. 10, 3D rendering of the pangolin scale sphere with 200-point source grid

The same method was used to plot the point detectors at the whole-body dosimetry depth for the pangolin at 1.395 cm on a phantom sphere for the whole-body detectors at a radius of 10.145 cm. The dosimetry depth already accounts for the DMSO penetration depth, so the radius was found by subtracting the dosimetric depth from the 11.54 cm keratin sphere radius. Since no averaging area is specified for whole-body dosimetry, two hundred small, spherical detectors were placed directly behind each point source at 1.395 cm from the source radius of 11.535 cm into the soft tissue inner sphere of the pangolin model with the same density and material definition as the soft tissue. The sphere macrobody (SPH) was used to model each point source detector. Using the mass of the disc used in the point source +F6 tally of $10.004 \mu\text{g}$ and the density of soft tissue of 1 g cm^{-3} , a corresponding sphere radius of 0.0134 cm was originally used for each sphere detector. However, such a small target did not produce reliable results even with 10 billion particle histories. The radius of each whole-body detector was increased to 0.1 cm for better statistics without sacrificing physical accuracy. Figs. 11 – 15

below are 3D renderings of the whole-body point detector locations. Reference Appendix E for full whole-body dose detector location calculations.

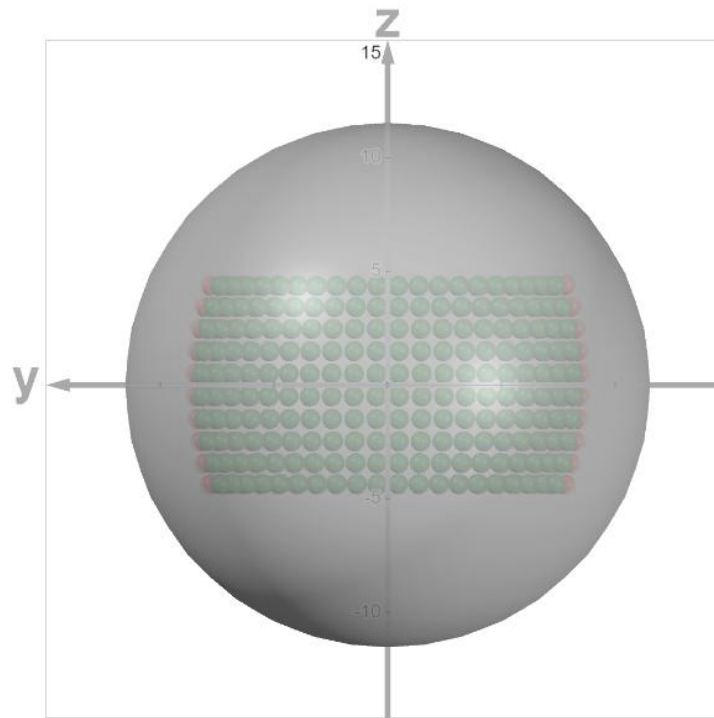


Fig. 11, 3D rendering of the pangolin scale sphere with 200 point source grid and 200 whole body point detectors

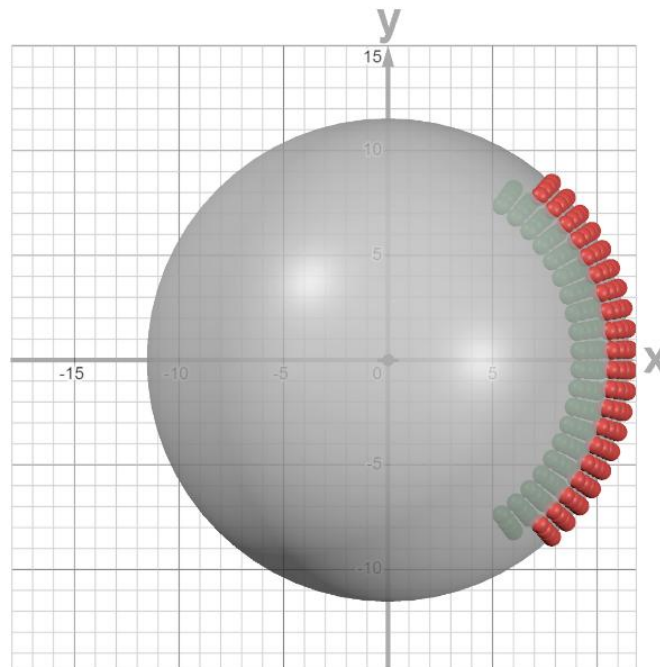


Fig. 12, 3D rendering of the pangolin scale sphere with 200 point source grid and 200 whole body point detectors

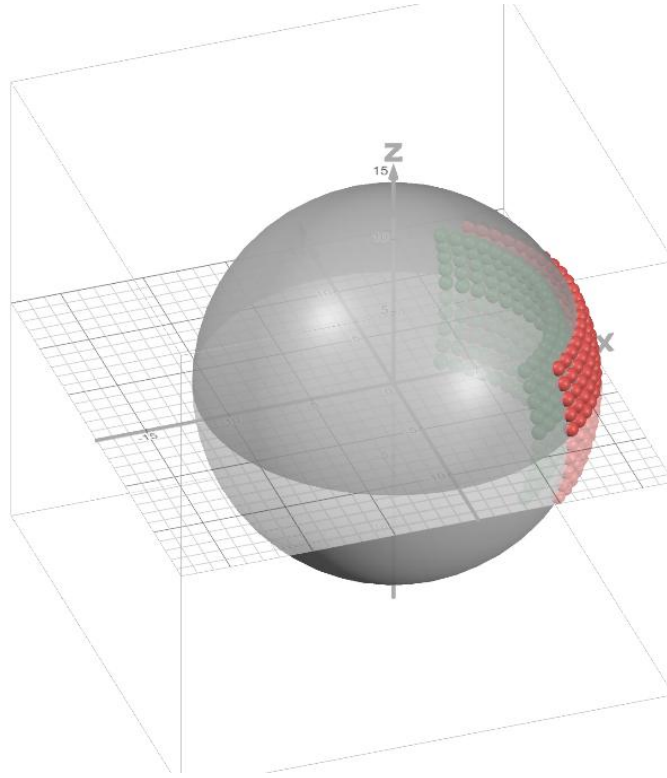


Fig. 13, 3D rendering of the pangolin scale sphere with 200 point source grid and 200 whole body point detectors

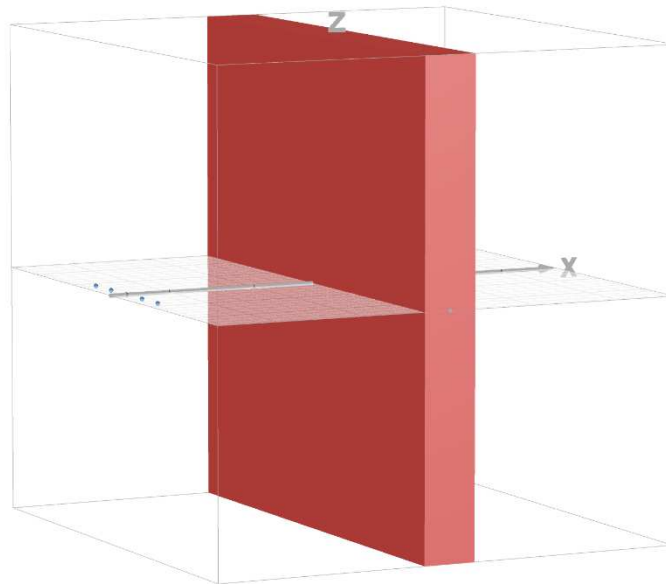


Fig. 14, 3D rendering of the pangolin scale in red with whole-body point detectors in blue at 0.0134 cm radius

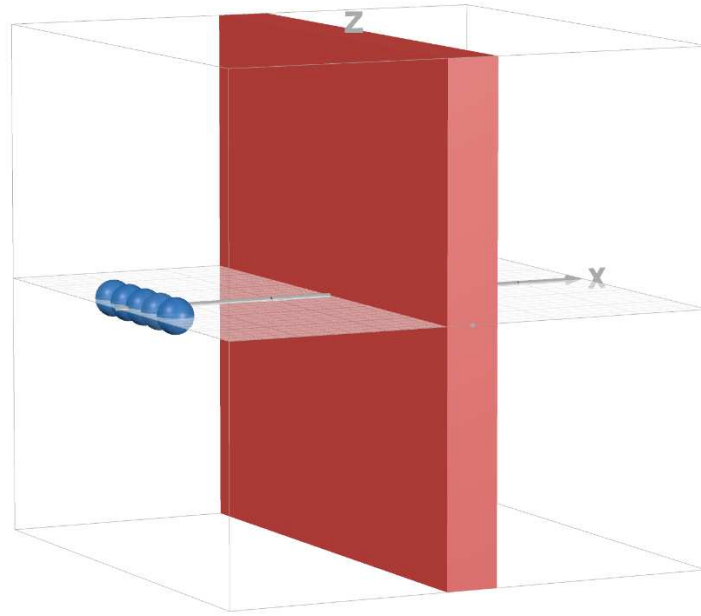


Fig. 15, 3D rendering of the pangolin scale in red with whole-body point detectors in blue at 0.1 cm radius

The same method was again used to plot the point detectors at the basal layer of the skin dosimetry depth for the pangolin at 0.402 cm on a phantom sphere for the basal layer of the skin detectors at a radius of 11.138 cm. The dosimetry depth already accounts for the DMSO penetration depth, so the radius was found by subtracting the dosimetric depth from the 11.54 cm keratin sphere radius. Since the recommended dosimetric averaging area skin dose is 1 cm^2 , two hundred small, spherical point approximation detectors were plotted directly behind each point source at 0.402 cm from the source radius of 11.535 cm into the soft tissue layer of the pangolin model with the same density and material composition as the soft tissue. The sphere macrobody (SPH) was used to model each point source detector. Using the mass of the disc used in the point source +F6 tally of $1000.04 \text{ } \mu\text{g}$ and the density of soft tissue of 1 g cm^{-3} , a corresponding sphere radius of 0.134 cm should have been used for each sphere detector. However, with the 0.295 cm scale thickness and the 0.134 cm detector radius centered at 0.402

cm from the surface of the scale, the detector would have extended 0.027 cm into the scale. The detector radius of 0.0134 cm was instead used to mitigate this issue. However, the small size of the target did not produce reliable results even after running 10 billion particle histories.

The point detectors were replaced with RCC detectors that were 0.01 cm thick rather than 0.001 cm as used in the point source +F6 tally, and 0.45 cm in radius to ensure no discs overlapped one another. The MCNP RCC input uses the cartesian coordinates for the base of the cylinder rather than the center of the cylinder. The bases of the RCCs were moved 0.005 cm into the soft tissue on a phantom sphere for the basal layer of the skin detectors at a radius of 11.133 cm and angled radially outwards for 0.01 cm with the center of the bases facing towards the origin to account for the curvature of the sphere. Thus, the detector discs are tangent to the inner sphere of 11.133 cm. The maximum range of the discs is derived from the radial component and the perpendicular component in the manner below. The maximum range of the discs is 11.153 cm, which is less than the 11.24 cm radius of the soft tissue inner layer of the pangolin and no discs protruded from the soft tissue into the scale.

$$\text{range}_{\max} = \sqrt{(\text{radial component})^2 + (\text{perpendicular component})^2}$$

$$\text{range}_{\max} = \sqrt{(11.133 \text{ cm} + 0.01 \text{ cm})^2 + (0.45 \text{ cm})^2} = 11.153 \text{ cm}$$

Figs. 16 – 22 below are 3D renderings of both the spherical and thin, disc detectors for the basal layer of the skin. Reference Appendix E for full basal layer of the skin dose detector location calculations.

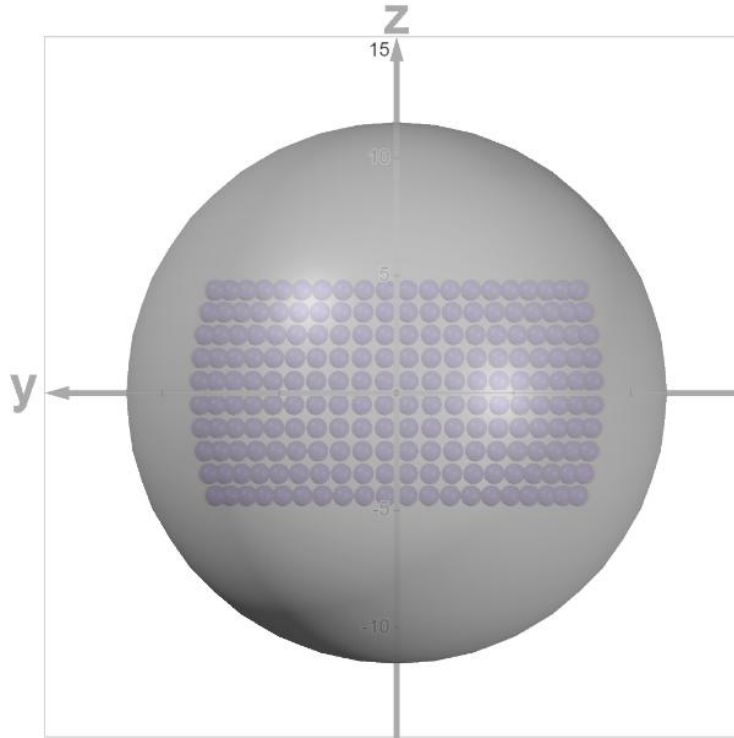


Fig. 16, 3D rendering of the pangolin scale sphere with 200 point source grid and 200 basal layer of the skin point detectors

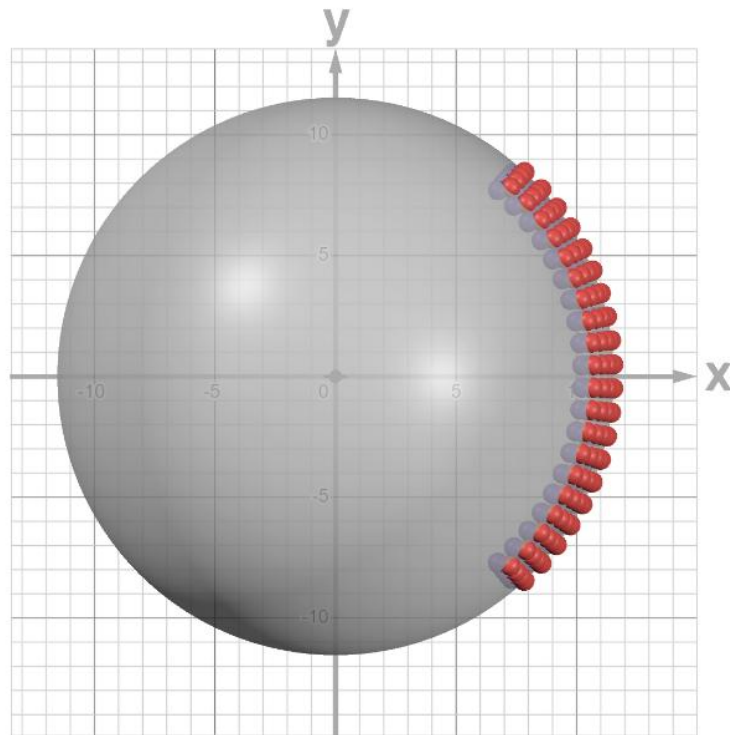


Fig. 17, 3D rendering of the pangolin scale sphere with 200 point source grid and 200 basal layer of the skin point detectors

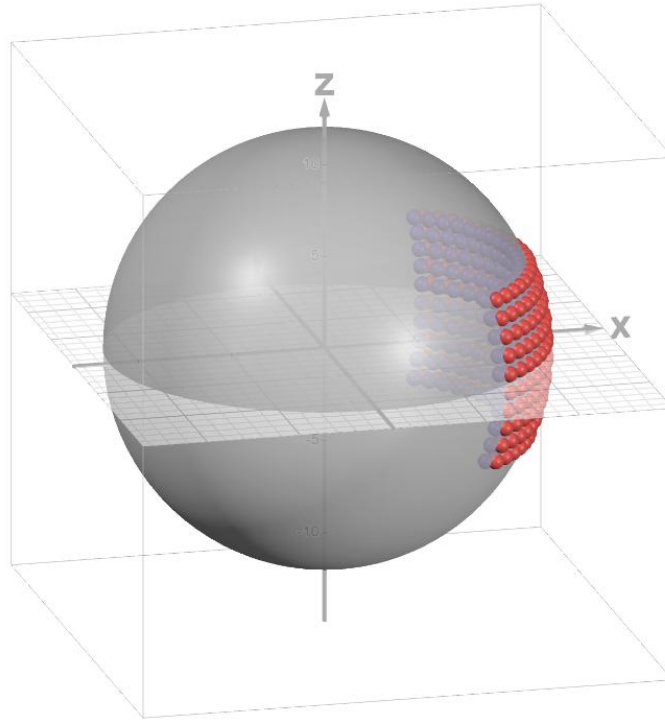


Fig. 18, 3D rendering of the pangolin scale sphere with 200 point source grid and 20 basal layer of the skin point detectors

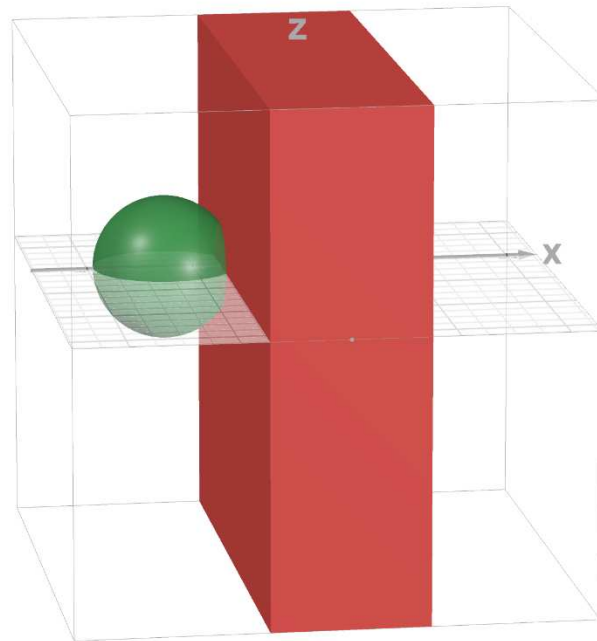


Fig. 19, Representation of basal layer of the skin detector in green overlap into the pangolin scale in red at 0.134 cm radius

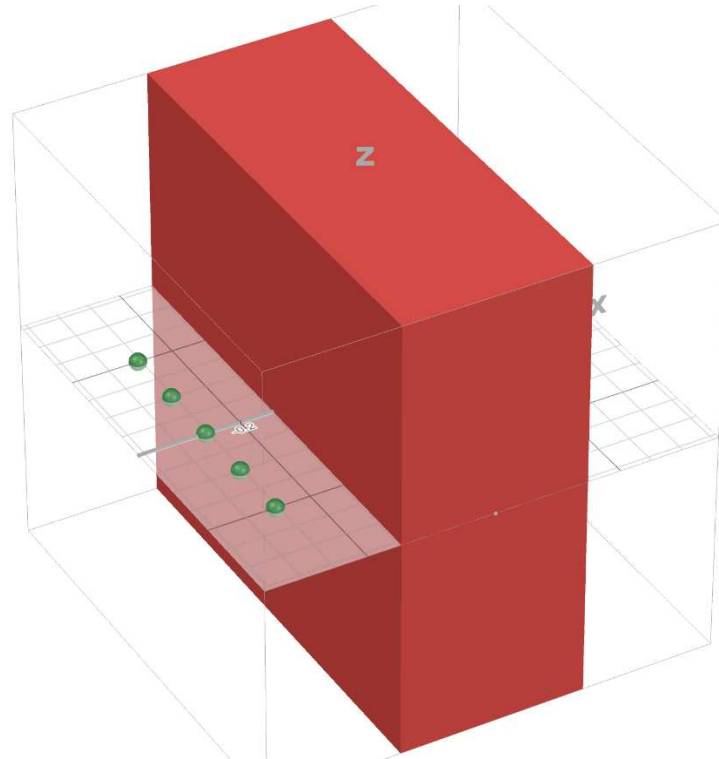


Fig. 20, Representation of pangolin scale in red and basal layer point detectors in green at 0.0134 cm radius

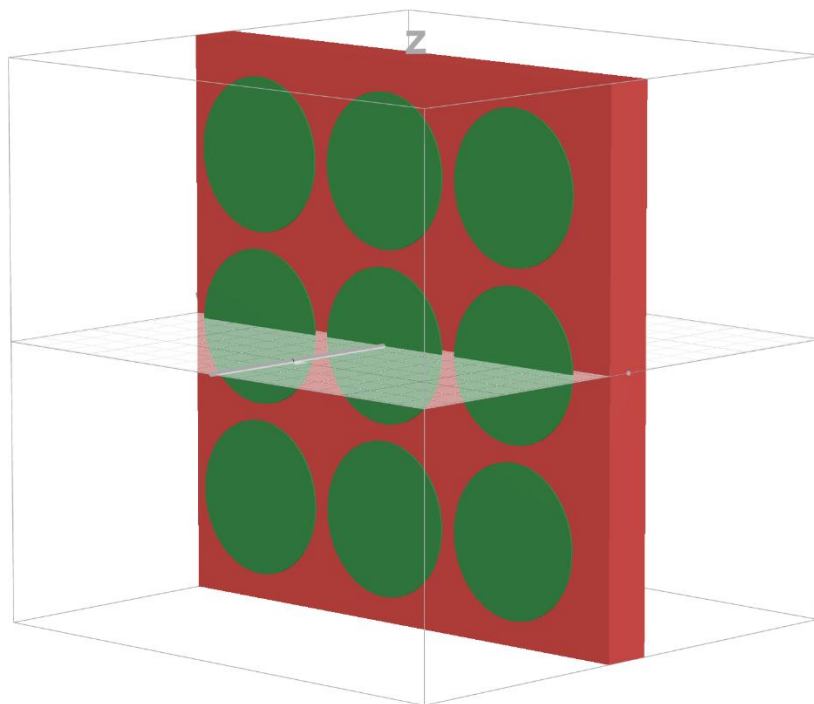


Fig. 21, Representation of pangolin scale in red and basal layer circular detectors in green

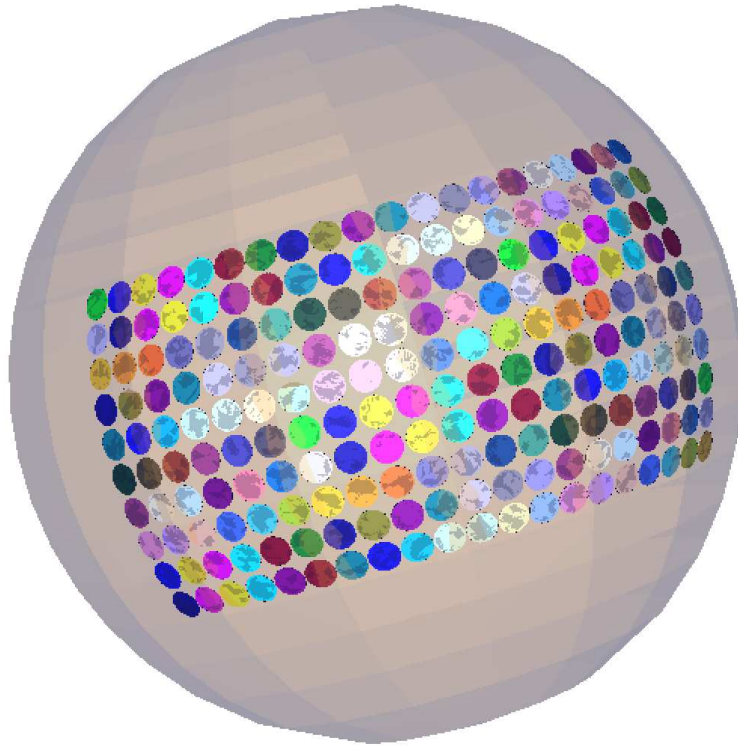


Fig. 22, Representation of pangolin sphere and 200 disc detectors

The +F6 tally was used for each of the two hundred point detector models for the whole body and basal layer of the skin and the disc detector model for the basal layer of the skin to track energy deposition from both photons and secondary electrons. The +F6 point detector simulations ran for ten billion particle histories. The +F6 basal layer of the skin disc detector simulation ran 180 million particle histories. A summation tally provided an average energy absorption in MeV g^{-1} with relative uncertainty, which was converted to a whole body or basal layer of the skin radiation dose. Reference Appendix E for full MCNP tallies and dose calculations.

Beta Particle Range in Keratin

MCNP was also used to model the beta-particle range in the keratin scales. Thirty nested keratin spheres were modeled in 0.1 mm radius intervals with a ^{60}Co beta source placed at the origin. The keratin spheres were defined with the same keratin density and material composition

as defined in the F5 and +F6 transport simulations. For the MCNP simulation, the full beta particle energy spectrum was divided into energy bins and the probability of emission in that bin assigned including both the higher abundance 0.318 MeV beta particle and the much lower abundance 1.48 MeV beta particle.

The probabilities in particles per nuclear transition were summed for each of the energy bins listed in Table 2 below.

Table 2, ⁶⁰Co Beta Particle Energy Bins

Energy Bins (MeV)
< 0
0 - 0.02
0.02 - 0.04
0.04 - 0.06
0.06 - 0.08
0.08 - 0.10
0.10 - 0.12
0.12 - 0.14
0.14 - 0.16
0.16 - 0.18
0.18 - 0.20
0.20 - 0.22
0.22 - 0.24
0.24 - 0.26
0.26 - 0.30
0.30 - 0.318
0.318 - 1.49

The energy bins in MCNP are defined only by the upper boundary. Reference Appendix E for ⁶⁰Co beta particle probability distributions and bin probabilities. The probability of ⁶⁰Co beta particles energies is shown in Fig. 23 below.

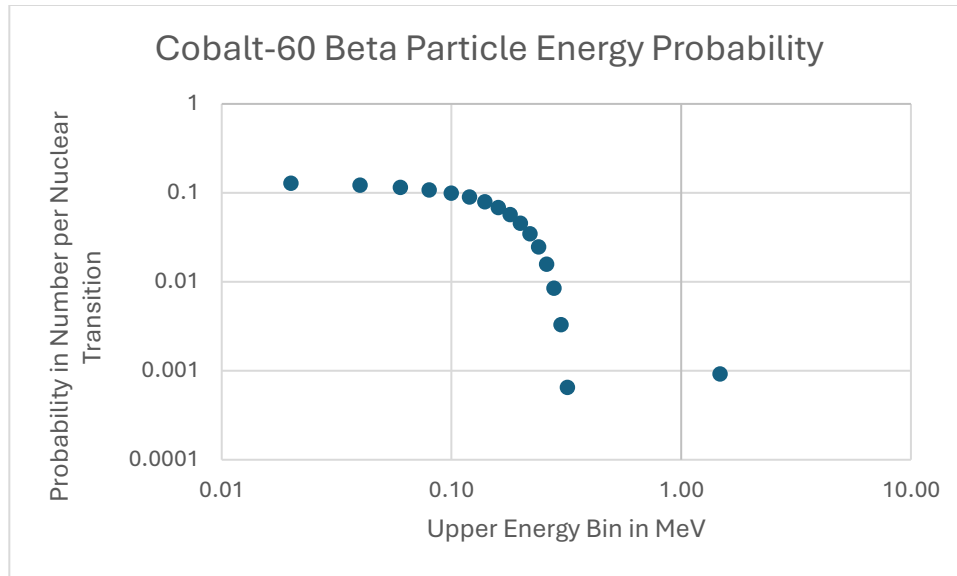


Fig. 23, ^{60}Co beta particle energy probability distribution function

An F4 volume-averaged flux tally was conducted in each 0.1 mm sphere to determine the point at which the electron fluence dropped to zero particles cm^{-2} . The beta-particles were tracked in electron mode only.

MIRD Comparison

To demonstrate the MIRD method with an MCNP simulation, the general pangolin geometry and source coordinates remained the same from the F5 and +F6 whole-body dose point source simulations. The F6 tally was used in primary photon and secondary electron mode. The F6 tally calculates volume averaged heat deposition in a specified cell. The entirety of the inner, soft tissue sphere was used as the target of interest for heat deposition as this corresponds immediately to absorbed dose. The simulation ran 100 million particle histories.

Reference Appendix D for full MCNP input cards.

RESULTS

Beta Particle Range

The results for the beta particle range calculations and simulation are shown in Tables 3 through 5 below.

Table 3, Beta Particle Range from the Bethe-Bloch Equation

	Range (cm)	Range (mm)
Soft Tissue	0.0277	0.277
Keratin	0.0186	0.186

Table 4, Beta Particle Range from the Empirical Range Formula

	Range (cm)	Range (mm)
Soft Tissue	0.0837	0.837
Keratin	0.0625	0.625
Air	64.8	648

Table 5, Beta Particle Range from MCNP Simulation

	Range (cm)	Range (mm)
Keratin	0.09-0.10	0.9-1.0

Gamma Dose

The results for the gamma dose to the pangolin from calculations, models, and simulations are shown in Tables 6 through 9 below.

Table 6, Gamma Dose from Bremsstrahlung

	Absorbed Dose from Point Source (mGy y ⁻¹)	Absorbed Dose from Point Source (μGy h ⁻¹)
Whole Body	6.42×10^{-5}	7.32×10^{-6}
Basal Layer of the Skin	7.73×10^{-4}	8.82×10^{-5}

Table 7, Gamma Dose from Point Source Calculation

	Absorbed Dose from Point Source (mGy y⁻¹)	Absorbed Dose from Point Source (μGy h⁻¹)
Whole Body	5620	641
Basal Layer of the Skin	67700	7720
Basal Layer of the Skin (Corrected)	38400	4380
Reproductive Organs	313	35.7

Table 8, Gamma Dose from Planar Source Calculation

	Absorbed Dose from Planar Source (mGy y⁻¹)	Absorbed Dose from Planar Source (μGy h⁻¹)
Whole Body	549	62.6
Basal Layer of the Skin	933	106
Reproductive Organs	162	18.5

Table 9, Gamma Dose from NRC V+ Model

Area of Co-60 Application (cm²)	Photon Skin Dose (mSv y⁻¹)	Photon Skin Dose (μSv h⁻¹)	Photon Deep Dose (mSv y⁻¹)	Photon Deep Dose (μSv h⁻¹)
0	41000	4680	5900	673
50	2700	308	1300	148
100	1400	160	810	92.4
150	1000	114	590	67.3
200	770	87.8	470	53.6
250	620	70.7	390	44.5

Figs. 24 and 25 show the modeled whole body and basal layer of the skin dose to the pangolin from different application diameters of ^{60}Co to the scales.

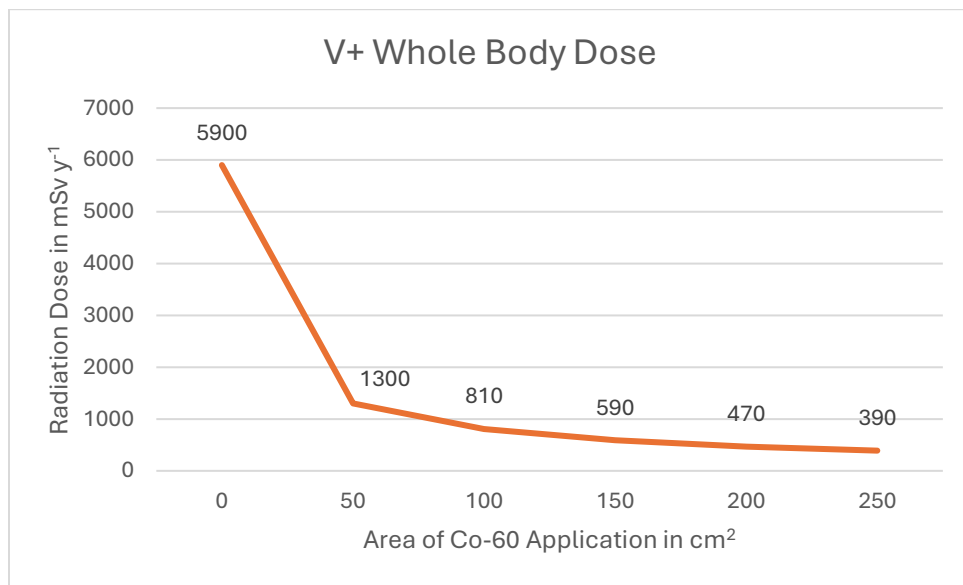


Fig 24, Whole body dose to the pangolin in mSv y⁻¹ at different application diameters

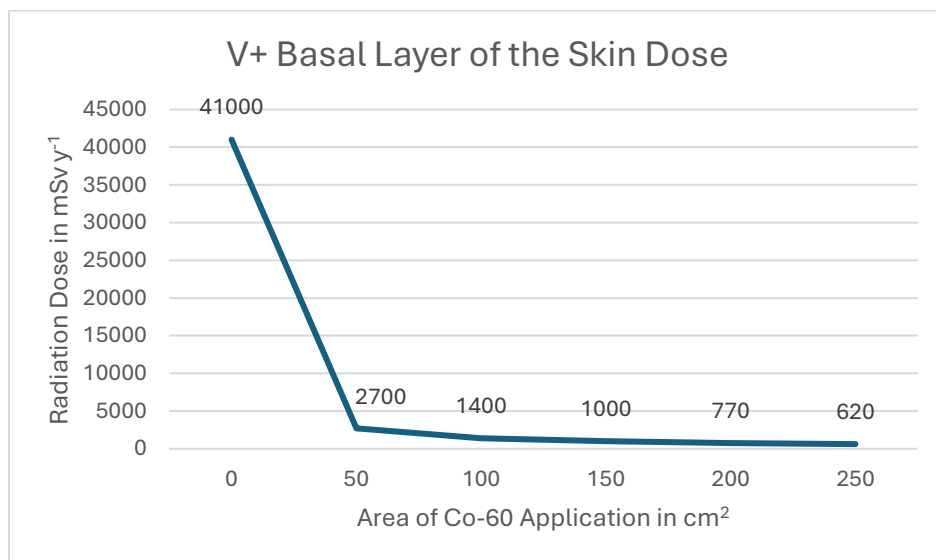


Fig 25, Basal layer of the skin dose to the pangolin in mSv y⁻¹ at different application diameters

Tables 10 through 14 below give gamma dose results from the ICRP 136 model, the BiotaDC model, the MIRD method, and the various MCNP tallies and the corresponding gamma doses.

Table 10, Gamma Dose from the ICRP 136 Model

	Absorbed Dose (mGy y⁻¹)	Absorbed Dose (μGy h⁻¹)
In Soil	649	74.0

Table 11, Gamma Dose from the Biota DC Model

	Absorbed Dose (mGy y⁻¹)	Absorbed Dose (μGy h⁻¹)
In Soil	521	59.4

Table 12, Gamma Dose from the MIRD Method

	Absorbed Dose (mGy y⁻¹)	Absorbed Dose (μGy h⁻¹)
Volume Averaged	217	24.8

Table 13, MCNP Tallies

	Tally (starting particle⁻¹)	Unit	Relative Error
Whole Body Point Source F5	4.31123×10^{-2}	particles cm ⁻²	0.0001
Whole Body Point Source +F6	1.48229×10^{-3}	MeV g ⁻¹	0.0610
Whole Body Planar Source +F6 Sum	1.15121×10^{-4}	MeV g ⁻¹	0.0006
Basal Layer Point Source F5	5.13092×10^{-1}	particles cm ⁻²	$< 5 \times 10^{-5}$
Basal Layer Point Source +F6	1.04061×10^{-2}	MeV g ⁻¹	0.0250
Basal Layer Planar Source +F6 Sum (Point Detectors)	2.36093×10^{-4}	MeV g ⁻¹	0.0039
Basal Layer Planar Source +F6 Sum (Disc Detectors)	2.24622×10^{-4}	MeV g ⁻¹	0.0015
MIRD Whole Body Point Source F6	5.01201×10^{-5}	MeV g ⁻¹	0.0002

Table 14, Gamma Dose from MCNP Simulation

	Absorbed Dose (mGy y⁻¹)	± 2 σ (mGy y⁻¹)	Absorbed Dose (μGy h⁻¹)	± 2 σ (μGy h⁻¹)
Whole Body Point Source F5	5920	1	676	1
Whole Body Point Source +F6	5550	677	633	77
Whole Body Planar Source +F6	431	1	49.1	0.1
Basal Layer Point Source F5	70500	6	8040	1
Basal Layer Point Source +F6	38900	1950	4440	222
Basal Layer Planar Source +F6 (Point Detectors)	883	7	101	1
Basal Layer Planar Source +F6 (Disc Detectors)	840	3	95.8	0.3
MIRD Whole Body Point Source F6	188	1	21.4	0.1

DISCUSSION

Dose from Beta Particles

Using all calculation methods: the Bethe-Bloch equation, the empirical range formula, NRC V+ at 200 cm², and MCNP radiation transport simulation, the maximum energy beta particles from ⁶⁰Co are not energetic enough to penetrate the pangolin scale at 2.95 mm. However, the maximum energy beta particles from ⁶⁰Co will travel approximately 65 cm in air and must be considered in future studies as a potential radiation source to any pangolin pup that is on its mother's tail. The beta particles applied to the pangolin scale will not contribute any radiation dose to the pangolin itself, but may contribute some radiation dose to the pangolin pups that ride on their mothers' backs.

The calculated dose from bremsstrahlung photons created from the beta particle interactions were exceedingly small at 6.42×10^{-5} mGy y⁻¹ (7.32×10^{-6} μGy h⁻¹) for the whole body and 7.73×10^{-4} mGy y⁻¹ (8.82×10^{-5} μGy h⁻¹) for the basal layer of the skin even when including the maximum energy beta particles. The bremsstrahlung dose is more than 400,000 times smaller than the dose-rate goal of 350 mGy y⁻¹ (40 μGy h⁻¹) for the basal layer of the skin and more than five million times smaller than the same dose rate goal for the whole-body. For comparison, the ICRP 103 recommendation for radiation exposure to members of the public is 1 mSv y⁻¹ above background radiation levels (ICRP 2008b). For photon purposes, assume that 1 Sievert is equal to 1 Gray. The bremsstrahlung dose to the pangolin's basal layer of the skin is more than fifteen-thousand times smaller and the bremsstrahlung dose to the pangolin's whole-body is more than one-thousand times smaller than the radiation dose that the ICRP considers low enough risk to the members of the public to be acceptable. The 0.09577 MeV mean energy

of the ^{60}Co beta particle is only 30% of the maximum beta energy for ^{60}Co , so the dose contribution from the bremsstrahlung is likely only a third of the calculated, most conservative value. Thus, the bremsstrahlung dose is not modeled with more sophisticated methods and is disregarded for this study as a potential source of significant exposure to the pangolin.

Dose from Gamma Rays

The whole-body radiation doses to the pangolin from a point source based on MCNP simulation is $5550 \pm 677 \text{ mGy y}^{-1}$. Calculated doses ranged from 5550 – 5920 mGy y^{-1} . The absorbed dose calculated by first principles calculations (5620 mGy y^{-1}) and the MCNP point source simulation using the F5 tally ($5920 \pm 1 \text{ mGy y}^{-1}$) were both truly collision KERMA calculations, which assumed electronic equilibrium. The values matched very closely to the absorbed dose from the V+ point source (5900 mSv y^{-1}) and the MCNP point source simulation using the +F6 tally ($5550 \pm 677 \text{ mGy y}^{-1}$), which demonstrates that the charged particle equilibrium assumption is an appropriate approximation for dose absorbed at the depth of 1.395 cm into the pangolin scales and soft tissue. The values remained within a narrow margin, with a maximum spread of 6.67%. The uncertainty for the MCNP point source simulation using the +F6 tally is high at 6.1%, but could have been alleviated if more particle histories were run. The simulation was run as a demonstration of charged particle equilibrium rather than to assign dose to the pangolin and was not further investigated.

The whole-body radiation dose to the pangolin from a 200 cm^2 planar source using MCNP simulation is $431 \pm 1 \text{ mGy y}^{-1}$. Five of the individual two hundred spherical tally regions failed at least one of MCNP's built-in statistical checks, but the simulation showed strong statistics in the summation tally bin of all two hundred tally regions totaled together. These pooled statistics indicate good convergence and reliability of the MCNP results. Calculated doses

ranged from 431 – 649 mGy y⁻¹. Although charged particle equilibrium was already assumed at the whole-body dosimetric depth of 1.395 cm, planar sources are less sensitive to charged particle equilibrium concerns in general since there is lateral contribution of secondary electrons to replace electrons that may escape the dose volume. The fluence-based first-principles calculations (549 mGy y⁻¹) very closely matched the V+ output (470 mSv y⁻¹), the MCNP planar source simulation using the +F6 tally (431 ± 1 mGy y⁻¹), the ICRP 136 dose-coefficient model (649 mGy y⁻¹), and the BiotaDC dose-coefficient model (521 mGy y⁻¹) with maximum spread at 40.4%. The percent difference includes both the general ICRP 136 and BiotaDC models, which only approximate the planar source geometry and do not account for the density thickness difference of the scale. The first-principles calculation also does not consider the density thickness of the scale, but rather assumes soft tissue. The V+ output and the MCNP simulation both consider the appropriate geometry and scale density thickness difference, and are thus the most accurate to assess radiation dose to the pangolin from a point source. The percent difference between the V+ output and the MCNP simulation is 8.66%. The whole-body dose rate goal for this study was to achieve a dose rate at or below 350 mGy y⁻¹ (40 µGy h⁻¹) with a planar source, which was not achieved using 0.37 MBq of ⁶⁰Co.

The basal layer of the skin radiation KERMA to the pangolin from a point source is 70500 ± 6 mGy y⁻¹ based on MCNP simulation. Calculated doses ranged from 67700 – 70500 mGy y⁻¹. The dose calculated by first principles calculations (67700 mGy y⁻¹) and the MCNP point source simulation using the F5 tally (70500 ± 6 mGy y⁻¹) were measures of collision KERMA to a dosimetric depth of 0.402 cm into the pangolin scales and soft tissue and differed by only 4.05%. The dosimetric depth is less than the d_{max} for ⁶⁰Co photons; therefore, the assumptions for charged particle equilibrium assumption are not met. The collision KERMA

values overestimated the dose to the basal layer of the skin of the pangolin since secondary electrons were assumed to locally deposit all energy immediately upon creation, which is not true to the physics mechanisms in place. Without charged particle equilibrium, more secondary electrons deposit their energy outside of the dosimetric volume than energy that is transferred to these electrons. The collision KERMA calculation and simulation were performed to demonstrate potential errors in using first-principles calculations with improper assumptions or inappropriate simulation tallies to calculate radiation dose and not for assigning potential radiation dose to the pangolin.

The basal layer of the skin radiation dose to the pangolin from a point source is 38900 ± 1950 mGy y^{-1} from MCNP simulation. Calculated doses ranged from 38400 – 41000 mGy y^{-1} . Using an f_{cpe} correction factor, the corrected first principles dose calculations (38400 mGy y^{-1}) aligned much more closely to the V+ point source dose (41000 mSv y^{-1}) and the MCNP point source simulation using the +F6 tally (38900 ± 1950 mGy y^{-1}) with the maximum spread at only 6.55%. The difference between these calculations and the previous KERMA calculations show the impact of properly calculating radiation dose in an area of charged particle disequilibrium as energy absorbed rather than energy transferred.

The basal layer of the skin radiation doses to the pangolin from a planar source is 840 ± 3 mGy y^{-1} using MCNP simulation. Calculated doses ranged from 770 – 933 mGy y^{-1} . As with the whole-body dose, the basal layer of the skin dose from a planar source was much less susceptible to variation from charged particle disequilibrium. The dose calculated based on first principles and assumed charged particle equilibrium (933 mGy y^{-1}) was very close to both the V+ value (770 mSv y^{-1}) and to the MCNP planar source simulation using the +F6 tally with point detectors (883 ± 7 mGy y^{-1}) and the MCNP planar source simulation using the +F6 tally with disc

detectors ($840 \pm 3 \text{ mGy y}^{-1}$) with the maximum spread at 19.2%. The basal layer of the skin +F6 point detector tally ran 10 billion histories. Even with so many particle histories, sixty-six of the two hundred detectors failed at least one of the ten MCNP built-in statistical checks likely due to low interaction probability from the small size of the point detector. Overall, the simulation had strong statistics via the summation tally. The +F6 disc detector simulation ran 180 million particle histories with only three of the individual detectors failing at least one of the MCNP statistical checks. The disc detector simulation was also successful due to the summation tallies, and showed faster convergence with fewer particles. The disc technique maintained stronger physical accuracy by not extending as deep into the tissue with the disc thickness at 0.01 cm compared to the point detector radius of 0.0134 cm and each disc had a diameter of 0.9 cm to better match the human dosimetry method of averaging the dose over 1 cm^2 . Combined with stronger statistical trends, the disc detector method was used for potential dose to the basal layer of the skin for the pangolin from MCNP simulation. The basal layer of the skin dose rate goal for this study was to achieve a dose rate at or below 350 mGy y^{-1} ($40 \text{ } \mu\text{Gy h}^{-1}$) with a planar source, which was not achieved using 0.37 MBq of ^{60}Co . The study showed that if basal layer of the skin dose can be kept below the DCRL, the whole-body doses will also not exceed goal values.

The radiation dose to the pangolin's reproductive organs from a point source was calculated at 313 mGy y^{-1} , which does meet the dose rate goal of 350 mGy y^{-1} to prevent detriment to pangolin populations. The reproductive organ dose from a point source was only 5.64% of the whole-body dose to the pangolin from a point source as calculated by MCNP simulation. The radiation dose to the pangolin's reproductive organs from a planar source was calculated at 162 mGy y^{-1} , which also meets the dose rate goal of 350 mGy y^{-1} . The reproductive organ dose from a planar source was only 37.6% of the whole-body dose at dosimetric depth

from a planar source as calculated by MCNP simulation. Maintaining the whole-body dose at dosimetric depth below dose-rate goals will ensure that the dose to the reproductive organs also remains below dose-rate goals. Depending on the agency that wishes to use this technique to save pangolin populations, dose to the reproductive organs may be another benchmark goal rather than dosimetric depth depending on the agency's established risk acceptance for the pangolin, the public, and the environment.

The dangers of using volume averaging instead of dosimetric calculation methods in cases where the source is very close to or on the pangolin were also highlighted. The MIRD method produced a whole-body radiation absorbed dose from a point source of 217 mGy y^{-1} and the MCNP volume averaged model produced a whole-body radiation absorbed dose from a point source of $188 \pm 1 \text{ mGy y}^{-1}$. The percentage difference between these two methods is found to be 14.32% as shown below, and shows that these two methods are accurate approximations of one another.

$$\left| \frac{(\text{MIRD Absorbed Dose} - \text{MCNP Absorbed Dose})}{\left(\frac{\text{MIRD Absorbed Dose} + \text{MCNP Absorbed Dose}}{2} \right)} \right| * 100 = \text{Percentage Difference}$$

$$\left| \frac{\left(217 \frac{\text{mGy}}{\text{y}} - 188 \frac{\text{mGy}}{\text{y}} \right)}{\left(\frac{217 \frac{\text{mGy}}{\text{y}} + 188 \frac{\text{mGy}}{\text{y}}}{2} \right)} \right| * 100 = 14.32\%$$

The relatively low radiation absorbed doses found by volume averaging are an order of magnitude lower than the radiation dose found by calculating the whole-body radiation dose from a point source on the surface of the pangolin to dosimetric depth. The difference highlights the intense radiation dose gradient from surface contamination in the pangolin that is very high at the skin surface and much lower throughout the body of the pangolin. The dangers of underestimating the radiation dose to the pangolin of this magnitude can inadvertently lead to serious health effects to the individual pangolin and the pangolin population.

The MIRD method dose and the volume averaged MCNP output were shown for illustrative purposes only, and do not represent the expected absorbed dose to the pangolin for this study which used the dosimetric depths of 0.402 cm for radiation dose to the basal layer of the skin and 1.395 cm for radiation dose to the whole-body radiation dose. However, this method also shows that the dosimetric depth calculations represent the worst-case scenario for dose to the pangolin. Depending on the agency that wishes to implement this technique to save pangolin populations, there may be some greater tolerance for higher worst-case doses and lower volume-averaged doses depending on the agency's risk assessment for the pangolin, the public, and the environment.

Comparison of Methods

Tables 15 through 21 and Figs. 24 through 30 below compare results for the whole-body dose and basal layer of the skin for methods and analogues from a point source and planar source. The bremsstrahlung dose was excluded from this comparison as the bremsstrahlung dose was low enough to not be considered in the overall radiation dose to the pangolin.

Table 15, Comparison of Calculated Whole-Body Doses to the Pangolin from a Point Source

	Absorbed Dose (mGy y⁻¹)	± 2σ (mGy y⁻¹)	Absorbed Dose (μGy h⁻¹)	± 2σ (μGy h⁻¹)
Point Source Calculation	5620	-	641	-
V+*	5900	-	673	-
MCNP Fluence (F5)	5920	1	676	1
MCNP Dose (+F6)	5550	677	633	77

* For comparison purposes, assume that 1 Sv = 1 Gy

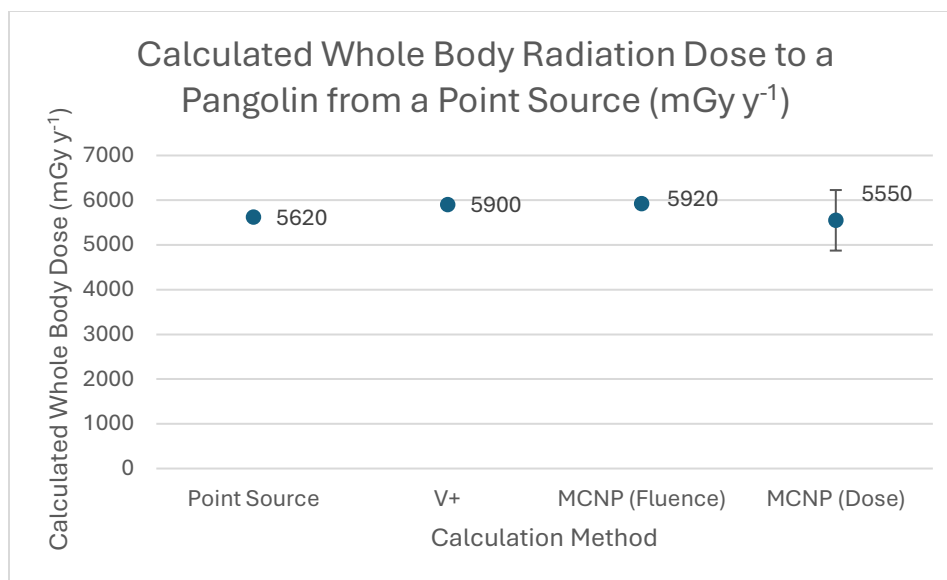


Fig. 24, Comparison of calculated whole-body dose to the pangolin from a point source

Table 16, Comparison of Calculated Whole-Body Dose to the Pangolin from a Planar Source

	Absorbed Dose (mGy y ⁻¹)	± 2σ (mGy y ⁻¹)	Absorbed Dose (μGy h ⁻¹)	± 2σ (μGy h ⁻¹)
Planar Source Calculation	549	-	62.6	-
V+ (200 cm²)*	470	-	53.6	-
MCNP Dose (+F6)	431	1	49.131	0.1
ICRP 136	649	-	74.0	-
BiotaDC	521	-	59.4	-

* For comparison purposes, assume that 1 Sv = 1 Gy

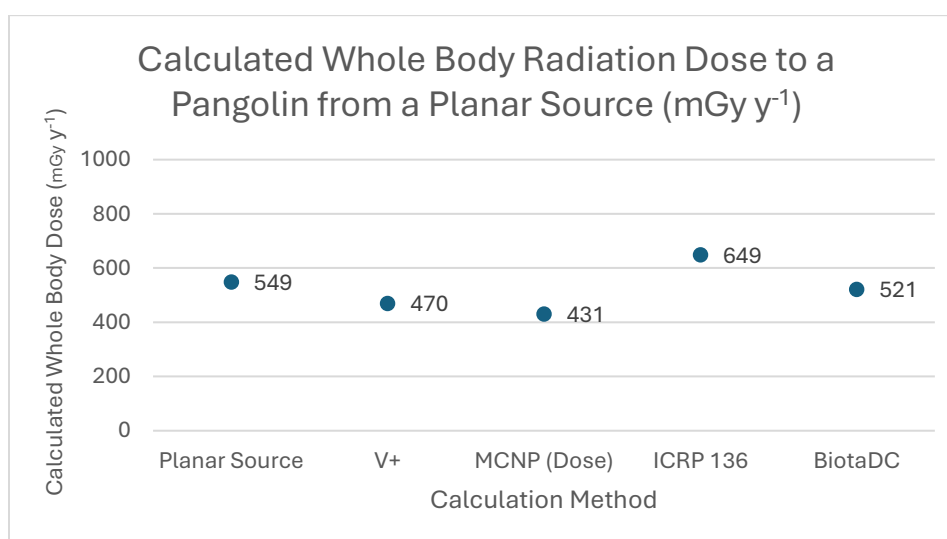


Fig. 25, Comparison of calculated whole-body dose to the pangolin from a planar source

Table 17, Comparison of Calculated, Volume-Averaged Whole-Body Dose to the Pangolin

	Absorbed Dose (mGy y ⁻¹)	± 2σ (mGy y ⁻¹)	Absorbed Dose (μGy h ⁻¹)	± 2σ (μGy h ⁻¹)
MIRD Method	217	-	24.8	-
MCNP (F6 Dose)	188	1	21.4	0.1

Fig. 26, Comparison of calculated, volume-averaged whole-body dose to the pangolin

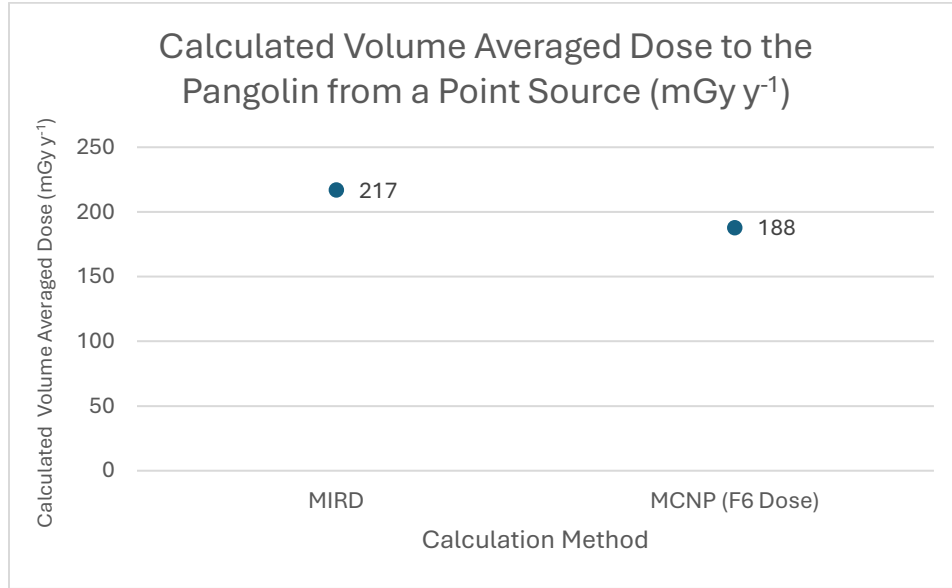


Table 18, Comparison of Pangolin Calculated Basal Layer of the Skin KERMA from a Point Source

	Absorbed Dose (mGy y ⁻¹)	± 2σ (mGy y ⁻¹)	Absorbed Dose (μGy h ⁻¹)	± 2σ (μGy h ⁻¹)
Point Source Calculation	67700	-	7723	-
MCNP Fluence (F5)	70500	6	8040	1

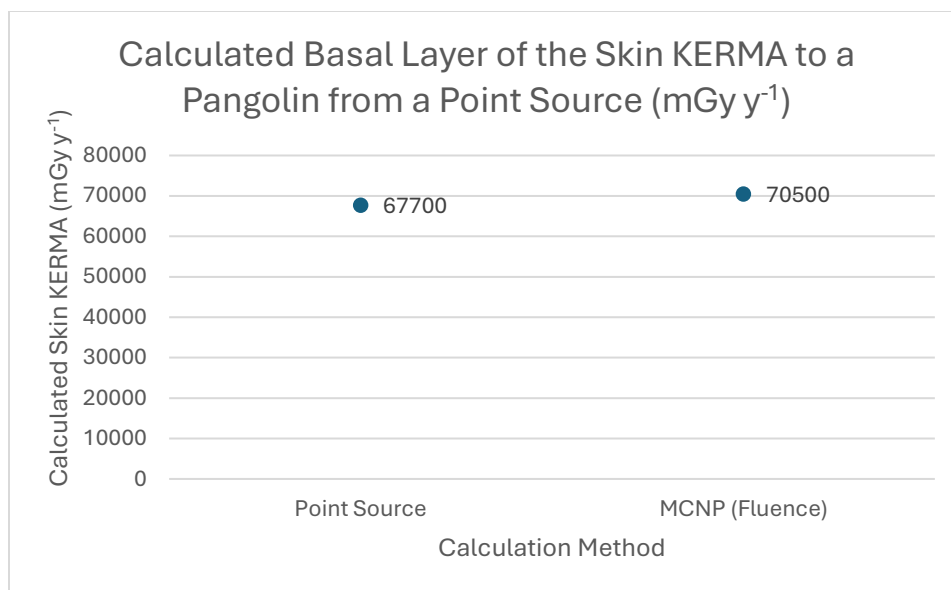


Fig. 27, Comparison of calculated basal layer of the skin KERMA to the pangolin from a point source

Table 19, Comparison of Calculated Pangolin Basal Layer of the Skin Dose from a Point Source

	Absorbed Dose (mGy y ⁻¹)	± 2σ (mGy y ⁻¹)	Absorbed Dose (μGy h ⁻¹)	± 2σ (μGy h ⁻¹)
V+*	41000	-	4680	-
Point Source Calculation (f _{cpe})	38400	-	4380	-
MCNP Dose (+F6)	38900	1950	4440	222

* For comparison purposes, assume that 1 Sv = 1 Gy

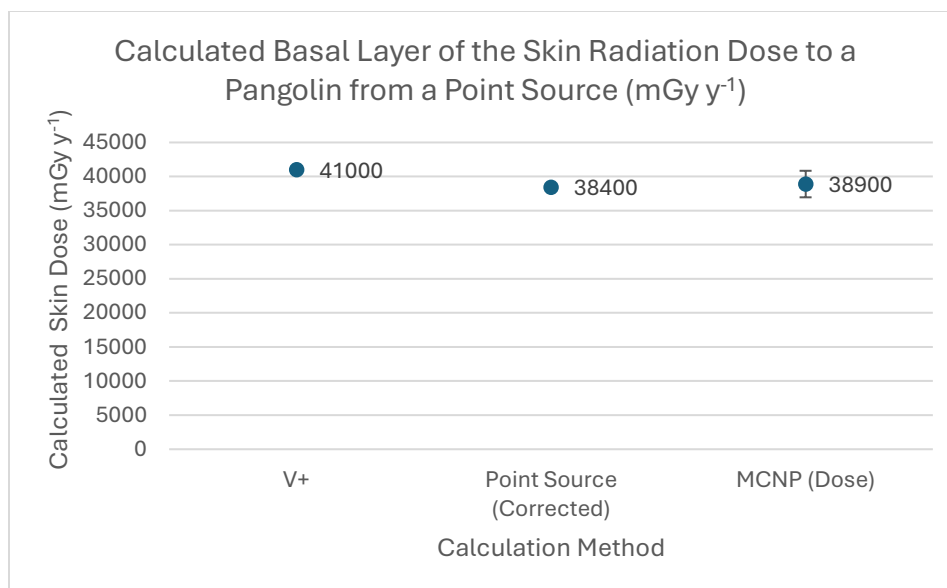


Fig. 28, Comparison of calculated basal layer of the skin dose to the pangolin from a point source

Table 20, Comparison of Calculated Pangolin Basal Layer of the Skin Dose from a Planar Source

	Absorbed Dose (mGy y ⁻¹)	± 2σ (mGy y ⁻¹)	Absorbed Dose (μGy h ⁻¹)	± 2σ (μGy h ⁻¹)
Planar Source Calculation	933	-	106	-
V+ (200 cm²)*	770	-	87.8	-
MCNP Dose (+F6 – Point)	883	7	101	1
MCNP Dose (+F6 – Disc)	840	3	95.8	0.3

* For comparison purposes, assume that 1 Sv = 1 Gy

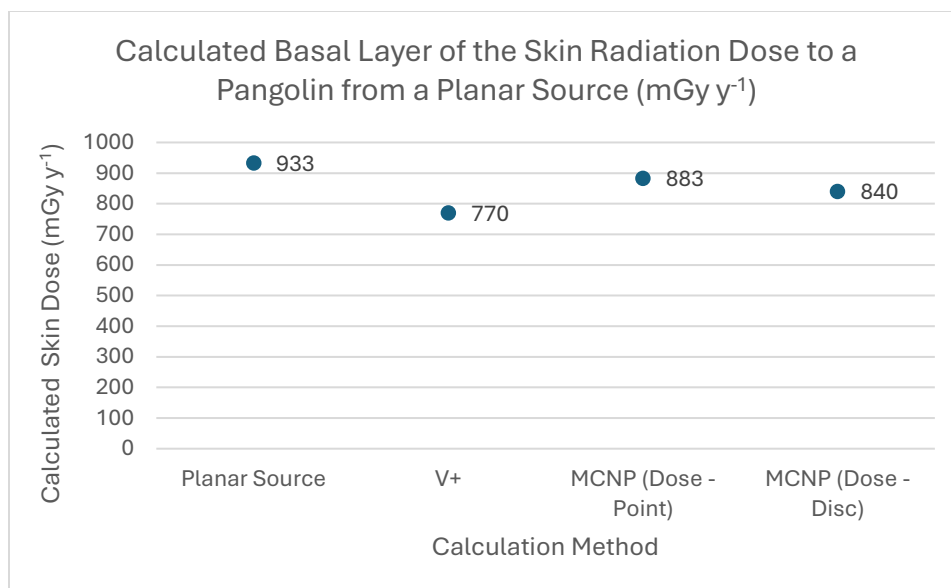


Fig. 29, Comparison of calculated basal layer of the skin dose to the pangolin from a planar source

Table 21, Comparison of Calculated Reproductive Organ Dose to the Pangolin

	Absorbed Dose (mGy y ⁻¹)	± 2σ (mGy y ⁻¹)	Absorbed Dose (μGy h ⁻¹)	± 2σ (μGy h ⁻¹)
Point Source	313	-	35.7	-
Planar Source	162	-	18.5	-

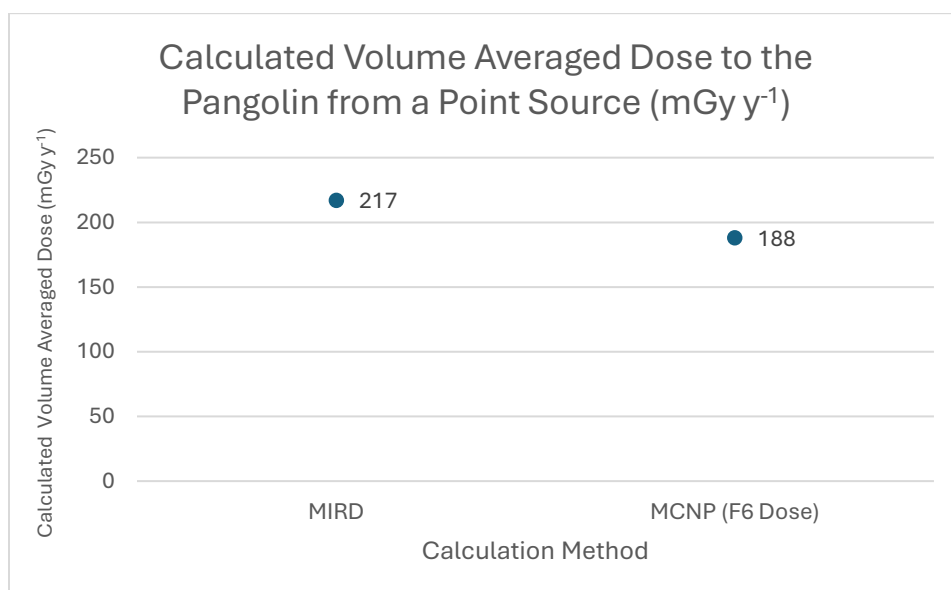


Fig. 30, Comparison of calculated reproductive organ dose to the pangolin

Recommendations

Neither the whole-body radiation dose nor the radiation dose to the basal layer of the skin met the study's dose rate goals. The application of radioactivity to pangolin scales could be feasible from a dosimetric standpoint if the shipment in bulk theory is correct by applying less radioactivity. The limiting radiation dose is the dose to the basal layer of the skin. From the basal layer of the skin dose from a planar source MCNP model using disc detectors, the initial radioactivity applied must be below 0.154 MBq to meet the DCRL goal of 350 mGy y⁻¹ (40 µGy h⁻¹) for the basal layer of the skin. The following Tables 22 and 23 and Figs. 31 and 32 below show the anticipated dose rates from application of different radioactivity concentrations to the whole body and to the basal layer of the skin of the pangolin. Reference Appendix E for full calculations.

Table 22, Potential Whole-Body Radiation Dose to the Pangolin from a Planar Source

Radioactivity (MBq)	Calculated Dose (mGy y ⁻¹)
0.37	431
0.301	350
0.2	233
0.154	180
0.1	116
0.037	43.1
0.01	11.6

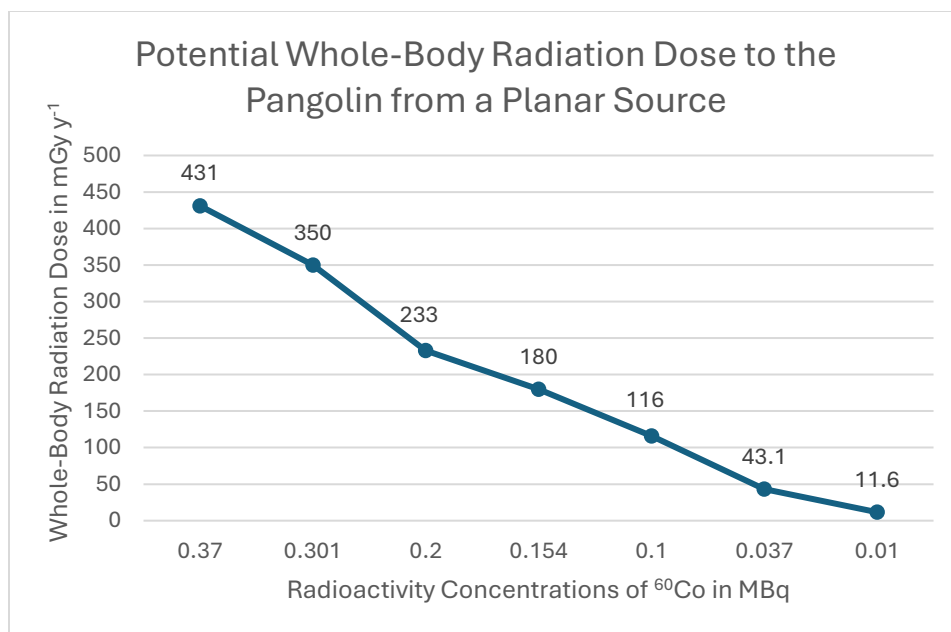


Fig. 31, Potential whole-body radiation dose to the pangolin from a planar source

Table 23, Potential Pangolin Basal Layer of the Skin Radiation Dose from a Planar Source

Radioactivity (MBq)	Calculated Dose (mGy y^{-1})
0.37	840
0.301	684
0.2	454
0.154	350
0.1	227
0.037	84.0
0.01	22.7

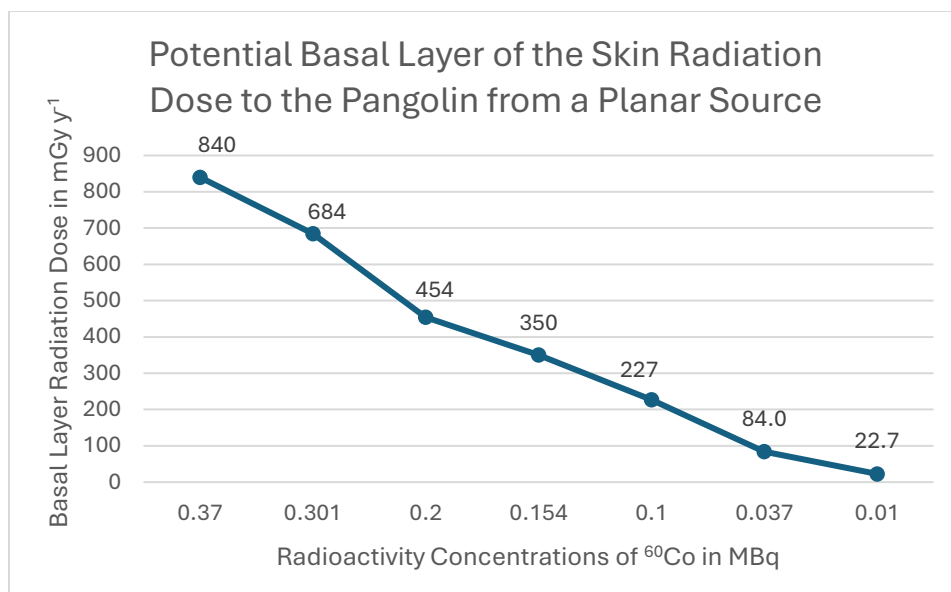


Fig. 32, Potential basal layer of the skin radiation dose to the pangolin from a planar source

For example, applying a factor of ten less radioactivity than originally used in this study, 0.037 MBq or 37 kBq, produces an expected whole-body dose to the pangolin of $43.1 \pm 0.1 \text{ mGy y}^{-1}$ and an expected basal layer of the skin dose to the pangolin of $84.0 \pm 0.3 \text{ mGy y}^{-1}$. The lower radioactivity strategy allows detection by leveraging that pangolins are generally smuggled in large groups while maintaining pangolin doses well below the dose rate goals of 350 mGy y^{-1} for the whole-body and basal layer of the skin dose.

Gamma Dose Implications

The radiation dose rate goals for both the whole body and the basal layer of the skin were not met with the 0.37 MBq of ^{60}Co used in this study, and the limiting dose is the basal layer of the skin dose. The result implies that individual deterministic effects to the basal layer of the skin may lead to detrimental effects at a population level. Using the rat RAP in ICRP 108 and ICRP 136, there is a very low probability of detrimental population effects when an individual is exposed to radiation levels at or below the DCRL, which are also this study's dose rate goal of

350 mGy y⁻¹ (40 µGy h⁻¹) for both the whole body and basal layer of the skin. For individuals exposed up to ten times the DCRL, 3,510 mGy y⁻¹ (400 µGy h⁻¹), there is a potential for reduced reproductive success due to reduced fertility in males and females. For individuals exposed from ten times the DCRL to one thousand times the DCRL, 3,510 mGy y⁻¹ – 3,510,000 mGy y⁻¹ (400 – 40,000 µGy h⁻¹), expected effects include increased morbidity, possible reduced lifespan, and reduced reproductive success. If an individual receives greater than one thousand times the DCRL, > 3,510,000 mGy y⁻¹ (40,000 µGy h⁻¹), a reduction in lifespan is expected due to various causes (ICRP 2008a). However, the exact risk to the population is not quantified and is impossible to know as this species is not well studied in general, with data from radiosensitivity experiments being nonexistent.

Extrapolating from other species, smaller mammals tend to be more radioresistant to both acute and chronic exposures to radiation than humans (Smirnova and Yonezawa 2004; Rasina et al. 2017). It is reasonable to assume that the pangolins would also be at least as radiosensitive as humans. To analyze the risk of radiation exposure above the recommended DCRL, the nominal risk coefficient for radiation detriment to humans will be used as an analogue. In ICRP 103, detriment is defined as the total harm to health to a group and its descendants from that group's radiation exposure including the development of both fatal and non-fatal cancers, the probability of severe heritable effects, and the length of potential life lost due to the development of harmful effects for a general, diverse population of all ages and sexes. The ICRP quantified the total nominal risk coefficient of radiation detriment to a human population at $574 \times 10^{-4} \text{ Sv}^{-1}$ (ICRP 2008b); meaning that in humans there is a 5.74% increased risk of health effects that impact the population per Sievert of radiation dose received over an individual's lifetime. It is reasonable to assume that a Sievert is equivalent to a Gray for purposes of defining risk to the pangolin from

the proposed chronic gamma exposure. Using the potential basal layer of the skin radiation dose as the limiting dose at the previously exemplified radioactivity level of 0.037 MBq of 84.0 ± 0.3 mGy y^{-1} , the risk of detriment to the pangolin population based on this radiation exposure is $0.482 \pm 0.001\% y^{-1}$.

As previously discussed, the average African pangolin scale shipment is 2200 kg and could represent up to 1047 individual Temminck's pangolins. On average, there are about 16.25 significant seizures of pangolin scale shipments per year in Africa alone (Nethavhani et al. 2025). It is impossible to know the exact species of the pangolins seized, but to be conservative it will be assumed that only one shipment of 1047 pangolins represent all Temminck's pangolins seized in a year. This assumption is likely a gross underestimation as it only represents about 6% of total pangolin scale seizures, but is useful as a conservative estimate for poaching risk. Assuming the highest population estimate at 32,135 individuals, the risk of death due to poaching is approximately $3.26\% y^{-1}$. Loss to the Temminck's pangolin population is equally high to death by electric fence, estimated at 1,028 animals y^{-1} , and by loss in road collisions, estimated at 280 animals y^{-1} . Annually, this is a total anthropogenic biodiversity loss to the population of 2,355 animals y^{-1} , increasing the risk of death by all anthropogenic means to $7.32\% y^{-1}$. The risk of pangolin population loss due to the proposed radiation exposure is approximately 15% of the risk of population loss due to poaching and 6% of the risk of population loss due to all anthropogenic means.

The ICRP's overarching principles of radiological protection include three steps: the principle of justification, the principle of optimization of protection, and the principle of application of dose limits. The principle of justification states that "any decision that alters the radiation exposure situation should do more good than harm". For the pangolins, this study has

shown that current conservation efforts are not enough to maintain pangolin populations and that the risk of applied radioactivity can be much lower than the risk of poaching or other anthropogenic risks depending on the amount of radioactivity applied. It can be argued that this use of radioactivity can produce more good than harm for the pangolin populations. The principle of optimization of protection means that “the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors”. Pangolins are solitary creatures with limited interactions with humans. With proper public notice, local populations will be aware that encountering a pangolin could potentially expose the public to unnecessary doses of radiation. Finally, the principle of application of dose limits was accomplished with this study. The ICRP states that by following this principle, “the total dose to any individual...should not exceed the appropriate limits recommended by the [ICRP]” (ICRP 2008b).

Potential Sources of Error

Several assumptions have been made to consider radiation dose to the pangolin. Firstly, it is assumed that radioactivity can be applied at an equal concentration across 200 cm². It is assumed that DMSO can successfully ligand with ⁶⁰Co and transport the ⁶⁰Co approximately 50 µm into the scales. The scale thickness of a Temminck’s pangolin is assumed to be approximately 3 mm thick at the application site. The reference Temminck’s pangolin is assumed to be approximately 6 kg in mass. Additionally, radiological decay was not factored into any dose equations; the reported dose to the pangolin is the highest expected dose without any radiological decay. Since the wear and growth rate of the pangolin scales is unknown, any removal of radioactivity from natural wear on the scales was also not considered. The

reproductive organs of the pangolin were not positively identified, but were assumed to be in the lower abdomen. Any difference in these assumptions are potential sources of error in the calculations of radiation dose to the pangolin.

Further Research

Before the project can be brought into reality, there are several other areas of research that must be explored. Whether or not ^{60}Co can successfully bind with DMSO must be researched, then it must be understood how deeply the DMSO/ ^{60}Co blend will penetrate a pangolin scale. Application methods of the DMSO/ ^{60}Co blend must be investigated that can apply an even concentration of radioactivity across the area while not aerosolizing the compound, which would create an internal radiation hazard to both the pangolin and the applicator. DMSO and radiation can both cause structural changes to the keratin structure of the pangolin scale. The potential effects of these changes must be investigated to ensure that the application of the DMSO/ ^{60}Co blend does not degrade the pangolin scale and make the pangolin more susceptible to predation, scale breakage, or infection. The radiation dose to the pangolin pups must also be investigated since the pangolin pups ride on their mothers' backs for up to two years, and their vulnerable underbellies without keratinous scales will be in contact with the DMSO/ ^{60}Co blend. Finally, the pangolin scale wear and growth rate must be better understood to know how long the DMSO/ ^{60}Co blend will remain on the pangolin to determine potential reapplication timelines and if significant amounts will escape into the environment

CONCLUSION

If radioactivity can reliably and uniformly be applied to the pangolin scale at a depth of 0.050 mm without negatively impacting the integrity of the scale, a detectible amount of ^{60}Co radioactivity from a single animal may still be detrimental to both an individual pangolin and the pangolin population. It is recommended to utilize a lower activity concentration of ^{60}Co and to rely on detecting bulk shipments to prevent harm to the pangolin population.

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APPENDIX A

The images in Appendix A were obtained from the 3D Slicer program, and show different angles, renderings, and measurements of the pangolin used in calculating radiation dose to the pangolin.



Fig. A.1, Pangolin scale thickness (3.456 mm)



Fig. A.2, Image of closest distance from tail to center mass (95.24 mm) and unoccupied space (35.76 mm) for distance correction

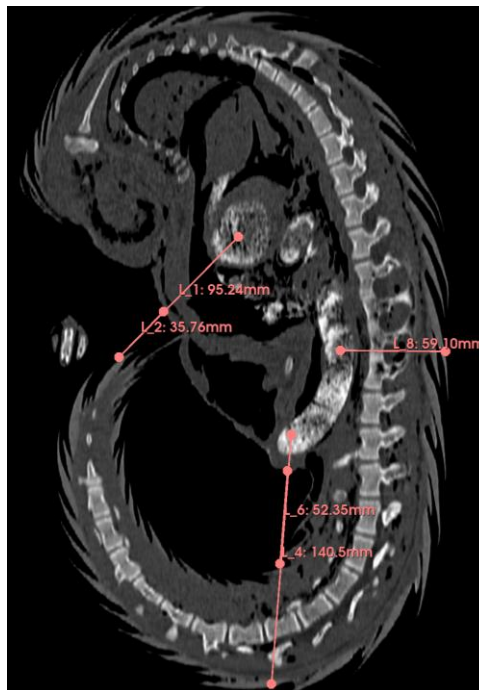


Fig. A.3, Image of closest distance from back scale to potential reproductive organs (59.10 mm) and closest distance from tail to reproductive organs (140.5 mm) and unoccupied space (52.35 mm) for distance correction



Fig. A.4, Image of empty space for removal in pangolin height measurement

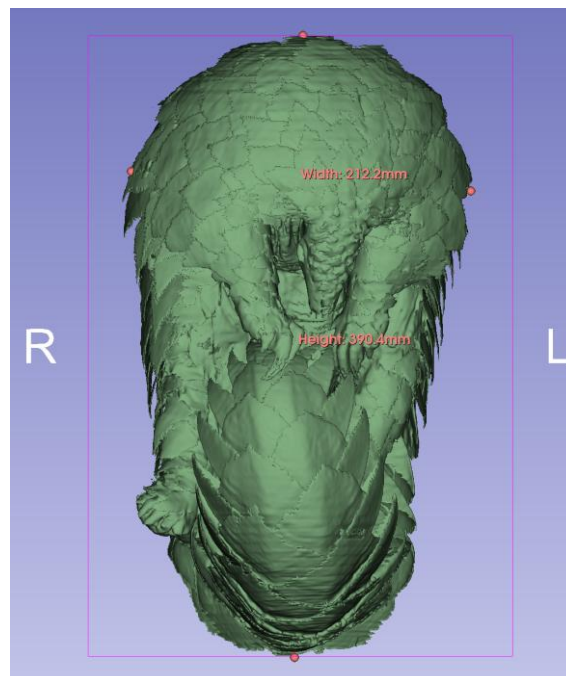


Fig. A.5, Anterior-posterior view of pangolin showing maximum width (212.2 mm) and height (390.4 mm)

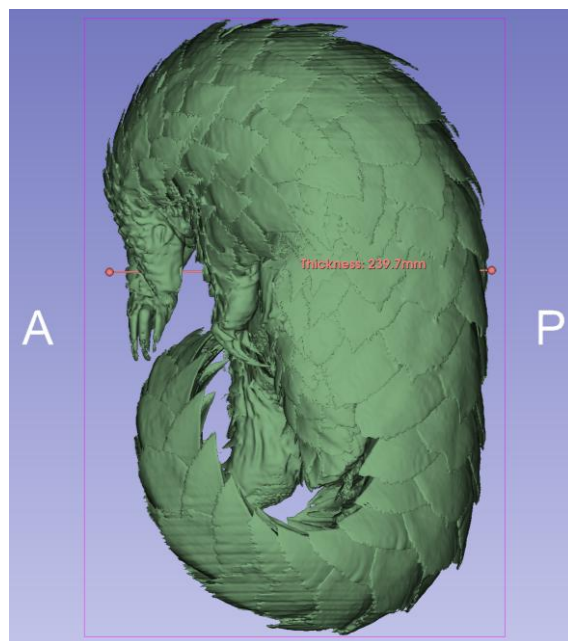


Fig. A.6, Left lateral view of pangolin showing maximum thickness (239.7 mm)



Fig. A.7, Anterior-posterior view of pangolin showing potential 10 cm x 20 cm application area on the tail

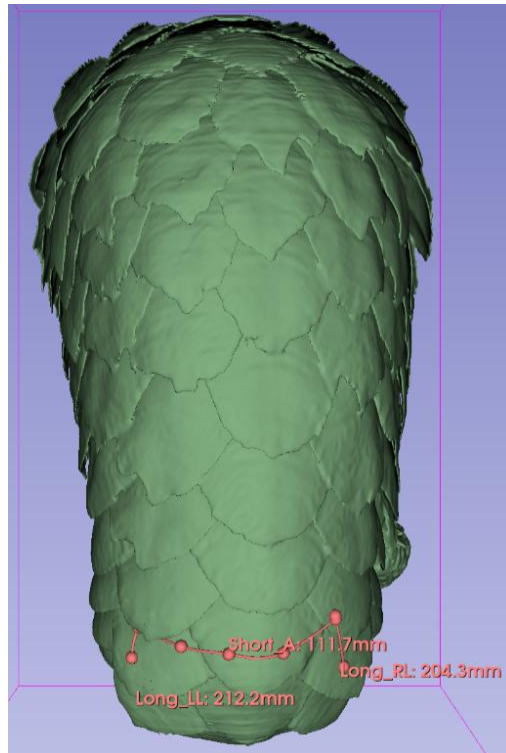


Fig. A.8, Posterior-anterior view of pangolin showing potential 10 cm x 20 cm application area on the tail

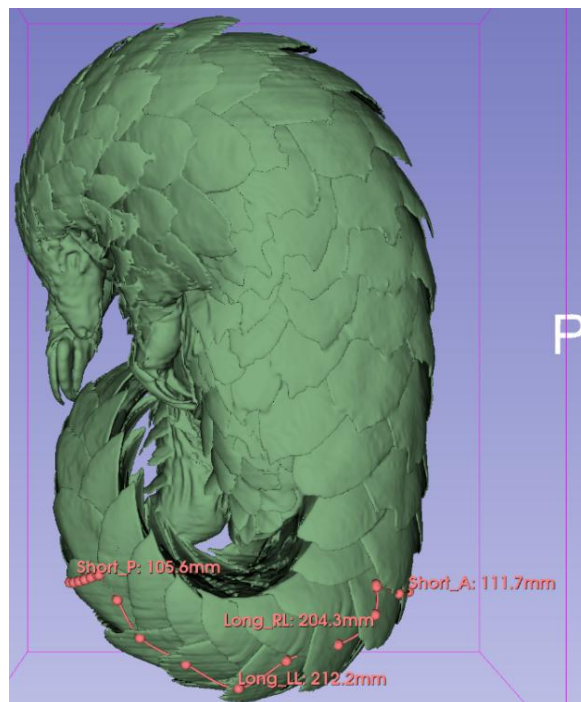


Fig. A.9, Left lateral view of pangolin showing potential 10 cm x 20 cm application area on the tail

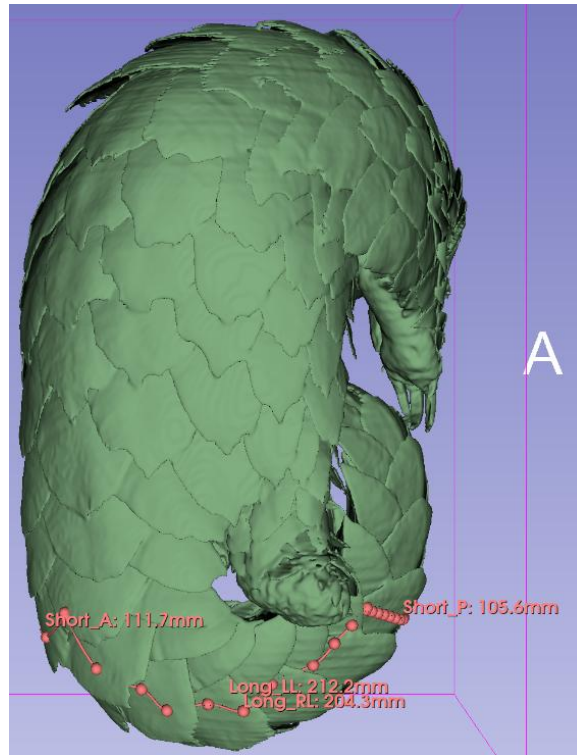


Fig. A.10, Right lateral view of pangolin showing potential 10 cm x 20 cm application area on the tail

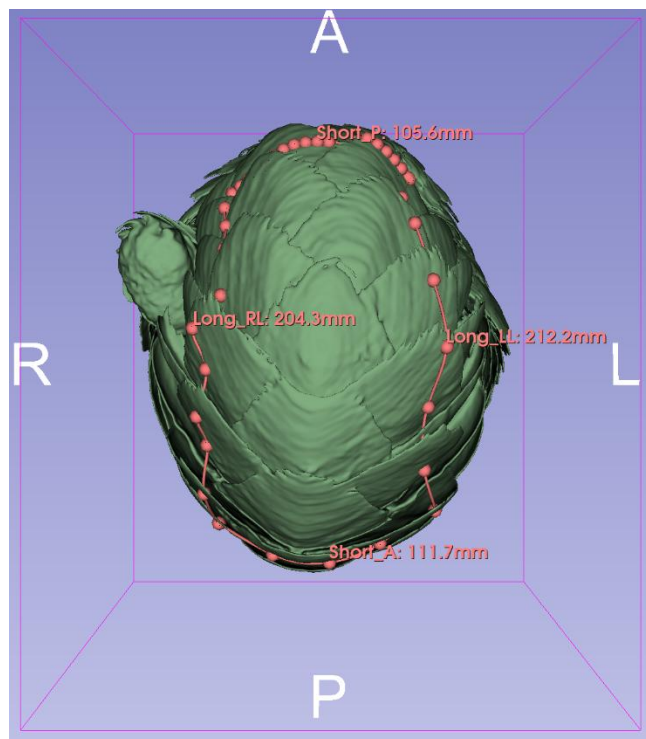


Fig. A.11, Inferior view of pangolin showing potential 10 cm x 20 cm application area on the tail

APPENDIX B

Appendix B shows calculations and supplemental material for first principles calculations.

Bethe-Bloch Equation

Soft Tissue

Linear rate of energy loss calculated using Bethe-Bloch equation in keratin:

$$\frac{dE}{dx} = \frac{2\pi q^4 N Z (3 \times 10^9)^4}{E_m \beta^2 (1 \times 10^{-6})^2} \left(\ln \left(\frac{E_m E_k \beta^2}{I^2 (1 - \beta^2)} \right) - \beta^2 \right) \text{MeV cm}^{-1}$$

Where:

$$q = \text{charge of the electron} = 1.602 \times 10^{-19} \text{ C}$$

$$N = \text{number of absorber atoms cm}^{-3} = 9 \times 10^{22} \frac{\text{atoms}}{\text{cm}^3} \text{ soft tissue}$$

$$Z = \text{atomic number of the absorber} = 6.82$$

$$E_m = \text{electron mass energy} = 0.511 \text{ MeV}$$

$$E_k = \text{kinetic energy of beta particles} = 0.318 \text{ MeV from } ^{60}\text{Co}$$

$$\beta = v/c = \text{ratio of particle's velocity to the speed of light} = 0.788$$

$$I = \text{mean ionization and excitation potential in MeV} = 0.00007459 \text{ MeV}$$

Supporting calculations of values:

- N: The number of soft tissue atoms cm^{-3} is given as $9 \times 10^{22} \frac{\text{atoms}}{\text{cm}^3}$ soft tissue (Johnson 2017).

$$\text{Soft tissue } \frac{\text{atoms}}{\text{cm}^3} = 9 \times 10^{25} \frac{\text{atoms}}{\text{kg}} \cdot \frac{1 \text{ kg}}{1000 \text{ g}} \cdot \frac{1.0 \text{ g}}{\text{cm}^3} = 9 \times 10^{22} \frac{\text{atoms}}{\text{cm}^3} \text{ soft tissue}$$

- Z: The effective atomic number (Z_{eff}) of soft tissue is calculated as 6.82 by elemental composition (ibid.)

$$Z_{eff} = \sum_i (n_i \times Z_i)$$

Where:

n_i = number of atoms of element per molecule

Z_i = atomic number

Table B-1, Calculated Effective Atomic Number by Elemental Composition

Element	Atomic Number	ICRP Soft Tissue	$n_i \times Z_i$
H	1	0.104472	0.104472
C	6	0.23219	1.39314
N	7	0.02488	0.17416
O	8	0.630238	5.041904
Na	11	0.00113	0.01243
Mg	12	0.00013	0.00156
P	15	0.00133	0.01995
S	16	0.00199	0.03184
Cl	17	0.00134	0.02278
K	19	0.00199	0.03781
Ca	20	0.00023	0.0046
Fe	26	0.00005	0.0013
Zn	30	0.00003	0.0009
Sum			6.846846

- β : In terms of relativity, $\beta = \frac{v}{c}$. The value for β is calculated as 0.788.

$$m_e c^2 = 0.511 \text{ MeV (rest mass energy of an electron)}$$

$$\text{Kinetic energy (K) of Co - 60 beta particle} = 0.318 \text{ MeV}$$

$$\text{Total Energy (E)} = K + \text{Rest Mass Energy} = 0.829 \text{ MeV}$$

$$\frac{v}{c} = \sqrt{1 - \left(\frac{m_e c^2}{E}\right)^2}$$

$$\frac{v}{c} = \sqrt{1 - \left(\frac{0.511 \text{ MeV}}{0.829 \text{ MeV}}\right)^2} = 0.788$$

- I: The ionization potential of soft tissue is approximately that of water and is given as 0.00007459 MeV (ibid.)

$$\frac{dE}{dx} = \frac{2\pi q^4 N Z \cdot (3 \times 10^9)^4}{E_m \beta^2 (1 \times 10^{-6})^2} \left(\ln \left(\frac{E_m E_k \beta^2}{I^2 (1 - \beta^2)} \right) - \beta^2 \right) \text{MeV cm}^{-1} = 11.47 \frac{\text{MeV}}{\text{cm}}$$

The linear rate of energy loss of ^{60}Co beta particles in soft tissue is $11.47 \text{ MeV cm}^{-1}$. The range the beta particles will travel in soft tissue is calculated by dividing the maximum beta particle energy by the linear rate of energy loss calculated for soft tissue.

$$\text{Range} = \frac{\text{Max } E}{\left(\frac{dE}{dx}\right)} = \frac{0.318 \text{ MeV}}{11.47 \frac{\text{MeV}}{\text{cm}}} = 0.0277 \text{ cm or } 0.277 \text{ mm}$$

The beta particles from ^{60}Co will travel approximately 0.277 mm into keratin.

Keratin

Linear rate of energy loss calculated using Bethe-Bloch equation in keratin:

$$\frac{dE}{dx} = \frac{2\pi q^4 N Z \cdot (3 \times 10^9)^4}{E_m \beta^2 (1 \times 10^{-6})^2} \left(\ln \left(\frac{E_m E_k \beta^2}{I^2 (1 - \beta^2)} \right) - \beta^2 \right) \text{MeV cm}^{-1}$$

Where:

$$q = \text{charge of the electron} = 1.602 \times 10^{-19} \text{ C}$$

$$N = \text{number of absorber atoms cm}^{-3} = 1.494 \times 10^{19} \frac{\text{atoms}}{\text{cm}^3}$$

$$Z = \text{atomic number of the absorber} = 7.5$$

$$E_m = \text{electron mass energy} = 0.511 \text{ MeV}$$

$$E_k = \text{kinetic energy of beta particles} = 0.318 \text{ MeV from } ^{60}\text{Co}$$

$$\beta = v/c = \text{ratio of particle's velocity to the speed of light} = 0.788$$

$$I = \text{mean ionization and excitation potential in MeV} = 0.00007459 \text{ MeV}$$

Supporting calculations of values:

- $\text{Keratin} \frac{\text{atoms}}{\text{cm}^3} = \frac{1 \text{ mol}}{54,000 \text{ g}} \cdot \frac{6.022 \times 10^{23} \text{ atoms}}{1 \text{ mol}} \cdot \frac{1.34 \text{ g}}{\text{cm}^3} = 1.494 \times 10^{19} \frac{\text{atoms}}{\text{cm}^3} \text{ keratin}$
- Z : The effective atomic number (Z_{eff}) of keratin using human fingernails as an analogue is 7.5 (Almugren et al. 2024; Katsikini et al. 2010).
- β : In terms of relativity, $\beta = \frac{v}{c}$. The value for β is calculated as 0.788.

$$m_e c^2 = 0.511 \text{ MeV (rest mass energy of an electron)}$$

$$\text{Kinetic energy (K) of Co – 60 beta particle} = 0.318 \text{ MeV}$$

$$\text{Total Energy (E)} = K + \text{Rest Mass Energy} = 0.829 \text{ MeV}$$

$$\frac{v}{c} = \sqrt{1 - \left(\frac{m_e c^2}{E}\right)^2}$$

$$\frac{v}{c} = \sqrt{1 - \left(\frac{0.511 \text{ MeV}}{0.829 \text{ MeV}}\right)^2} = 0.788$$

- I: The ionization potential of keratin is approximately that of water and is given as 0.00007459 MeV (ibid.)

$$\frac{dE}{dx} = \frac{2\pi q^4 N Z \cdot (3 \times 10^9)^4}{E_m \beta^2 (1 \times 10^{-6})^2} \left(\ln \left(\frac{E_m E_k \beta^2}{I^2 (1 - \beta^2)} \right) - \beta^2 \right) \text{ MeV cm}^{-1} = 17.06 \frac{\text{MeV}}{\text{cm}}$$

The linear rate of energy loss of ^{60}Co beta particles in keratin is $17.06 \text{ MeV cm}^{-1}$. The range the beta particles will travel in keratin is calculated by dividing the maximum beta particle energy by the linear rate of energy loss calculated for keratin.

$$\text{Range} = \frac{\text{Max } E}{\left(\frac{dE}{dx}\right)} = \frac{0.318 \text{ MeV}}{17.06 \frac{\text{MeV}}{\text{cm}}} = 0.0186 \text{ cm or } 0.186 \text{ mm}$$

The beta particles from ^{60}Co will travel approximately 0.186 mm into keratin.

Empirical Range Formula

Soft Tissue

$$R = \frac{0.407 E^{1.38}}{\rho}$$

Where:

$$E = \text{energy of beta particle in MeV} = 0.318 \text{ MeV}$$

$$\rho = \text{material density} = 1 \text{ g cm}^{-3} \text{ for soft tissue}$$

$$R = \frac{0.407 (0.318 \text{ MeV})^{1.38}}{1 \frac{\text{g}}{\text{cm}^3}} = 0.0837 \text{ cm or } 0.837 \text{ mm}$$

The range of ^{60}Co beta particles in soft tissue is 0.848 mm.

Keratin

$$R = \frac{0.407E^{1.38}}{\rho}$$

Where:

E = energy of beta particle in MeV = 0.318 MeV

ρ = material density = 1.34 g cm^{-3} for keratin

$$R = \frac{0.407(0.318 \text{ MeV})^{1.38}}{1.34 \frac{\text{g}}{\text{cm}^3}} = 0.0625 \text{ cm or } 0.625 \text{ mm}$$

The range of ^{60}Co beta particles in keratin is 0.625 mm.

Air

$$R = \frac{0.407E^{1.38}}{\rho}$$

Where:

E = energy of beta particle in MeV = 0.318 MeV

ρ = material density = $0.001292 \text{ g cm}^{-3}$ for air

$$R = \frac{0.407(0.318 \text{ MeV})^{1.38}}{0.001292 \frac{\text{g}}{\text{cm}^3}} = 64.82 \text{ cm or } 648.2 \text{ mm}$$

The range of ^{60}Co beta particles in air is 64.82 cm or 648.2 mm.

Bremsstrahlung Dose

Whole Body

$$\dot{D} = \frac{f \cdot A \cdot E \cdot \mu_l}{\rho \cdot 4\pi d^2}$$

Where:

f_β = fraction of beta particle energy converted to bremsstrahlung = 0.00083475

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} = 3.7 \times 10^5 \frac{\text{decays}}{\text{s}}$$

$$E_m = \text{maximum beta energy of the beta particle} = 0.318 \text{ MeV}$$

$$\mu_l = \text{linear energy absorption coefficient} = 3.164 \text{ m}^{-1}$$

$$\rho = \text{material density in } \frac{\text{kg}}{\text{m}^3} = 1000 \frac{\text{kg}}{\text{m}^3}$$

$$d = \text{dosimetric depth for the whole body} = 1.395 \text{ cm}$$

Supporting calculations of values:

$$- f_\beta = 3.5 \times 10^{-4} Z E_m$$

Where:

$$Z_{eff} = \text{effective atomic number of the absorber} = 7.5$$

$$- \mu_l = \text{linear energy absorption coefficient for the quantum energy of the bremsstrahlung.}$$

For tissue at 0.3 MeV the mass energy absorption coefficient, $\frac{\mu_a}{\rho}$, is $0.03164 \frac{\text{cm}^2}{\text{g}}$ (ibid.)

To find the linear energy absorption coefficient, the mass energy absorption coefficient is multiplied by the tissue density of $1 \frac{\text{g}}{\text{cm}^3}$ and converted to m^{-1} .

$$\mu_l = 0.03164 \frac{\text{cm}^2}{\text{g}} \cdot 1 \frac{\text{g}}{\text{cm}^3} \cdot \frac{100 \text{ cm}}{1 \text{ m}} = 3.164 \text{ m}^{-1}$$

$$- \rho = \text{material density in } \frac{\text{kg}}{\text{m}^3} = 1 \frac{\text{g}}{\text{cm}^3} \cdot \frac{1 \text{ kg}}{1000 \text{ g}} \cdot \frac{1 \text{ cm}^3}{1 \times 10^{-6} \text{ m}^3} = 1000 \frac{\text{kg}}{\text{m}^3}$$

$$\dot{D} = \frac{0.00083475 \cdot 3.7 \times 10^5 \frac{\text{decays}}{\text{s}} \cdot 0.318 \frac{\text{MeV}}{\text{decay}} \cdot 3.164 \text{ m}^{-1} \cdot 1.6 \times 10^{-13} \frac{\text{J}}{\text{MeV}} \cdot 86400 \frac{\text{s}}{\text{d}} \cdot 365.25 \frac{\text{d}}{\text{y}}}{1000 \frac{\text{kg}}{\text{m}^3} \cdot 4\pi(1.395)^2 \cdot 1 \frac{\text{kg}}{\text{Gy}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}} =$$

$$6.42 \times 10^{-5} \frac{\text{mGy}}{\text{y}} \text{ or } 7.32 \times 10^{-6} \frac{\mu\text{Gy}}{\text{h}}.$$

Basal Layer of the Skin

$$\dot{D} = \frac{f \cdot A \cdot E \cdot \mu_l}{\rho \cdot 4\pi d^2}$$

Where:

$$f_{\beta} = \text{fraction of beta particle energy converted to bremsstrahlung} = 0.00083475$$

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} = 3.7 \times 10^5 \frac{\text{decays}}{\text{s}}$$

$$E_m = \text{maximum beta energy of the beta particle} = 0.318 \text{ MeV}$$

$$\mu_l = \text{linear energy absorption coefficient} = 3.164 \text{ m}^{-1}$$

$$\rho = \text{material density in } \frac{\text{kg}}{\text{m}^3} = 1000 \frac{\text{kg}}{\text{m}^3}$$

$$d = \text{dosimetric depth for the basal layer of the skin} = 0.402 \text{ cm}$$

Supporting calculations of values:

$$- f_{\beta} = 3.5 \times 10^{-4} Z E_m$$

Where:

$$Z_{eff} = \text{effective atomic number of the absorber} = 7.5$$

$$- \mu_l = \text{linear energy absorption coefficient for the quantum energy of the bremsstrahlung.}$$

For tissue at 0.3 MeV the mass energy absorption coefficient, $\frac{\mu_a}{\rho}$, is $0.03164 \frac{\text{cm}^2}{\text{g}}$ (ibid.).

To find the linear energy absorption coefficient, the mass energy absorption coefficient is multiplied by the tissue density of $1 \frac{\text{g}}{\text{cm}^3}$ and converted to m^{-1} .

$$\mu_l = 0.03164 \frac{\text{cm}^2}{\text{g}} \cdot 1 \frac{\text{g}}{\text{cm}^3} \cdot \frac{100 \text{ cm}}{1 \text{ m}} = 3.164 \text{ m}^{-1}$$

$$- \rho = \text{material density in } \frac{\text{kg}}{\text{m}^3} = 1 \frac{\text{g}}{\text{cm}^3} \cdot \frac{1 \text{ kg}}{1000 \text{ g}} \cdot \frac{1 \text{ cm}^3}{1 \times 10^{-6} \text{ m}^3} = 1000 \frac{\text{kg}}{\text{m}^3}$$

$$\dot{D} = \frac{0.00083475 \cdot 3.7 \times 10^5 \frac{\text{decays}}{\text{s}} \cdot 0.318 \frac{\text{MeV}}{\text{decay}} \cdot 3.164 \text{ m}^{-1} \cdot 1.6 \times 10^{-13} \frac{\text{J}}{\text{MeV}} \cdot 86400 \frac{\text{s}}{\text{d}} \cdot 365.25 \frac{\text{d}}{\text{y}}}{1000 \frac{\text{kg}}{\text{m}^3} \cdot 4\pi(0.402)^2 \cdot 1 \frac{\text{kg}}{\text{Gy}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}} =$$

$$7.73 \times 10^{-4} \frac{\text{mGy}}{\text{y}} \text{ or } 8.82 \times 10^{-5} \frac{\mu\text{Gy}}{\text{h}}.$$

Dosimetric Point Source Calculations

Whole Body

$$\dot{D} = \varphi E \frac{\mu_{en}}{\rho}$$

Where:

$$\varphi = \text{particle fluence rate in particles s}^{-1} \text{ cm}^{-1} = 30260 \frac{\gamma}{\text{s} \cdot \text{cm}^2}$$

$$E = \text{energy photon}^{-1} \text{ in MeV photon}^{-1} = 1.25 \frac{\text{MeV}}{\text{photon}}$$

$$\frac{\mu_{en}}{\rho} = \frac{0.02938 \text{ cm}^2}{\text{g}}; \text{ the mass attenuation coefficient for soft tissue at 1.25 MeV}$$

(Johnson 2017)

Supporting calculations of values:

$$- \quad \varphi = \frac{A \cdot \gamma}{4\pi r^2} = 30260 \frac{\gamma}{\text{s} \cdot \text{cm}^2}$$

Where:

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} = 3.7 \times 10^5 \frac{\text{decays}}{\text{s}}$$

$$\gamma = \text{photons decay}^{-1} = 2 \frac{\gamma}{\text{decay}}; {}^{60}\text{Co emits two photons decay}^{-1}$$

$$r = \text{dosimetric depth for the whole body of the pangolin} = 1.395 \text{ cm}$$

- E: ${}^{60}\text{Co}$ photons are 1.173 MeV, emitted following 99.85% of decays, and 1.332 MeV, emitted following 99.98% of decays. The average gamma energy is $1.25 \frac{\text{MeV}}{\text{photon}}$.
- $\frac{\mu_{en}}{\rho}$: the mass attenuation coefficient for soft tissue at 1.25 MeV is $\frac{0.02938 \text{ cm}^2}{\text{g}}$ (ibid.)

$$\dot{D} = \frac{30260 \frac{\text{photons}}{\text{s} \cdot \text{cm}^2} \cdot 1.25 \frac{\text{MeV}}{\text{photon}} \cdot \frac{0.02938 \text{ cm}^2}{\text{g}} \cdot 10^3 \frac{\text{g}}{\text{kg}} \cdot 1.602 \times 10^{-13} \frac{\text{J}}{\text{MeV}} \cdot 86400 \frac{\text{s}}{\text{d}} \cdot 365.25 \frac{\text{day}}{\text{y}}}{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}} =$$

$$5620 \frac{\text{mGy}}{\text{y}} \text{ or } 641 \frac{\mu\text{Gy}}{\text{h}}.$$

Basal Layer of the Skin

The dose rate formula was modified to read KERMA rate as this is truly a collision KERMA calculation. The charged particle disequilibrium and averaging area corrections are then applied to arrive at absorbed dose.

$$\dot{K} = \varphi E \frac{\mu_{en}}{\rho}$$

Where:

$$\varphi = \text{particle fluence rate in particles s}^{-1} \text{ cm}^{-2} = 3.644 \times 10^5 \frac{\gamma}{\text{s} \cdot \text{cm}^2}$$

$$E = \text{energy photon}^{-1} \text{ in MeV photon}^{-1} = 1.25 \frac{\text{MeV}}{\text{photon}}$$

$$\frac{\mu_{en}}{\rho} = \frac{0.02938 \text{ cm}^2}{\text{g}}; \text{ the mass attenuation coefficient for soft tissue at 1.25 MeV}$$

(ibid.)

Supporting calculations of values:

$$\varphi = \frac{A \cdot \gamma}{4\pi r^2} = 3.644 \times 10^5 \frac{\gamma}{\text{s} \cdot \text{cm}^2}$$

Where:

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} = 3.7 \times 10^5 \frac{\text{decays}}{\text{s}}$$

$$\gamma = \text{photons decay}^{-1} = 2 \frac{\gamma}{\text{decay}}; {}^{60}\text{Co emits two photons decay}^{-1}$$

$$r = \text{dosimetric depth for the basal layer of the skin of the pangolin} = 0.402 \text{ cm}$$

- E: ${}^{60}\text{Co}$ photons are 1.173 MeV, emitted following 99.85% of decays, and 1.332 MeV, emitted following 99.98% of decays. The average gamma energy is $1.25 \frac{\text{MeV}}{\text{photon}}$.

- $\frac{\mu_{en}}{\rho}$: the mass attenuation coefficient for soft tissue at 1.25 MeV is $\frac{0.02938 \text{ cm}^2}{\text{g}}$ (ibid.)

$$\dot{K} = \frac{3.644 \times 10^5 \frac{\gamma}{s \cdot cm^2} \cdot 1.25 \frac{MeV}{photon} \cdot \frac{0.02938 cm^2}{g} \cdot 10^3 \frac{g}{kg} \cdot 1.602 \times 10^{-13} \frac{J}{MeV} \cdot 86400 \frac{s}{d} \cdot 365.25 \frac{d}{y}}{\frac{\frac{J}{kg}}{Gy} \cdot \frac{10^{-3} Gy}{mGy}} =$$

$$67700 \frac{mGy}{y} \text{ or } 7720 \frac{\mu Gy}{h}.$$

The fraction of charged particle equilibrium correction is calculated below using empirical values founded in the NRC V+ SkinDose Manual (Hamby 2024).

$$f_{cpe}(E, d) = \frac{D}{K}$$

Supporting calculations of values:

$$f_{cpe}(d) = \frac{1}{a+b \cdot \ln(x) + \frac{c}{\sqrt{x}}}$$

Where:

$$a = 19.78 + 0.1492E \ln E - 0.008390E^{1.5} + 0.00003624 E^2 + 3.343 \sqrt{E} \ln E -$$

$$\frac{10.72E}{\ln E} = -0.7959$$

$$b = 0.217 \times 10^{-12}E^4 - 5.673 \times 10^{-9}E^3 + 7.942 \times 10^{-6}E^2 - 0.002028E +$$

$$0.3296 = 2.095$$

$$c = 9.694 \times 10^{-13}E^4 - 4.861 \times 10^{-9}E^3 + 7.765 \times 10^{-6}E^2 - 0.001856E +$$

$$0.1467 = 2.832$$

x = point kernel distance between source point and dose point in cm = 0.402 cm

E = photon energy in keV = 1250 keV

$$f_{cpe}(d) = \frac{1}{279.407 + 2.095 \cdot \ln(0.402) + \frac{2.832}{\sqrt{0.402}}} = 0.5677$$

$$0.5677 = \frac{D}{67654.709 \frac{mGy}{y}} = 38400 \frac{mGy}{y} \text{ or } 4380 \frac{\mu Gy}{h}.$$

Reproductive Organs

$$\dot{D} = \varphi E \frac{\mu_{en}}{\rho}$$

Where:

$$\varphi = \text{particle fluence rate in particles s}^{-1} \text{ cm}^{-1} = 30260 \frac{\gamma}{\text{s} \cdot \text{cm}^2}$$

$$E = \text{energy photon}^{-1} \text{ in MeV photon}^{-1} = 1.25 \frac{\text{MeV}}{\text{photon}}$$

$$\frac{\mu_{en}}{\rho} = \frac{0.02938 \text{ cm}^2}{\text{g}}; \text{ the mass attenuation coefficient for soft tissue at 1.25 MeV}$$

(Johnson 2017)

Supporting calculations of values:

$$- \quad \varphi = \frac{A \cdot \gamma}{4\pi r^2} = 1686 \frac{\gamma}{\text{s} \cdot \text{cm}^2}$$

Where:

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} = 3.7 \times 10^5 \frac{\text{decays}}{\text{s}}$$

$$\gamma = \text{photons decay}^{-1} = 2 \frac{\gamma}{\text{decay}}; {}^{60}\text{Co emits two photons decay}^{-1}$$

$$r = \text{dosimetric depth for the pangolin's reproductive organs} = 5.91 \text{ cm}$$

- E: ${}^{60}\text{Co}$ photons are 1.173 MeV, emitted following 99.85% of decays, and 1.332 MeV, emitted following 99.98% of decays. The average gamma energy is $1.25 \frac{\text{MeV}}{\text{photon}}$.

- $\frac{\mu_{en}}{\rho}$: the mass attenuation coefficient for soft tissue at 1.25 MeV is $\frac{0.02938 \text{ cm}^2}{\text{g}}$ (ibid.)

$$\dot{D} = \frac{1686 \frac{\text{photons}}{\text{s} \cdot \text{cm}^2} \cdot 1.25 \frac{\text{MeV}}{\text{photon}} \cdot \frac{0.02938 \text{ cm}^2}{\text{g}} \cdot 10^3 \frac{\text{g}}{\text{kg}} \cdot 1.602 \times 10^{-13} \frac{\text{J}}{\text{MeV}} \cdot 86400 \frac{\text{s}}{\text{d}} \cdot 365.25 \frac{\text{day}}{\text{y}}}{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}} =$$

$$313 \frac{\text{mGy}}{\text{y}} \text{ or } 35.7 \frac{\mu\text{Gy}}{\text{h}}.$$

Dosimetric Planar Source Calculations

Whole Body

$$\dot{D} = \pi \Gamma C_a \ln \left(\frac{R^2 + h^2}{h^2} \right)$$

Where:

R = radius for 200 cm² circular source in m = 0.0798 m

h = dosimetry depth for the whole body of the pangolin in m = 0.01395 m

Γ_{Co-60} = gamma constant for ⁶⁰Co = $3.062 \times 10^{-4} \frac{mSv}{h \cdot MBq}$ at 1 m and assume 1

Gray is equal to 1 Sievert for photons (Peplow 2020)

$$C_a = \text{concentration area for } ^{60}\text{Co} = \frac{0.37 \text{ MBq}}{200 \text{ cm}^2} \cdot \frac{10^4 \text{ cm}^2}{m^2} = 18.5 \frac{\text{MBq}}{m^2}$$

$$\dot{D} = \pi \cdot \left(3.062 \times 10^{-4} \frac{mSv \cdot m^2}{h \cdot MBq} \right) \cdot 18.5 \frac{\text{MBq}}{m^2} \cdot \ln \left(\frac{(0.0798 \text{ m})^2 + (0.01395 \text{ m})^2}{(0.01395 \text{ m})^2} \right) \cdot \frac{1 \text{ mGy}}{1 \text{ mSv}} \cdot \frac{24 \text{ h}}{1 \text{ d}} \cdot$$

$$\frac{365.25 \text{ d}}{1 \text{ y}} = 549 \frac{\text{mGy}}{\text{y}} \text{ or } 62.6 \frac{\mu\text{Gy}}{\text{h}}$$

Basal Layer of the Skin

$$\dot{D} = \pi \Gamma C_a \ln \left(\frac{R^2 + h^2}{h^2} \right)$$

Where:

R = radius for 200 cm² circular source in m = 0.0798 m

h = dosimetry depth for the whole body of the pangolin in m = 0.00402 m

Γ_{Co-60} = gamma constant for ⁶⁰Co = $3.062 \times 10^{-4} \frac{mSv}{h \cdot MBq}$ at 1 m and assume 1

Gray is equal to 1 Sievert for photons (ibid.)

$$C_a = \text{concentration area for } ^{60}\text{Co} = \frac{0.37 \text{ MBq}}{200 \text{ cm}^2} \cdot \frac{10^4 \text{ cm}^2}{m^2} = 18.5 \frac{\text{MBq}}{m^2}$$

$$\dot{D} = \pi \cdot \left(3.062 \times 10^{-4} \frac{mSv \cdot m^2}{h \cdot MBq} \right) \cdot 18.5 \frac{MBq}{m^2} \cdot \ln \left(\frac{(0.0798 m)^2 + (0.00402 m)^2}{(0.00402 m)^2} \right) \cdot \frac{1 mGy}{1 mSv} \cdot \frac{24 h}{1 d} \cdot$$

$$\frac{365.25 d}{1 y} = 933 \frac{mGy}{y} \text{ or } 106 \frac{\mu Gy}{h}$$

Reproductive Organs

$$\dot{D} = \pi \Gamma C_a \ln \left(\frac{R^2 + h^2}{h^2} \right)$$

Where:

R = radius for 200 cm² circular source in m = 0.0798 m

h = dosimetry depth for the pangolin's reproductive organs in m = 0.0591 m

Γ_{Co-60} = gamma constant for ⁶⁰Co = $3.062 \times 10^{-4} \frac{mSv}{h \cdot MBq}$ at 1 m and assume 1

Gray is equal to 1 Sievert for photons (Peplow 2020)

$$C_a = \text{concentration area for } ^{60}\text{Co} = \frac{0.37 MBq}{200 cm^2} \cdot \frac{10^4 cm^2}{m^2} = 18.5 \frac{MBq}{m^2}$$

$$\dot{D} = \pi \cdot \left(3.062 \times 10^{-4} \frac{mSv \cdot m^2}{h \cdot MBq} \right) \cdot 18.5 \frac{MBq}{m^2} \cdot \ln \left(\frac{(0.0798 m)^2 + (0.0591 m)^2}{(0.0591 m)^2} \right) \cdot \frac{1 mGy}{1 mSv} \cdot \frac{24 h}{1 d} \cdot$$

$$\frac{365.25 d}{1 y} = 162 \frac{mGy}{y} \text{ or } 18.5 \frac{\mu Gy}{h}$$

APPENDIX C

Appendix C explains the full input and output variables for the various model calculations used to estimate radiation dose to the pangolin.

NRC V+

The full input applicable to all calculations included the cover, the source activity, and the exposure time. The cover to mimic effective scale thickness and density was defined at $1.34 \frac{g}{cm^3}$ density, 2.95 mm thickness, and $0.395 \frac{g}{cm^2}$ density thickness. The ^{60}Co activity was defined at 0.37 MBq for a one-year exposure period.

For disc sources, the diameter was defined in cm to correspond to a desired rectangular area for application onto the pangolin scales. The desired areas were 50 cm², 100 cm², 150 cm², 200 cm², and 250 cm², which correlated to disc diameters of 7.98 cm, 11.28 cm, 13.82 cm, 15.96 cm, and 17.84 cm, respectively.

Radiation dose to the whole body of the pangolin was calculated at a dose depth of $1000 \frac{mg}{cm^2}$ and averaging area of 1 mm² and radiation dose the basal layer of the skin was calculated at a dose depth of $7 \frac{mg}{cm^2}$ and averaging area of 1 cm² to align with human dosimetry methods. Results for both whole body and basal layer of the skin are shown in Tables C-1 and C-2 below.

Table C-1, Whole-Body Radiation Dose to the Pangolin from NRC V+ Software

Area of Disc (cm ²)	0	50	100	150	200	250
Source Type	Point	Disk	Disk	Disk	Disk	Disk
Electron (Beta) Dose to Whole Body (mSv y ⁻¹)	0	0	0	0	0	0
Gamma (Photon) Dose to Whole Body (mSv y ⁻¹)	5900	1300	810	590	470	390
Gamma (Photon) Dose to Whole Body (μSv h ⁻¹)	670	150	92	67	54	45

Table C-2, Basal Layer of the Skin Radiation Dose from NRC V+ Software

Area of Disc (cm ²)	0	50	100	150	200	250
Source Type	Point	Disk	Disk	Disk	Disk	Disk
Electron (Beta) Dose to Basal Layer (mSv y ⁻¹)	0	0	0	0	0	0
Gamma (Photon) Dose to Basal Layer (mSv y ⁻¹)	41000	2700	1400	1000	770	620
Gamma (Photon) Dose to Basal Layer (μSv h ⁻¹)	4700	310	160	110	88	71

ICRP 136

Table C-3, Select Dose Coefficients for ⁶⁰Co External Exposure from ICRP 136

	In Soil (μGy h ⁻¹ Bq ⁻¹ kg)	On Ground (μGy h ⁻¹ Bq ⁻¹ kg)
Reference animal: Rat	1.2×10^{-3}	5.1×10^{-4}

For this calculation, an activity of 3.7×10^5 Bq and average weight of 6 kg for the Temminck's pangolin was assumed. In soil calculations are more appropriate for the pangolin as it lives close to the ground and is a burrow dweller. It is assumed the pangolin is like a rat for dosimetry purposes. For this external exposure scenario for a rat RAP in soil with ⁶⁰Co, the dose coefficient of $1.2 \times 10^{-3} \frac{\mu\text{Gy} \cdot \text{kg}}{\text{h} \cdot \text{Bq}}$.

The calculations for the annual absorbed dose using the ICRP 136 dose coefficient are shown below and results in 649 mGy y⁻¹ to the pangolin.

$$1.2 \times 10^{-3} \frac{\mu\text{Gy} \cdot \text{kg}}{\text{h} \cdot \text{Bq}} \cdot 3.7 \times 10^5 \text{ Bq} \cdot \frac{1 \text{ pangolin}}{6 \text{ kg}} \cdot \frac{24 \text{ h}}{1 \text{ d}} \cdot \frac{365.25 \text{ d}}{1 \text{ y}} \cdot \frac{1 \text{ mGy}}{10^3 \mu\text{Gy}} = 649 \frac{\text{mGy}}{\text{y}} \text{ or } 74.0 \frac{\mu\text{Gy}}{\text{h}}$$

BiotaDC

The BiotaDC v.1.5.2 input parameters were as follows:

Ecosystem: terrestrial.

Type of terrestrial organism: fauna.

Exposure pathway: external.

Mass of organism [kg]: 6

External exposure of terrestrial fauna source: in-soil.

Radionuclide element and mass number: Co-60

Effect of radioactive progeny method: time-integral activities ratio.

Time [d]: 365.2425

The BiotaDC v.1.5.2 output was as follows:

Parent radionuclide: Co-60 (half-life: 1925 d).

Contribution of radioactive progeny is estimated using ratio(s) of integral activities for T = 365.24 d.

Accounted decay chain members (rel.activity): Co-60 (1.000000)

Terrestrial ecosystem

Fauna

Organism of mass 6 kg (tissue-equivalent sphere)

‘In-soil’ external exposure

External DC = 9.63E-004 (μGy h⁻² per Bq kg⁻¹)

From the output, the calculated in soil dose coefficient from the BiotaDC software is $9.63 \times 10^{-4} \frac{\mu Gy \cdot kg}{h \cdot Bq}$. The calculations for the annual absorbed dose using BiotaDC dose coefficient are shown below and results in 521 mGy y⁻¹ to the pangolin.

$$9.63 \times 10^{-4} \frac{\mu Gy \cdot kg}{h \cdot Bq} \cdot 3.7 \times 10^5 Bq \cdot \frac{1 pangolin}{6 kg} \cdot \frac{24 h}{1 d} \cdot \frac{365.25 d}{1 y} \cdot \frac{1 mGy}{10^3 \mu Gy} = 521 \frac{mGy}{y} \text{ or } 59.4 \frac{\mu Gy}{h}$$

MIRD

$$\dot{D} = \frac{\dot{\gamma} \cdot E \cdot \phi}{m}$$

Where:

$$\dot{\gamma} = 3.7 \times 10^5 \frac{decays}{s} \cdot 2 \frac{\gamma}{decay} = 7.4 \times 10^5 \frac{\gamma}{s}$$

$$E = 1.25 \frac{MeV}{\gamma}; {}^{60}\text{Co photons are 1.173 MeV, emitted following 99.85\% of decays,}$$

and 1.332 MeV, emitted following 99.98% of decays. The average gamma energy is $1.25 \frac{MeV}{photon}$.

$$\phi = 0.3065, \text{ photon absorbed fraction}$$

$$m = 6.6036 kg$$

MIRD Pamphlet No. 3 published a table of absorbed fractions for central point sources in spheres for both 6 kg spheres and 8 kg spheres at 0.662 MeV and 2.750 MeV photon energies. A summary table of the values is provided in Table C-4 (Brownell et al. 1968).

Table C-4, Absorbed Fractions for Central Point Sources in Spheres

Absorbed Fractions by Photon Energy and Mass		
Energy in MeV	6kg	8kg
0.662	0.33	0.359
2.75	0.238	0.259

A double, logarithmic interpolation was performed to find the absorbed fraction for a central point source at 1.25 MeV in a 6.6036 kg sphere. The general logarithmic interpolation formula used was:

$$\log(y) = \log(y_0) + \frac{\log(x) - \log(x_0)}{\log(x_1) - \log(x_0)} \cdot [\log(y_1) - \log(y_0)]$$

To interpolate energy at 1.25 MeV at 6 kg:

$$\log(y) = \log(0.33) + \frac{\log(1.25) - \log(0.662)}{\log(2.75) - \log(0.662)} \cdot [\log(0.238) - \log(0.33)] = 0.2979$$

To interpolate energy at 1.25 MeV at 8 kg:

$$\log(y) = \log(0.359) + \frac{\log(1.25) - \log(0.662)}{\log(2.75) - \log(0.662)} \cdot [\log(0.259) - \log(0.359)] = 0.3241$$

To interpolate for 6.6036 kg at the interpolated photon absorbed fraction values:

$$\log(y) = \log(0.2979) + \frac{\log(6.6036) - \log(6)}{\log(8) - \log(6)} \cdot [\log(0.3241) - \log(0.2979)] = 0.3065$$

The mass was found by using the MCNP model geometry of two nested spheres, the outer sphere with a radius of 11.54 cm and the inner sphere with a radius of 11.24 cm. The volume for the total pangolin including the scale layer is $V = \frac{4}{3}\pi(11.54^3) = 6437.33 \text{ cm}^3$ and the volume for the inner, soft tissue sphere for the pangolin model is $V = \frac{4}{3}\pi(11.24^3) = 5948.23 \text{ cm}^3$. To find the volume of just the scales, the inner sphere was subtracted from the outer sphere. The volume of the scale layer is $6437.33 \text{ cm}^3 - 5948.23 \text{ cm}^3 = 489.1 \text{ cm}^3$. The density of the keratin layer is defined as $1.34 \frac{\text{g}}{\text{cm}^3}$. Thus, the mass of the keratin scales is $489.1 \text{ cm}^3 \cdot 1.34 \frac{\text{g}}{\text{cm}^3} = 655.4 \text{ g}$.

The density of the inner sphere of soft tissue is assumed to be $1 \frac{g}{cm^3}$, and thus the mass of the inner sphere is $5948.23 \text{ cm}^3 \cdot 1 \frac{g}{cm^3} = 5948.2 \text{ g}$. The total mass of the pangolin model is $655.4 \text{ g} + 5948.2 \text{ g} = 6603.6 \text{ g}$ or 6.6036 kg .

$$\dot{D} = \frac{7.4 \times 10^5 \frac{Y}{s} \cdot 1.25 \frac{MeV}{\gamma} \cdot 0.3065 \cdot 1.602 \times 10^{-13} \frac{J}{MeV} \cdot 86400 \frac{s}{d} \cdot 365.25 \frac{d}{y}}{6.6036 \text{ kg} \cdot \frac{J}{kg} \cdot \frac{10^{-3} \text{ Gy}}{mGy}} = 217 \frac{mGy}{y} \text{ or } 24.8 \frac{\mu Gy}{h}$$

APPENDIX D

Appendix D lists the full MCNP input for all MCNP simulations used to estimate radiation dose to the pangolin.

F5 Whole Body Dose from a Point Source

c Isotropic Co-60 source on pangolin scales

c ***** BLOCK 1: CELL CARDS *****

```
1 1 -0.001205 +20 -30 imp:p=1 imp:e=1 $ universe air
2 3 -1.00 -10 imp:p=3 imp:e=3 $ soft tissue ellipsoid
3 2 -1.35 -20 +10 imp:p=2 imp:e=2 $ keratin ellipsoid
999 0 +30 imp:p=0 imp:e=0 $ outside world / void
```

c ***** BLOCK 2: SURFACE CARDS *****

c soft tissue sphere r=11.24

c scales sphere r=11.54

```
10 sph 0 0 0 11.24 $ pangolin soft tissue
20 sph 0 0 0 11.54 $ pangolin keratin scales
30 rpp -15 15 -15 15 -15 15 $ universe bounds
```

c ***** BLOCK 3: DATA CARDS *****

c --- Material Definitions ---

c Air (mass fractions)

```
m1 6000 -0.000151 7000 -0.784437 8000 -0.210750 18000 &
-0.004671 $ C, N, O, Ar
```

c Fingernail / keratin-like (mass fractions)

```
m2 1000 -0.108355 6000 -0.438425 7000 -0.143325 8000 &
-0.278820 16000 -0.031075 $ H, C, N, O, S
```

c ICRU 4-tissue (mass fractions)

```
m3 1000 -0.101172 6000 -0.111000 7000 -0.026000 8000 &
-0.761828 $ H, C, N, O
```

c --- Source Definition ---

SDEF pos=0 -11.535 0 erg=d1 par=2 vec=0 1 0

si1 l 1.173 1.332 \$ discrete Co-60 energies in MeV

sp1 d 1.0 1.0 \$ equally probable

c --- Tally Definition ---

F5:p 0 -10.145 0 0.25

c --- Physics Parameters ---

mode p e \$ photon and secondary electron mode

nps 5E8 \$ Add more as needed

F5 Basal Layer of the Skin Dose from a Point Source

c Isotropic Co-60 source on pangolin scales

c ***** BLOCK 1: CELL CARDS *****

```
1 1 -0.001205 +20 -30 imp:p=1 imp:e=1 $ universe air
2 3 -1.00 -10 imp:p=3 imp:e=3 $ soft tissue ellipsoid
3 2 -1.35 -20 +10 imp:p=2 imp:e=2 $ keratin ellipsoid
999 0 +30 imp:p=0 imp:e=0 $ outside world / void
```

c ***** BLOCK 2: SURFACE CARDS *****

c soft tissue sphere r=11.24

c scales sphere r=11.54

```
10 sph 0 0 0 11.24 $ pangolin soft tissue
20 sph 0 0 0 11.54 $ pangolin keratin scales
30 rpp -15 15 -15 15 -15 15 $ universe bounds
```

c ***** BLOCK 3: DATA CARDS *****

c --- Material Definitions ---

c Air (mass fractions)

```
m1 6000 -0.000151 7000 -0.784437 8000 -0.210750 18000 &
-0.004671 $ C, N, O, Ar
```

c Fingernail / keratin-like (mass fractions)

```
m2 1000 -0.108355 6000 -0.438425 7000 -0.143325 8000 &
-0.278820 16000 -0.031075 $ H, C, N, O, S
```

c ICRU 4-tissue (mass fractions)

```
m3 1000 -0.101172 6000 -0.111000 7000 -0.026000 8000 &
-0.761828 $ H, C, N, O
```

c --- Source Definition ---

SDEF pos=0 -11.535 0 erg=d1 par=2 vec=0 1 0

si1 1 1.173 1.332 \$ discrete Co-60 energies in MeV

sp1 d 1.0 1.0 \$ equally probable

c --- Tally Definition ---

F5:p 0 -11.138 0 0.25

c --- Physics Parameters ---

```
mode p $ photon only, F5 unable to secondary e
nps 5E8 $ Add more as needed
```

+F6 Whole Body Dose from a Point Source

c Isotropic Co-60 source on pangolin scales

c ***** BLOCK 1: CELL CARDS *****

```
1 1 -0.001205 +20 -30 imp:p=1 imp:e=1 $ universe air
2 3 -1.00 -10 +40 imp:p=1 imp:e=1 $ soft tissue sphere
3 2 -1.35 -20 +40 +10 imp:p=1 imp:e=1 $ keratin sphere
4 3 -1.00 -40 imp:p=1 imp:e=1 $ detector disc
999 0 +30 imp:p=0 imp:e=0 $ outside world / void
```

c ***** BLOCK 2: SURFACE CARDS *****

c soft tissue sphere r=11.24

c scales sphere r=11.54

c whole body detector sphere depth at 1.395 cm

```
10 sph 0 0 0 11.24 $ pangolin soft tissue
20 sph 0 0 0 11.54 $ pangolin keratin scales
30 rpp -15 15 -15 15 -15 15 $ universe bounds
40 rcc 0 -10.145 0 0 0.001 0 0.05642 $ detector disc
```

c ***** BLOCK 3: DATA CARDS *****

c --- Material Definitions ---

c Air (mass fractions)

```
m1 6000 -0.000151 7000 -0.784437 8000 -0.210750 18000 &
-0.004671 $ C, N, O, Ar
```

c Fingernail / keratin-like (mass fractions)

```
m2 1000 -0.108355 6000 -0.438425 7000 -0.143325 8000 &
-0.278820 16000 -0.031075 $ H, C, N, O, S
```

c ICRU 4-tissue (mass fractions)

```
m3 1000 -0.101172 6000 -0.111000 7000 -0.026000 8000 &
-0.761828 $ H, C, N, O
```

c --- Source Definition ---

SDEF pos=0 -11.535 0 erg=d1 par=2

si1 l 1.173 1.332 \$ discrete Co-60 energies in MeV

sp1 d 1.0 1.0 \$ equally probable

c --- Tally Definition ---

+F6 4

*F8:p,e 4

c --- Physics Parameters ---

mode p e \$ photon and secondary electron mode

PRDMP 4J 10000000

nps 5E8 \$ Add more as needed

+F6 Basal Layer of the Skin Dose from a Point Source

c Isotropic Co-60 source on pangolin scales

c ***** BLOCK 1: CELL CARDS *****

```
1 1 -0.001205 +20 -30 imp:p=1 imp:e=1 $ universe air
2 3 -1.00 -10 +40 imp:p=1 imp:e=1 $ soft tissue sphere
3 2 -1.35 -20 +40 +10 imp:p=1 imp:e=1 $ keratin sphere
4 3 -1.00 -40 imp:p=1 imp:e=1 $ detector disc
999 0 +30 imp:p=0 imp:e=0 $ outside world / void
```

c ***** BLOCK 2: SURFACE CARDS *****

c soft tissue sphere r=11.24

c scales sphere r=11.54

c whole body detector sphere depth at 1.395 cm

```
10 sph 0 0 0 11.24 $ pangolin soft tissue
20 sph 0 0 0 11.54 $ pangolin keratin scales
30 rpp -15 15 -15 15 -15 15 $ universe bounds
40 rcc 0 -11.138 0 0 0.001 0 0.5642 $ detector disc
```

c ***** BLOCK 3: DATA CARDS *****

c --- Material Definitions ---

c Air (mass fractions)

```
m1 6000 -0.000151 7000 -0.784437 8000 -0.210750 18000 &
-0.004671 $ C, N, O, Ar
```

c Fingernail / keratin-like (mass fractions)

```
m2 1000 -0.108355 6000 -0.438425 7000 -0.143325 8000 &
-0.278820 16000 -0.031075 $ H, C, N, O, S
```

c ICRU 4-tissue (mass fractions)

```
m3 1000 -0.101172 6000 -0.111000 7000 -0.026000 8000 &
-0.761828 $ H, C, N, O
```

c --- Source Definition ---

SDEF pos=0 -11.535 0 erg=d1 par=2

si1 l 1.173 1.332 \$ discrete Co-60 energies in MeV

sp1 d 1.0 1.0 \$ equally probable

c --- Tally Definition ---

+F6 4

*F8:p,e 4

c --- Physics Parameters ---

mode p e \$ photon and secondary electron mode

PRDMP 4J 10000000

nps 5E8 \$ Add more as needed

+F6 Whole Body Dose from a Planar Source

c Isotropic Co-60 source on pangolin scales

c ** BLOCK 1: CELL CARDS **

1 1 -0.001205 +20 -30 imp:p=1 imp:e=1 \$

universe air

2 3 -1.00 -10 +101 +102 +103 +104 +105

+106 +107 +108 +109 +110 +111 +112

+113

+114 +115 +116 +117 +118 +119 +120

+121 +122 +123 +124 +125 +126 +127

+128

+129 +130 +131 +132 +133 +134 +135

+136 +137 +138 +139 +140 +141 +142

+143

+144 +145 +146 +147 +148 +149 +150

+151 +152 +153 +154 +155 +156 +157

+158

+159 +160 +161 +162 +163 +164 +165

+166 +167 +168 +169 +170 +171 +172

+173

+174 +175 +176 +177 +178 +179 +180

+181 +182 +183 +184 +185 +186 +187

+188

+189 +190 +191 +192 +193 +194 +195

+196 +197 +198 +199 +200 +201 +202

+203

+204 +205 +206 +207 +208 +209 +210

+211 +212 +213 +214 +215 +216 +217

+218

+219 +220 +221 +222 +223 +224 +225

+226 +227 +228 +229 +230 +231 +232

+233

+234 +235 +236 +237 +238 +239 +240

+241 +242 +243 +244 +245 +246 +247

+248

+249 +250 +251 +252 +253 +254 +255

+256 +257 +258 +259 +260 +261 +262

+263

+264 +265 +266 +267 +268 +269 +270

+271 +272 +273 +274 +275 +276 +277

+278

+279 +280 +281 +282 +283 +284 +285

+286 +287 +288 +289 +290 +291 +292

+293

+294 +295 +296 +297 +298 +299 +300

imp:p=1 imp:e=1 \$ soft tissue sphere

3 2 -1.35 -20 +10 +101 +102 +103 +104

+105 +106 +107 +108 +109 +110 +111

+112

+113 +114 +115 +116 +117 +118 +119

+120 +121 +122 +123 +124 +125 +126

+127

+128 +129 +130 +131 +132 +133 +134

+135 +136 +137 +138 +139 +140 +141

+142

+143 +144 +145 +146 +147 +148 +149

+150 +151 +152 +153 +154 +155 +156

+157

+158 +159 +160 +161 +162 +163 +164

+165 +166 +167 +168 +169 +170 +171

+172

+173 +174 +175 +176 +177 +178 +179

+180 +181 +182 +183 +184 +185 +186

+187

+188 +189 +190 +191 +192 +193 +194

+195 +196 +197 +198 +199 +200 +201

+202

+203 +204 +205 +206 +207 +208 +209

+210 +211 +212 +213 +214 +215 +216

+217

+218 +219 +220 +221 +222 +223 +224

+225 +226 +227 +228 +229 +230 +231

+232

+233 +234 +235 +236 +237 +238 +239

+240 +241 +242 +243 +244 +245 +246

+247

+248 +249 +250 +251 +252 +253 +254
 +255 +256 +257 +258 +259 +260 +261
 +262
 +263 +264 +265 +266 +267 +268 +269
 +270 +271 +272 +273 +274 +275 +276
 +277
 +278 +279 +280 +281 +282 +283 +284
 +285 +286 +287 +288 +289 +290 +291
 +292
 +293 +294 +295 +296 +297 +298 +299
 +300 imp:p=1 imp:e=1 \$ keratin sphere
 101 3 -1.00 -101 imp:p=1 imp:e=1 \$
 detector sphere 1
 102 3 -1.00 -102 imp:p=1 imp:e=1 \$
 detector sphere 2
 103 3 -1.00 -103 imp:p=1 imp:e=1 \$
 detector sphere 3
 104 3 -1.00 -104 imp:p=1 imp:e=1 \$
 detector sphere 4
 105 3 -1.00 -105 imp:p=1 imp:e=1 \$
 detector sphere 5
 106 3 -1.00 -106 imp:p=1 imp:e=1 \$
 detector sphere 6
 107 3 -1.00 -107 imp:p=1 imp:e=1 \$
 detector sphere 7
 108 3 -1.00 -108 imp:p=1 imp:e=1 \$
 detector sphere 8
 109 3 -1.00 -109 imp:p=1 imp:e=1 \$
 detector sphere 9
 110 3 -1.00 -110 imp:p=1 imp:e=1 \$
 detector sphere 10
 111 3 -1.00 -111 imp:p=1 imp:e=1 \$ detector
 sphere 11
 112 3 -1.00 -112 imp:p=1 imp:e=1 \$
 detector sphere 12
 113 3 -1.00 -113 imp:p=1 imp:e=1 \$
 detector sphere 13
 114 3 -1.00 -114 imp:p=1 imp:e=1 \$
 detector sphere 14

115 3 -1.00 -115 imp:p=1 imp:e=1 \$
 detector sphere 15
 116 3 -1.00 -116 imp:p=1 imp:e=1 \$
 detector sphere 16
 117 3 -1.00 -117 imp:p=1 imp:e=1 \$
 detector sphere 17
 118 3 -1.00 -118 imp:p=1 imp:e=1 \$
 detector sphere 18
 119 3 -1.00 -119 imp:p=1 imp:e=1 \$
 detector sphere 19
 120 3 -1.00 -120 imp:p=1 imp:e=1 \$
 detector sphere 20
 121 3 -1.00 -121 imp:p=1 imp:e=1 \$
 detector sphere 21
 122 3 -1.00 -122 imp:p=1 imp:e=1 \$
 detector sphere 22
 123 3 -1.00 -123 imp:p=1 imp:e=1 \$
 detector sphere 23
 124 3 -1.00 -124 imp:p=1 imp:e=1 \$
 detector sphere 24
 125 3 -1.00 -125 imp:p=1 imp:e=1 \$
 detector sphere 25
 126 3 -1.00 -126 imp:p=1 imp:e=1 \$
 detector sphere 26
 127 3 -1.00 -127 imp:p=1 imp:e=1 \$
 detector sphere 27
 128 3 -1.00 -128 imp:p=1 imp:e=1 \$
 detector sphere 28
 129 3 -1.00 -129 imp:p=1 imp:e=1 \$
 detector sphere 29
 130 3 -1.00 -130 imp:p=1 imp:e=1 \$
 detector sphere 30
 131 3 -1.00 -131 imp:p=1 imp:e=1 \$
 detector sphere 31
 132 3 -1.00 -132 imp:p=1 imp:e=1 \$
 detector sphere 32
 133 3 -1.00 -133 imp:p=1 imp:e=1 \$
 detector sphere 33
 134 3 -1.00 -134 imp:p=1 imp:e=1 \$
 detector sphere 34

135 3 -1.00 -135 imp:p=1 imp:e=1 \$
 detector sphere 35
 136 3 -1.00 -136 imp:p=1 imp:e=1 \$
 detector sphere 36
 137 3 -1.00 -137 imp:p=1 imp:e=1 \$
 detector sphere 37
 138 3 -1.00 -138 imp:p=1 imp:e=1 \$
 detector sphere 38
 139 3 -1.00 -139 imp:p=1 imp:e=1 \$
 detector sphere 39
 140 3 -1.00 -140 imp:p=1 imp:e=1 \$
 detector sphere 40
 141 3 -1.00 -141 imp:p=1 imp:e=1 \$
 detector sphere 41
 142 3 -1.00 -142 imp:p=1 imp:e=1 \$
 detector sphere 42
 143 3 -1.00 -143 imp:p=1 imp:e=1 \$
 detector sphere 43
 144 3 -1.00 -144 imp:p=1 imp:e=1 \$
 detector sphere 44
 145 3 -1.00 -145 imp:p=1 imp:e=1 \$
 detector sphere 45
 146 3 -1.00 -146 imp:p=1 imp:e=1 \$
 detector sphere 46
 147 3 -1.00 -147 imp:p=1 imp:e=1 \$
 detector sphere 47
 148 3 -1.00 -148 imp:p=1 imp:e=1 \$
 detector sphere 48
 149 3 -1.00 -149 imp:p=1 imp:e=1 \$
 detector sphere 49
 150 3 -1.00 -150 imp:p=1 imp:e=1 \$
 detector sphere 50
 151 3 -1.00 -151 imp:p=1 imp:e=1 \$
 detector sphere 51
 152 3 -1.00 -152 imp:p=1 imp:e=1 \$
 detector sphere 52
 153 3 -1.00 -153 imp:p=1 imp:e=1 \$
 detector sphere 53
 154 3 -1.00 -154 imp:p=1 imp:e=1 \$
 detector sphere 54

155 3 -1.00 -155 imp:p=1 imp:e=1 \$
 detector sphere 55
 156 3 -1.00 -156 imp:p=1 imp:e=1 \$
 detector sphere 56
 157 3 -1.00 -157 imp:p=1 imp:e=1 \$
 detector sphere 57
 158 3 -1.00 -158 imp:p=1 imp:e=1 \$
 detector sphere 58
 159 3 -1.00 -159 imp:p=1 imp:e=1 \$
 detector sphere 59
 160 3 -1.00 -160 imp:p=1 imp:e=1 \$
 detector sphere 60
 161 3 -1.00 -161 imp:p=1 imp:e=1 \$
 detector sphere 61
 162 3 -1.00 -162 imp:p=1 imp:e=1 \$
 detector sphere 62
 163 3 -1.00 -163 imp:p=1 imp:e=1 \$
 detector sphere 63
 164 3 -1.00 -164 imp:p=1 imp:e=1 \$
 detector sphere 64
 165 3 -1.00 -165 imp:p=1 imp:e=1 \$
 detector sphere 65
 166 3 -1.00 -166 imp:p=1 imp:e=1 \$
 detector sphere 66
 167 3 -1.00 -167 imp:p=1 imp:e=1 \$
 detector sphere 67
 168 3 -1.00 -168 imp:p=1 imp:e=1 \$
 detector sphere 68
 169 3 -1.00 -169 imp:p=1 imp:e=1 \$
 detector sphere 69
 170 3 -1.00 -170 imp:p=1 imp:e=1 \$
 detector sphere 70
 171 3 -1.00 -171 imp:p=1 imp:e=1 \$
 detector sphere 71
 172 3 -1.00 -172 imp:p=1 imp:e=1 \$
 detector sphere 72
 173 3 -1.00 -173 imp:p=1 imp:e=1 \$
 detector sphere 73
 174 3 -1.00 -174 imp:p=1 imp:e=1 \$
 detector sphere 74

175 3 -1.00 -175 imp:p=1 imp:e=1 \$
 detector sphere 75
 176 3 -1.00 -176 imp:p=1 imp:e=1 \$
 detector sphere 76
 177 3 -1.00 -177 imp:p=1 imp:e=1 \$
 detector sphere 77
 178 3 -1.00 -178 imp:p=1 imp:e=1 \$
 detector sphere 78
 179 3 -1.00 -179 imp:p=1 imp:e=1 \$
 detector sphere 79
 180 3 -1.00 -180 imp:p=1 imp:e=1 \$
 detector sphere 80
 181 3 -1.00 -181 imp:p=1 imp:e=1 \$
 detector sphere 81
 182 3 -1.00 -182 imp:p=1 imp:e=1 \$
 detector sphere 82
 183 3 -1.00 -183 imp:p=1 imp:e=1 \$
 detector sphere 83
 184 3 -1.00 -184 imp:p=1 imp:e=1 \$
 detector sphere 84
 185 3 -1.00 -185 imp:p=1 imp:e=1 \$
 detector sphere 85
 186 3 -1.00 -186 imp:p=1 imp:e=1 \$
 detector sphere 86
 187 3 -1.00 -187 imp:p=1 imp:e=1 \$
 detector sphere 87
 188 3 -1.00 -188 imp:p=1 imp:e=1 \$
 detector sphere 88
 189 3 -1.00 -189 imp:p=1 imp:e=1 \$
 detector sphere 89
 190 3 -1.00 -190 imp:p=1 imp:e=1 \$
 detector sphere 90
 191 3 -1.00 -191 imp:p=1 imp:e=1 \$
 detector sphere 91
 192 3 -1.00 -192 imp:p=1 imp:e=1 \$
 detector sphere 92
 193 3 -1.00 -193 imp:p=1 imp:e=1 \$
 detector sphere 93
 194 3 -1.00 -194 imp:p=1 imp:e=1 \$
 detector sphere 94

195 3 -1.00 -195 imp:p=1 imp:e=1 \$
 detector sphere 95
 196 3 -1.00 -196 imp:p=1 imp:e=1 \$
 detector sphere 96
 197 3 -1.00 -197 imp:p=1 imp:e=1 \$
 detector sphere 97
 198 3 -1.00 -198 imp:p=1 imp:e=1 \$
 detector sphere 98
 199 3 -1.00 -199 imp:p=1 imp:e=1 \$
 detector sphere 99
 200 3 -1.00 -200 imp:p=1 imp:e=1 \$
 detector sphere 100
 201 3 -1.00 -201 imp:p=1 imp:e=1 \$
 detector sphere 101
 202 3 -1.00 -202 imp:p=1 imp:e=1 \$
 detector sphere 102
 203 3 -1.00 -203 imp:p=1 imp:e=1 \$
 detector sphere 103
 204 3 -1.00 -204 imp:p=1 imp:e=1 \$
 detector sphere 104
 205 3 -1.00 -205 imp:p=1 imp:e=1 \$
 detector sphere 105
 206 3 -1.00 -206 imp:p=1 imp:e=1 \$
 detector sphere 106
 207 3 -1.00 -207 imp:p=1 imp:e=1 \$
 detector sphere 107
 208 3 -1.00 -208 imp:p=1 imp:e=1 \$
 detector sphere 108
 209 3 -1.00 -209 imp:p=1 imp:e=1 \$
 detector sphere 109
 210 3 -1.00 -210 imp:p=1 imp:e=1 \$
 detector sphere 110
 211 3 -1.00 -211 imp:p=1 imp:e=1 \$
 detector sphere 111
 212 3 -1.00 -212 imp:p=1 imp:e=1 \$
 detector sphere 112
 213 3 -1.00 -213 imp:p=1 imp:e=1 \$
 detector sphere 113
 214 3 -1.00 -214 imp:p=1 imp:e=1 \$
 detector sphere 114

215 3 -1.00 -215 imp:p=1 imp:e=1 \$
 detector sphere 115
 216 3 -1.00 -216 imp:p=1 imp:e=1 \$
 detector sphere 116
 217 3 -1.00 -217 imp:p=1 imp:e=1 \$
 detector sphere 117
 218 3 -1.00 -218 imp:p=1 imp:e=1 \$
 detector sphere 118
 219 3 -1.00 -219 imp:p=1 imp:e=1 \$
 detector sphere 119
 220 3 -1.00 -220 imp:p=1 imp:e=1 \$
 detector sphere 120
 221 3 -1.00 -221 imp:p=1 imp:e=1 \$
 detector sphere 121
 222 3 -1.00 -222 imp:p=1 imp:e=1 \$
 detector sphere 122
 223 3 -1.00 -223 imp:p=1 imp:e=1 \$
 detector sphere 123
 224 3 -1.00 -224 imp:p=1 imp:e=1 \$
 detector sphere 124
 225 3 -1.00 -225 imp:p=1 imp:e=1 \$
 detector sphere 125
 226 3 -1.00 -226 imp:p=1 imp:e=1 \$
 detector sphere 126
 227 3 -1.00 -227 imp:p=1 imp:e=1 \$
 detector sphere 127
 228 3 -1.00 -228 imp:p=1 imp:e=1 \$
 detector sphere 128
 229 3 -1.00 -229 imp:p=1 imp:e=1 \$
 detector sphere 129
 230 3 -1.00 -230 imp:p=1 imp:e=1 \$
 detector sphere 130
 231 3 -1.00 -231 imp:p=1 imp:e=1 \$
 detector sphere 131
 232 3 -1.00 -232 imp:p=1 imp:e=1 \$
 detector sphere 132
 233 3 -1.00 -233 imp:p=1 imp:e=1 \$
 detector sphere 133
 234 3 -1.00 -234 imp:p=1 imp:e=1 \$
 detector sphere 134

235 3 -1.00 -235 imp:p=1 imp:e=1 \$
 detector sphere 135
 236 3 -1.00 -236 imp:p=1 imp:e=1 \$
 detector sphere 136
 237 3 -1.00 -237 imp:p=1 imp:e=1 \$
 detector sphere 137
 238 3 -1.00 -238 imp:p=1 imp:e=1 \$
 detector sphere 138
 239 3 -1.00 -239 imp:p=1 imp:e=1 \$
 detector sphere 139
 240 3 -1.00 -240 imp:p=1 imp:e=1 \$
 detector sphere 140
 241 3 -1.00 -241 imp:p=1 imp:e=1 \$
 detector sphere 141
 242 3 -1.00 -242 imp:p=1 imp:e=1 \$
 detector sphere 142
 243 3 -1.00 -243 imp:p=1 imp:e=1 \$
 detector sphere 143
 244 3 -1.00 -244 imp:p=1 imp:e=1 \$
 detector sphere 144
 245 3 -1.00 -245 imp:p=1 imp:e=1 \$
 detector sphere 145
 246 3 -1.00 -246 imp:p=1 imp:e=1 \$
 detector sphere 146
 247 3 -1.00 -247 imp:p=1 imp:e=1 \$
 detector sphere 147
 248 3 -1.00 -248 imp:p=1 imp:e=1 \$
 detector sphere 148
 249 3 -1.00 -249 imp:p=1 imp:e=1 \$
 detector sphere 149
 250 3 -1.00 -250 imp:p=1 imp:e=1 \$
 detector sphere 150
 251 3 -1.00 -251 imp:p=1 imp:e=1 \$
 detector sphere 151
 252 3 -1.00 -252 imp:p=1 imp:e=1 \$
 detector sphere 152
 253 3 -1.00 -253 imp:p=1 imp:e=1 \$
 detector sphere 153
 254 3 -1.00 -254 imp:p=1 imp:e=1 \$
 detector sphere 154

255 3 -1.00 -255 imp:p=1 imp:e=1 \$
 detector sphere 155
 256 3 -1.00 -256 imp:p=1 imp:e=1 \$
 detector sphere 156
 257 3 -1.00 -257 imp:p=1 imp:e=1 \$
 detector sphere 157
 258 3 -1.00 -258 imp:p=1 imp:e=1 \$
 detector sphere 158
 259 3 -1.00 -259 imp:p=1 imp:e=1 \$
 detector sphere 159
 260 3 -1.00 -260 imp:p=1 imp:e=1 \$
 detector sphere 160
 261 3 -1.00 -261 imp:p=1 imp:e=1 \$
 detector sphere 161
 262 3 -1.00 -262 imp:p=1 imp:e=1 \$
 detector sphere 162
 263 3 -1.00 -263 imp:p=1 imp:e=1 \$
 detector sphere 163
 264 3 -1.00 -264 imp:p=1 imp:e=1 \$
 detector sphere 164
 265 3 -1.00 -265 imp:p=1 imp:e=1 \$
 detector sphere 165
 266 3 -1.00 -266 imp:p=1 imp:e=1 \$
 detector sphere 166
 267 3 -1.00 -267 imp:p=1 imp:e=1 \$
 detector sphere 167
 268 3 -1.00 -268 imp:p=1 imp:e=1 \$
 detector sphere 168
 269 3 -1.00 -269 imp:p=1 imp:e=1 \$
 detector sphere 169
 270 3 -1.00 -270 imp:p=1 imp:e=1 \$
 detector sphere 170
 271 3 -1.00 -271 imp:p=1 imp:e=1 \$
 detector sphere 171
 272 3 -1.00 -272 imp:p=1 imp:e=1 \$
 detector sphere 172
 273 3 -1.00 -273 imp:p=1 imp:e=1 \$
 detector sphere 173
 274 3 -1.00 -274 imp:p=1 imp:e=1 \$
 detector sphere 174

275 3 -1.00 -275 imp:p=1 imp:e=1 \$
 detector sphere 175
 276 3 -1.00 -276 imp:p=1 imp:e=1 \$
 detector sphere 176
 277 3 -1.00 -277 imp:p=1 imp:e=1 \$
 detector sphere 177
 278 3 -1.00 -278 imp:p=1 imp:e=1 \$
 detector sphere 178
 279 3 -1.00 -279 imp:p=1 imp:e=1 \$
 detector sphere 179
 280 3 -1.00 -280 imp:p=1 imp:e=1 \$
 detector sphere 180
 281 3 -1.00 -281 imp:p=1 imp:e=1 \$
 detector sphere 181
 282 3 -1.00 -282 imp:p=1 imp:e=1 \$
 detector sphere 182
 283 3 -1.00 -283 imp:p=1 imp:e=1 \$
 detector sphere 183
 284 3 -1.00 -284 imp:p=1 imp:e=1 \$
 detector sphere 184
 285 3 -1.00 -285 imp:p=1 imp:e=1 \$
 detector sphere 185
 286 3 -1.00 -286 imp:p=1 imp:e=1 \$
 detector sphere 186
 287 3 -1.00 -287 imp:p=1 imp:e=1 \$
 detector sphere 187
 288 3 -1.00 -288 imp:p=1 imp:e=1 \$
 detector sphere 188
 289 3 -1.00 -289 imp:p=1 imp:e=1 \$
 detector sphere 189
 290 3 -1.00 -290 imp:p=1 imp:e=1 \$
 detector sphere 190
 291 3 -1.00 -291 imp:p=1 imp:e=1 \$
 detector sphere 191
 292 3 -1.00 -292 imp:p=1 imp:e=1 \$
 detector sphere 192
 293 3 -1.00 -293 imp:p=1 imp:e=1 \$
 detector sphere 193
 294 3 -1.00 -294 imp:p=1 imp:e=1 \$
 detector sphere 194

295 3 -1.00 -295 imp:p=1 imp:e=1 \$
 detector sphere 195
 296 3 -1.00 -296 imp:p=1 imp:e=1 \$
 detector sphere 196
 297 3 -1.00 -297 imp:p=1 imp:e=1 \$
 detector sphere 197
 298 3 -1.00 -298 imp:p=1 imp:e=1 \$
 detector sphere 198
 299 3 -1.00 -299 imp:p=1 imp:e=1 \$
 detector sphere 199
 300 3 -1.00 -300 imp:p=1 imp:e=1 \$
 detector sphere 200
 999 0 +30 imp:p=0 imp:e=0 \$ outside
 world / void

c ****BLOCK 2: SURFACE CARDS ****

c soft tissue sphere r=11.24
 c scales sphere r=11.54
 10 sph 0 0 0 11.24 \$ pangolin
 soft tissue
 20 sph 0 0 0 11.54 \$ pangolin
 keratin scales
 30 rpp -15 15 -15 15 -15 15 \$ universe
 bounds
 c whole body detector sphere depth at 1.395
 cm
 101 sph 5.4308 -7.3805 4.3539 0.1 \$
 detector sphere 1
 102 sph 6.1308 -6.8102 4.3539 0.1 \$
 detector sphere 2
 103 sph 6.7712 -6.1738 4.3539 0.1 \$
 detector sphere 3
 104 sph 7.3459 -5.4775 4.3539 0.1 \$
 detector sphere 4
 105 sph 7.8493 -4.7279 4.3539 0.1 \$
 detector sphere 5
 106 sph 8.2765 -3.9325 4.3539 0.1 \$
 detector sphere 6
 107 sph 8.6233 -3.0990 4.3539 0.1 \$
 detector sphere 7

108 sph 8.8864 -2.2353 4.3539 0.1 \$
 detector sphere 8
 109 sph 9.0632 -1.3499 4.3539 0.1 \$
 detector sphere 9
 110 sph 9.1521 -0.4514 4.3539 0.1 \$
 detector sphere 10
 111 sph 9.1521 0.4514 4.3539 0.1 \$ detector
 sphere 11
 112 sph 9.0632 1.3499 4.3539 0.1 \$ detector
 sphere 12
 113 sph 8.8864 2.2353 4.3539 0.1 \$ detector
 sphere 13
 114 sph 8.6233 3.0990 4.3539 0.1 \$ detector
 sphere 14
 115 sph 8.2765 3.9325 4.3539 0.1 \$ detector
 sphere 15
 116 sph 7.8493 4.7279 4.3539 0.1 \$ detector
 sphere 16
 117 sph 7.3459 5.4775 4.3539 0.1 \$ detector
 sphere 17
 118 sph 6.7712 6.1738 4.3539 0.1 \$ detector
 sphere 18
 119 sph 6.1308 6.8102 4.3539 0.1 \$ detector
 sphere 19
 120 sph 5.4308 7.3805 4.3539 0.1 \$ detector
 sphere 20
 121 sph 5.6584 -7.6897 3.4310 0.1 \$
 detector sphere 21
 122 sph 6.3877 -7.0956 3.4310 0.1 \$
 detector sphere 22
 123 sph 7.0550 -6.4325 3.4310 0.1 \$
 detector sphere 23
 124 sph 7.6537 -5.7070 3.4310 0.1 \$
 detector sphere 24
 125 sph 8.1782 -4.9261 3.4310 0.1 \$
 detector sphere 25
 126 sph 8.6233 -4.0973 3.4310 0.1 \$
 detector sphere 26
 127 sph 8.9847 -3.2288 3.4310 0.1 \$
 detector sphere 27

128 sph 9.2588 -2.3290 3.4310 0.1 \$
 detector sphere 28
 129 sph 9.4431 -1.4065 3.4310 0.1 \$
 detector sphere 29
 130 sph 9.5356 -0.4703 3.4310 0.1 \$
 detector sphere 30
 131 sph 9.5356 0.4703 3.4310 0.1 \$ detector
 sphere 31
 132 sph 9.4431 1.4065 3.4310 0.1 \$ detector
 sphere 32
 133 sph 9.2588 2.3290 3.4310 0.1 \$ detector
 sphere 33
 134 sph 8.9847 3.2288 3.4310 0.1 \$ detector
 sphere 34
 135 sph 8.6233 4.0973 3.4310 0.1 \$ detector
 sphere 35
 136 sph 8.1782 4.9261 3.4310 0.1 \$ detector
 sphere 36
 137 sph 7.6537 5.7070 3.4310 0.1 \$ detector
 sphere 37
 138 sph 7.0550 6.4325 3.4310 0.1 \$ detector
 sphere 38
 139 sph 6.3877 7.0956 3.4310 0.1 \$ detector
 sphere 39
 140 sph 5.6584 7.6897 3.4310 0.1 \$ detector
 sphere 40
 141 sph 5.8310 -7.9244 2.4748 0.1 \$
 detector sphere 41
 142 sph 6.5826 -7.3121 2.4748 0.1 \$
 detector sphere 42
 143 sph 7.2702 -6.6288 2.4748 0.1 \$
 detector sphere 43
 144 sph 7.8873 -5.8811 2.4748 0.1 \$
 detector sphere 44
 145 sph 8.4277 -5.0764 2.4748 0.1 \$
 detector sphere 45
 146 sph 8.8864 -4.2224 2.4748 0.1 \$
 detector sphere 46
 147 sph 9.2588 -3.3273 2.4748 0.1 \$
 detector sphere 47

148 sph 9.5413 -2.4000 2.4748 0.1 \$
 detector sphere 48
 149 sph 9.7312 -1.4494 2.4748 0.1 \$
 detector sphere 49
 150 sph 9.8266 -0.4847 2.4748 0.1 \$
 detector sphere 50
 151 sph 9.8266 0.4847 2.4748 0.1 \$ detector
 sphere 51
 152 sph 9.7312 1.4494 2.4748 0.1 \$ detector
 sphere 52
 153 sph 9.5413 2.4000 2.4748 0.1 \$ detector
 sphere 53
 154 sph 9.2588 3.3273 2.4748 0.1 \$ detector
 sphere 54
 155 sph 8.8864 4.2224 2.4748 0.1 \$ detector
 sphere 55
 156 sph 8.4277 5.0764 2.4748 0.1 \$ detector
 sphere 56
 157 sph 7.8873 5.8811 2.4748 0.1 \$ detector
 sphere 57
 158 sph 7.2702 6.6288 2.4748 0.1 \$ detector
 sphere 58
 159 sph 6.5826 7.3121 2.4748 0.1 \$ detector
 sphere 59
 160 sph 5.8310 7.9244 2.4748 0.1 \$ detector
 sphere 60
 161 sph 5.9471 -8.0821 1.4945 0.1 \$
 detector sphere 61
 162 sph 6.7136 -7.4576 1.4945 0.1 \$
 detector sphere 62
 163 sph 7.4149 -6.7607 1.4945 0.1 \$
 detector sphere 63
 164 sph 8.0442 -5.9982 1.4945 0.1 \$
 detector sphere 64
 165 sph 8.5955 -5.1774 1.4945 0.1 \$
 detector sphere 65
 166 sph 9.0632 -4.3064 1.4945 0.1 \$
 detector sphere 66
 167 sph 9.4431 -3.3935 1.4945 0.1 \$
 detector sphere 67

168 sph 9.7312 -2.4478 1.4945 0.1 \$
 detector sphere 68
 169 sph 9.9248 -1.4782 1.4945 0.1 \$
 detector sphere 69
 170 sph 10.0221 -0.4943 1.4945 0.1 \$
 detector sphere 70
 171 sph 10.0221 0.4943 1.4945 0.1 \$
 detector sphere 71
 172 sph 9.9248 1.4782 1.4945 0.1 \$ detector
 sphere 72
 173 sph 9.7312 2.4478 1.4945 0.1 \$ detector
 sphere 73
 174 sph 9.4431 3.3935 1.4945 0.1 \$ detector
 sphere 74
 175 sph 9.0632 4.3064 1.4945 0.1 \$ detector
 sphere 75
 176 sph 8.5955 5.1774 1.4945 0.1 \$ detector
 sphere 76
 177 sph 8.0442 5.9982 1.4945 0.1 \$ detector
 sphere 77
 178 sph 7.4149 6.7607 1.4945 0.1 \$ detector
 sphere 78
 179 sph 6.7136 7.4576 1.4945 0.1 \$ detector
 sphere 79
 180 sph 5.9471 8.0821 1.4945 0.1 \$ detector
 sphere 80
 181 sph 6.0054 -8.1613 0.4998 0.1 \$
 detector sphere 81
 182 sph 6.7794 -7.5307 0.4998 0.1 \$
 detector sphere 82
 183 sph 7.4876 -6.8270 0.4998 0.1 \$
 detector sphere 83
 184 sph 8.1231 -6.0570 0.4998 0.1 \$
 detector sphere 84
 185 sph 8.6797 -5.2282 0.4998 0.1 \$
 detector sphere 85
 186 sph 9.1521 -4.3486 0.4998 0.1 \$
 detector sphere 86
 187 sph 9.5356 -3.4268 0.4998 0.1 \$
 detector sphere 87

188 sph 9.8266 -2.4718 0.4998 0.1 \$
 detector sphere 88
 189 sph 10.0221 -1.4927 0.4998 0.1 \$
 detector sphere 89
 190 sph 10.1204 -0.4992 0.4998 0.1 \$
 detector sphere 90
 191 sph 10.1204 0.4992 0.4998 0.1 \$
 detector sphere 91
 192 sph 10.0221 1.4927 0.4998 0.1 \$
 detector sphere 92
 193 sph 9.8266 2.4718 0.4998 0.1 \$ detector
 sphere 93
 194 sph 9.5356 3.4268 0.4998 0.1 \$ detector
 sphere 94
 195 sph 9.1521 4.3486 0.4998 0.1 \$ detector
 sphere 95
 196 sph 8.6797 5.2282 0.4998 0.1 \$ detector
 sphere 96
 197 sph 8.1231 6.0570 0.4998 0.1 \$ detector
 sphere 97
 198 sph 7.4876 6.8270 0.4998 0.1 \$ detector
 sphere 98
 199 sph 6.7794 7.5307 0.4998 0.1 \$ detector
 sphere 99
 200 sph 6.0054 8.1613 0.4998 0.1 \$ detector
 sphere 100
 201 sph 6.0054 -8.1613 -0.4998 0.1 \$
 detector sphere 101
 202 sph 6.7794 -7.5307 -0.4998 0.1 \$
 detector sphere 102
 203 sph 7.4876 -6.8270 -0.4998 0.1 \$
 detector sphere 103
 204 sph 8.1231 -6.0570 -0.4998 0.1 \$
 detector sphere 104
 205 sph 8.6797 -5.2282 -0.4998 0.1 \$
 detector sphere 105
 206 sph 9.1521 -4.3486 -0.4998 0.1 \$
 detector sphere 106
 207 sph 9.5356 -3.4268 -0.4998 0.1 \$
 detector sphere 107

208 sph 9.8266 -2.4718 -0.4998 0.1 \$
 detector sphere 108
 209 sph 10.0221 -1.4927 -0.4998 0.1 \$
 detector sphere 109
 210 sph 10.1204 -0.4992 -0.4998 0.1 \$
 detector sphere 110
 211 sph 10.1204 0.4992 -0.4998 0.1 \$
 detector sphere 111
 212 sph 10.0221 1.4927 -0.4998 0.1 \$
 detector sphere 112
 213 sph 9.8266 2.4718 -0.4998 0.1 \$
 detector sphere 113
 214 sph 9.5356 3.4268 -0.4998 0.1 \$
 detector sphere 114
 215 sph 9.1521 4.3486 -0.4998 0.1 \$
 detector sphere 115
 216 sph 8.6797 5.2282 -0.4998 0.1 \$
 detector sphere 116
 217 sph 8.1231 6.0570 -0.4998 0.1 \$
 detector sphere 117
 218 sph 7.4876 6.8270 -0.4998 0.1 \$
 detector sphere 118
 219 sph 6.7794 7.5307 -0.4998 0.1 \$
 detector sphere 119
 220 sph 6.0054 8.1613 -0.4998 0.1 \$
 detector sphere 120
 221 sph 5.9471 -8.0821 -1.4945 0.1 \$
 detector sphere 121
 222 sph 6.7136 -7.4576 -1.4945 0.1 \$
 detector sphere 122
 223 sph 7.4149 -6.7607 -1.4945 0.1 \$
 detector sphere 123
 224 sph 8.0442 -5.9982 -1.4945 0.1 \$
 detector sphere 124
 225 sph 8.5955 -5.1774 -1.4945 0.1 \$
 detector sphere 125
 226 sph 9.0632 -4.3064 -1.4945 0.1 \$
 detector sphere 126
 227 sph 9.4431 -3.3935 -1.4945 0.1 \$
 detector sphere 127

228 sph 9.7312 -2.4478 -1.4945 0.1 \$
 detector sphere 128
 229 sph 9.9248 -1.4782 -1.4945 0.1 \$
 detector sphere 129
 230 sph 10.0221 -0.4943 -1.4945 0.1 \$
 detector sphere 130
 231 sph 10.0221 0.4943 -1.4945 0.1 \$
 detector sphere 131
 232 sph 9.9248 1.4782 -1.4945 0.1 \$
 detector sphere 132
 233 sph 9.7312 2.4478 -1.4945 0.1 \$
 detector sphere 133
 234 sph 9.4431 3.3935 -1.4945 0.1 \$
 detector sphere 134
 235 sph 9.0632 4.3064 -1.4945 0.1 \$
 detector sphere 135
 236 sph 8.5955 5.1774 -1.4945 0.1 \$
 detector sphere 136
 237 sph 8.0442 5.9982 -1.4945 0.1 \$
 detector sphere 137
 238 sph 7.4149 6.7607 -1.4945 0.1 \$
 detector sphere 138
 239 sph 6.7136 7.4576 -1.4945 0.1 \$
 detector sphere 139
 240 sph 5.9471 8.0821 -1.4945 0.1 \$
 detector sphere 140
 241 sph 5.8310 -7.9244 -2.4748 0.1 \$
 detector sphere 141
 242 sph 6.5826 -7.3121 -2.4748 0.1 \$
 detector sphere 142
 243 sph 7.2702 -6.6288 -2.4748 0.1 \$
 detector sphere 143
 244 sph 7.8873 -5.8811 -2.4748 0.1 \$
 detector sphere 144
 245 sph 8.4277 -5.0764 -2.4748 0.1 \$
 detector sphere 145
 246 sph 8.8864 -4.2224 -2.4748 0.1 \$
 detector sphere 146
 247 sph 9.2588 -3.3273 -2.4748 0.1 \$
 detector sphere 147

248 sph 9.5413 -2.4000 -2.4748 0.1 \$
 detector sphere 148
 249 sph 9.7312 -1.4494 -2.4748 0.1 \$
 detector sphere 149
 250 sph 9.8266 -0.4847 -2.4748 0.1 \$
 detector sphere 150
 251 sph 9.8266 0.4847 -2.4748 0.1 \$
 detector sphere 151
 252 sph 9.7312 1.4494 -2.4748 0.1 \$
 detector sphere 152
 253 sph 9.5413 2.4000 -2.4748 0.1 \$
 detector sphere 153
 254 sph 9.2588 3.3273 -2.4748 0.1 \$
 detector sphere 154
 255 sph 8.8864 4.2224 -2.4748 0.1 \$
 detector sphere 155
 256 sph 8.4277 5.0764 -2.4748 0.1 \$
 detector sphere 156
 257 sph 7.8873 5.8811 -2.4748 0.1 \$
 detector sphere 157
 258 sph 7.2702 6.6288 -2.4748 0.1 \$
 detector sphere 158
 259 sph 6.5826 7.3121 -2.4748 0.1 \$
 detector sphere 159
 260 sph 5.8310 7.9244 -2.4748 0.1 \$
 detector sphere 160
 261 sph 5.6584 -7.6897 -3.4310 0.1 \$
 detector sphere 161
 262 sph 6.3877 -7.0956 -3.4310 0.1 \$
 detector sphere 162
 263 sph 7.0550 -6.4325 -3.4310 0.1 \$
 detector sphere 163
 264 sph 7.6537 -5.7070 -3.4310 0.1 \$
 detector sphere 164
 265 sph 8.1782 -4.9261 -3.4310 0.1 \$
 detector sphere 165
 266 sph 8.6233 -4.0973 -3.4310 0.1 \$
 detector sphere 166
 267 sph 8.9847 -3.2288 -3.4310 0.1 \$
 detector sphere 167

268 sph 9.2588 -2.3290 -3.4310 0.1 \$
 detector sphere 168
 269 sph 9.4431 -1.4065 -3.4310 0.1 \$
 detector sphere 169
 270 sph 9.5356 -0.4703 -3.4310 0.1 \$
 detector sphere 170
 271 sph 9.5356 0.4703 -3.4310 0.1 \$
 detector sphere 171
 272 sph 9.4431 1.4065 -3.4310 0.1 \$
 detector sphere 172
 273 sph 9.2588 2.3290 -3.4310 0.1 \$
 detector sphere 173
 274 sph 8.9847 3.2288 -3.4310 0.1 \$
 detector sphere 174
 275 sph 8.6233 4.0973 -3.4310 0.1 \$
 detector sphere 175
 276 sph 8.1782 4.9261 -3.4310 0.1 \$
 detector sphere 176
 277 sph 7.6537 5.7070 -3.4310 0.1 \$
 detector sphere 177
 278 sph 7.0550 6.4325 -3.4310 0.1 \$
 detector sphere 178
 279 sph 6.3877 7.0956 -3.4310 0.1 \$
 detector sphere 179
 280 sph 5.6584 7.6897 -3.4310 0.1 \$
 detector sphere 180
 281 sph 5.4308 -7.3805 -4.3539 0.1 \$
 detector sphere 181
 282 sph 6.1308 -6.8102 -4.3539 0.1 \$
 detector sphere 182
 283 sph 6.7712 -6.1738 -4.3539 0.1 \$
 detector sphere 183
 284 sph 7.3459 -5.4775 -4.3539 0.1 \$
 detector sphere 184
 285 sph 7.8493 -4.7279 -4.3539 0.1 \$
 detector sphere 185
 286 sph 8.2765 -3.9325 -4.3539 0.1 \$
 detector sphere 186
 287 sph 8.6233 -3.0990 -4.3539 0.1 \$
 detector sphere 187

288 sph 8.8864 -2.2353 -4.3539 0.1 \$
 detector sphere 188
 289 sph 9.0632 -1.3499 -4.3539 0.1 \$
 detector sphere 189
 290 sph 9.1521 -0.4514 -4.3539 0.1 \$
 detector sphere 190
 291 sph 9.1521 0.4514 -4.3539 0.1 \$
 detector sphere 191
 292 sph 9.0632 1.3499 -4.3539 0.1 \$
 detector sphere 192
 293 sph 8.8864 2.2353 -4.3539 0.1 \$
 detector sphere 193
 294 sph 8.6233 3.0990 -4.3539 0.1 \$
 detector sphere 194
 295 sph 8.2765 3.9325 -4.3539 0.1 \$
 detector sphere 195
 296 sph 7.8493 4.7279 -4.3539 0.1 \$
 detector sphere 196
 297 sph 7.3459 5.4775 -4.3539 0.1 \$
 detector sphere 197
 298 sph 6.7712 6.1738 -4.3539 0.1 \$
 detector sphere 198
 299 sph 6.1308 6.8102 -4.3539 0.1 \$
 detector sphere 199
 300 sph 5.4308 7.3805 -4.3539 0.1 \$
 detector sphere 200

c **BLOCK 3: DATA CARDS **

c --- Material Definitions ---

c Air (mass fractions)

m1 6000 -0.000151 7000 -0.784437 8000 -
 0.210750 18000

-0.004671 \$ C, N, O, Ar

c Fingernail / keratin-like (mass fractions)

m2 1000 -0.108355 6000 -0.438425 7000 -
 0.143325 8000

-0.278820 16000 -0.031075 \$ H,
 C, N, O, S

c ICRU 4-tissue (mass fractions)

m3 1000 -0.101172 6000 -0.111000 7000 -
 0.026000 8000

-0.761828 \$ H, C, N, O

c --- Source Definition ---

SDEF pos=d2 erg=d1 par=2

si1 1 1.173 1.332 \$ discrete

Co-60 energies in MeV

sp1 1 1 \$ equally

probable

si2 1 7.250 -7.826 4.387

7.901 -7.169 4.387

8.492 -6.458 4.387

9.019 -5.698 4.387

9.478 -4.896 4.387

9.867 -4.057 4.387

10.181 -3.188 4.387

10.419 -2.294 4.387

10.578 -1.383 4.387

10.658 -0.462 4.387

10.658 0.462 4.387

10.578 1.383 4.387

10.419 2.294 4.387

10.181 3.188 4.387

9.867 4.057 4.387

9.478 4.896 4.387

9.019 5.698 4.387

8.492 6.458 4.387

7.901 7.169 4.387

7.250 7.826 4.387

7.481 -8.075 3.447

8.152 -7.397 3.447

8.762 -6.664 3.447

9.306 -5.880 3.447

9.780 -5.052 3.447

10.181 -4.186 3.447

10.505 -3.289 3.447

10.751 -2.367 3.447

10.915 -1.427 3.447

10.998 -0.477 3.447

10.998 0.477 3.447

10.915 1.427 3.447	11.341 1.483 1.496
10.751 2.367 3.447	11.170 2.460 1.496
10.505 3.289 3.447	10.915 3.417 1.496
10.181 4.186 3.447	10.578 4.350 1.496
9.780 5.052 3.447	10.162 5.249 1.496
9.306 5.880 3.447	9.669 6.109 1.496
8.762 6.664 3.447	9.104 6.924 1.496
8.152 7.397 3.447	8.470 7.686 1.496
7.481 8.075 3.447	7.773 8.390 1.496
7.656 -8.264 2.480	7.832 -8.454 0.500
8.343 -7.570 2.480	8.534 -7.744 0.500
8.967 -6.819 2.480	9.173 -6.976 0.500
9.523 -6.017 2.480	9.742 -6.156 0.500
10.009 -5.170 2.480	10.239 -5.289 0.500
10.419 -4.284 2.480	10.658 -4.383 0.500
10.751 -3.366 2.480	10.998 -3.443 0.500
11.002 -2.422 2.480	11.255 -2.478 0.500
11.170 -1.461 2.480	11.427 -1.494 0.500
11.255 -0.488 2.480	11.513 -0.499 0.500
11.255 0.488 2.480	11.513 0.499 0.500
11.170 1.461 2.480	11.427 1.494 0.500
11.002 2.422 2.480	11.255 2.478 0.500
10.751 3.366 2.480	10.998 3.443 0.500
10.419 4.284 2.480	10.658 4.383 0.500
10.009 5.170 2.480	10.239 5.289 0.500
9.523 6.017 2.480	9.742 6.156 0.500
8.967 6.819 2.480	9.173 6.976 0.500
8.343 7.570 2.480	8.534 7.744 0.500
7.656 8.264 2.480	7.832 8.454 0.500
7.773 -8.390 1.496	7.832 -8.454 -0.500
8.470 -7.686 1.496	8.534 -7.744 -0.500
9.104 -6.924 1.496	9.173 -6.976 -0.500
9.669 -6.109 1.496	9.742 -6.156 -0.500
10.162 -5.249 1.496	10.239 -5.289 -0.500
10.578 -4.350 1.496	10.658 -4.383 -0.500
10.915 -3.417 1.496	10.998 -3.443 -0.500
11.170 -2.460 1.496	11.255 -2.478 -0.500
11.341 -1.483 1.496	11.427 -1.494 -0.500
11.427 -0.496 1.496	11.513 -0.499 -0.500
11.427 0.496 1.496	11.513 0.499 -0.500

11.427 1.494 -0.500	11.170 1.461 -2.480
11.255 2.478 -0.500	11.002 2.422 -2.480
10.998 3.443 -0.500	10.751 3.366 -2.480
10.658 4.383 -0.500	10.419 4.284 -2.480
10.239 5.289 -0.500	10.009 5.170 -2.480
9.742 6.156 -0.500	9.523 6.017 -2.480
9.173 6.976 -0.500	8.967 6.819 -2.480
8.534 7.744 -0.500	8.343 7.570 -2.480
7.832 8.454 -0.500	7.656 8.264 -2.480
7.773 -8.390 -1.496	7.481 -8.075 -3.447
8.470 -7.686 -1.496	8.152 -7.397 -3.447
9.104 -6.924 -1.496	8.762 -6.664 -3.447
9.669 -6.109 -1.496	9.306 -5.880 -3.447
10.162 -5.249 -1.496	9.780 -5.052 -3.447
10.578 -4.350 -1.496	10.181 -4.186 -3.447
10.915 -3.417 -1.496	10.505 -3.289 -3.447
11.170 -2.460 -1.496	10.751 -2.367 -3.447
11.341 -1.483 -1.496	10.915 -1.427 -3.447
11.427 -0.496 -1.496	10.998 -0.477 -3.447
11.427 0.496 -1.496	10.998 0.477 -3.447
11.341 1.483 -1.496	10.915 1.427 -3.447
11.170 2.460 -1.496	10.751 2.367 -3.447
10.915 3.417 -1.496	10.505 3.289 -3.447
10.578 4.350 -1.496	10.181 4.186 -3.447
10.162 5.249 -1.496	9.780 5.052 -3.447
9.669 6.109 -1.496	9.306 5.880 -3.447
9.104 6.924 -1.496	8.762 6.664 -3.447
8.470 7.686 -1.496	8.152 7.397 -3.447
7.773 8.390 -1.496	7.481 8.075 -3.447
7.656 -8.264 -2.480	7.250 -7.826 -4.387
8.343 -7.570 -2.480	7.901 -7.169 -4.387
8.967 -6.819 -2.480	8.492 -6.458 -4.387
9.523 -6.017 -2.480	9.019 -5.698 -4.387
10.009 -5.170 -2.480	9.478 -4.896 -4.387
10.419 -4.284 -2.480	9.867 -4.057 -4.387
10.751 -3.366 -2.480	10.181 -3.188 -4.387
11.002 -2.422 -2.480	10.419 -2.294 -4.387
11.170 -1.461 -2.480	10.578 -1.383 -4.387
11.255 -0.488 -2.480	10.658 -0.462 -4.387
11.255 0.488 -2.480	10.658 0.462 -4.387

10.578 1.383 -4.387	+F286 129
10.419 2.294 -4.387	+F296 130
10.181 3.188 -4.387	+F306 131
9.867 4.057 -4.387	+F316 132
9.478 4.896 -4.387	+F326 133
9.019 5.698 -4.387	+F336 134
8.492 6.458 -4.387	+F346 135
7.901 7.169 -4.387	+F356 136
7.250 7.826 -4.387	+F366 137
sp2 1 199R	+F376 138
c --- Tally Definition ---	+F386 139
c --- 200 Detectors at 1.395 cm depth ---	+F396 140
+F6 101	+F406 141
+F16 102	+F416 142
+F26 103	+F426 143
+F36 104	+F436 144
+F46 105	+F446 145
+F56 106	+F456 146
+F66 107	+F466 147
+F76 108	+F476 148
+F86 109	+F486 149
+F96 110	+F496 150
+F106 111	+F506 151
+F116 112	+F516 152
+F126 113	+F526 153
+F136 114	+F536 154
+F146 115	+F546 155
+F156 116	+F556 156
+F166 117	+F566 157
+F176 118	+F576 158
+F186 119	+F586 159
+F196 120	+F596 160
+F206 121	+F606 161
+F216 122	+F616 162
+F226 123	+F626 163
+F236 124	+F636 164
+F246 125	+F646 165
+F256 126	+F656 166
+F266 127	+F666 167
+F276 128	+F676 168

+F686 169	+F1086 209
+F696 170	+F1096 210
+F706 171	+F1106 211
+F716 172	+F1116 212
+F726 173	+F1126 213
+F736 174	+F1136 214
+F746 175	+F1146 215
+F756 176	+F1156 216
+F766 177	+F1166 217
+F776 178	+F1176 218
+F786 179	+F1186 219
+F796 180	+F1196 220
+F806 181	+F1206 221
+F816 182	+F1216 222
+F826 183	+F1226 223
+F836 184	+F1236 224
+F846 185	+F1246 225
+F856 186	+F1256 226
+F866 187	+F1266 227
+F876 188	+F1276 228
+F886 189	+F1286 229
+F896 190	+F1296 230
+F906 191	+F1306 231
+F916 192	+F1316 232
+F926 193	+F1326 233
+F936 194	+F1336 234
+F946 195	+F1346 235
+F956 196	+F1356 236
+F966 197	+F1366 237
+F976 198	+F1376 238
+F986 199	+F1386 239
+F996 200	+F1396 240
+F1006 201	+F1406 241
+F1016 202	+F1416 242
+F1026 203	+F1426 243
+F1036 204	+F1436 244
+F1046 205	+F1446 245
+F1056 206	+F1456 246
+F1066 207	+F1466 247
+F1076 208	+F1476 248

+F1486 249
 +F1496 250
 +F1506 251
 +F1516 252
 +F1526 253
 +F1536 254
 +F1546 255
 +F1556 256
 +F1566 257
 +F1576 258
 +F1586 259
 +F1596 260
 +F1606 261
 +F1616 262
 +F1626 263
 +F1636 264
 +F1646 265
 +F1656 266
 +F1666 267
 +F1676 268
 +F1686 269
 +F1696 270
 +F1706 271
 +F1716 272
 +F1726 273
 +F1736 274
 +F1746 275
 +F1756 276
 +F1766 277
 +F1776 278
 +F1786 279
 +F1796 280
 +F1806 281
 +F1816 282
 +F1826 283
 +F1836 284
 +F1846 285
 +F1856 286
 +F1866 287
 +F1876 288

+F1886 289
 +F1896 290
 +F1906 291
 +F1916 292
 +F1926 293
 +F1936 294
 +F1946 295
 +F1956 296
 +F1966 297
 +F1976 298
 +F1986 299
 +F1996 300
 +F2006 (101 102 103 104 105 106 107 108
 109 110 111 112 113 114 115 116 117
 118 119 120 121 122 123 124 125 126
 127 128 129 130 131 132 133 134
 135 136 137 138 139 140 141 142 143
 144 145 146 147 148 149 150 151
 152 153 154 155 156 157 158 159 160
 161 162 163 164 165 166 167 168
 169 170 171 172 173 174 175 176 177
 178 179 180 181 182 183 184 185
 186 187 188 189 190 191 192 193 194
 195 196 197 198 199 200 201 202
 203 204 205 206 207 208 209 210 211
 212 213 214 215 216 217 218 219
 220 221 222 223 224 225 226 227 228
 229 230 231 232 233 234 235 236
 237 238 239 240 241 242 243 244 245
 246 247 248 249 250 251 252 253
 254 255 256 257 258 259 260 261 262
 263 264 265 266 267 268 269 270
 271 272 273 274 275 276 277 278 279
 280 281 282 283 284 285 286 287
 288 289 290 291 292 293 294 295 296
 297 298 299 300)
 +F2016 (101 102 103 104 105 121 122 123
 124 125 141 142 143 144 145 161 162
 163 164 165 181 182 183 184 185) \$
 SQL: Top-Left

+F2026 (106 107 108 109 110 126 127 128
 129 130 146 147 148 149 150 166 167
 168 169 170 186 187 188 189 190) \$
 SQ2: Top-MidLeft
 +F2036 (111 112 113 114 115 131 132 133
 134 135 151 152 153 154 155 171 172
 173 174 175 191 192 193 194 195) \$
 SQ3: Top-MidRight
 +F2046 (116 117 118 119 120 136 137 138
 139 140 156 157 158 159 160 176 177
 178 179 180 196 197 198 199 200) \$
 SQ4: Top-Right
 +F2056 (201 202 203 204 205 221 222 223
 224 225 241 242 243 244 245 261 262
 263 264 265 281 282 283 284 285) \$
 SQ5: Bottom-Left
 +F2066 (206 207 208 209 210 226 227 228
 229 230 246 247 248 249 250 266 267

268 269 270 286 287 288 289 290) \$
 SQ6: Bottom-MidLeft
 +F2076 (211 212 213 214 215 231 232 233
 234 235 251 252 253 254 255 271 272
 273 274 275 291 292 293 294 295) \$
 SQ7: Bottom-MidRight
 +F2086 (216 217 218 219 220 236 237 238
 239 240 256 257 258 259 260 276 277
 278 279 280 296 297 298 299 300) \$
 SQ8: Bottom-Right
 c --- Physics Parameters ---
 mode p e \$ photon mode &
 secondary e mode
 PRDMP 4J 10000000
 nps 1E10 \$ Add more as
 needed

+F6 Basal Layer of the Skin Dose for Point Detectors from a Planar Source

c Isotropic Co-60 source on pangolin scales
c **BLOCK 1: CELL CARDS **
1 1 -0.001205 +20 -30 imp:p=1 imp:e=1 \$
universe air
2 3 -1.00 -10 +101 +102 +103 +104 +105
+106 +107 +108 +109 +110 +111 +112
+113
+114 +115 +116 +117 +118 +119 +120
+121 +122 +123 +124 +125 +126 +127
+128
+129 +130 +131 +132 +133 +134 +135
+136 +137 +138 +139 +140 +141 +142
+143
+144 +145 +146 +147 +148 +149 +150
+151 +152 +153 +154 +155 +156 +157
+158
+159 +160 +161 +162 +163 +164 +165
+166 +167 +168 +169 +170 +171 +172
+173
+174 +175 +176 +177 +178 +179 +180
+181 +182 +183 +184 +185 +186 +187
+188
+189 +190 +191 +192 +193 +194 +195
+196 +197 +198 +199 +200 +201 +202
+203
+204 +205 +206 +207 +208 +209 +210
+211 +212 +213 +214 +215 +216 +217
+218
+219 +220 +221 +222 +223 +224 +225
+226 +227 +228 +229 +230 +231 +232
+233
+234 +235 +236 +237 +238 +239 +240
+241 +242 +243 +244 +245 +246 +247
+248
+249 +250 +251 +252 +253 +254 +255
+256 +257 +258 +259 +260 +261 +262
+263

+264 +265 +266 +267 +268 +269 +270
+271 +272 +273 +274 +275 +276 +277
+278
+279 +280 +281 +282 +283 +284 +285
+286 +287 +288 +289 +290 +291 +292
+293
+294 +295 +296 +297 +298 +299 +300
imp:p=1 imp:e=1 \$ soft tissue sphere
3 2 -1.35 -20 +10 +101 +102 +103 +104
+105 +106 +107 +108 +109 +110 +111
+112
+113 +114 +115 +116 +117 +118 +119
+120 +121 +122 +123 +124 +125 +126
+127
+128 +129 +130 +131 +132 +133 +134
+135 +136 +137 +138 +139 +140 +141
+142
+143 +144 +145 +146 +147 +148 +149
+150 +151 +152 +153 +154 +155 +156
+157
+158 +159 +160 +161 +162 +163 +164
+165 +166 +167 +168 +169 +170 +171
+172
+173 +174 +175 +176 +177 +178 +179
+180 +181 +182 +183 +184 +185 +186
+187
+188 +189 +190 +191 +192 +193 +194
+195 +196 +197 +198 +199 +200 +201
+202
+203 +204 +205 +206 +207 +208 +209
+210 +211 +212 +213 +214 +215 +216
+217
+218 +219 +220 +221 +222 +223 +224
+225 +226 +227 +228 +229 +230 +231
+232
+233 +234 +235 +236 +237 +238 +239
+240 +241 +242 +243 +244 +245 +246
+247

+248 +249 +250 +251 +252 +253 +254
 +255 +256 +257 +258 +259 +260 +261
 +262
 +263 +264 +265 +266 +267 +268 +269
 +270 +271 +272 +273 +274 +275 +276
 +277
 +278 +279 +280 +281 +282 +283 +284
 +285 +286 +287 +288 +289 +290 +291
 +292
 +293 +294 +295 +296 +297 +298 +299
 +300 imp:p=1 imp:e=1 \$ keratin sphere
 101 3 -1.00 -101 imp:p=1 imp:e=1 \$
 detector sphere 1
 102 3 -1.00 -102 imp:p=1 imp:e=1 \$
 detector sphere 2
 103 3 -1.00 -103 imp:p=1 imp:e=1 \$
 detector sphere 3
 104 3 -1.00 -104 imp:p=1 imp:e=1 \$
 detector sphere 4
 105 3 -1.00 -105 imp:p=1 imp:e=1 \$
 detector sphere 5
 106 3 -1.00 -106 imp:p=1 imp:e=1 \$
 detector sphere 6
 107 3 -1.00 -107 imp:p=1 imp:e=1 \$
 detector sphere 7
 108 3 -1.00 -108 imp:p=1 imp:e=1 \$
 detector sphere 8
 109 3 -1.00 -109 imp:p=1 imp:e=1 \$
 detector sphere 9
 110 3 -1.00 -110 imp:p=1 imp:e=1 \$
 detector sphere 10
 111 3 -1.00 -111 imp:p=1 imp:e=1 \$ detector
 sphere 11
 112 3 -1.00 -112 imp:p=1 imp:e=1 \$
 detector sphere 12
 113 3 -1.00 -113 imp:p=1 imp:e=1 \$
 detector sphere 13
 114 3 -1.00 -114 imp:p=1 imp:e=1 \$
 detector sphere 14

115 3 -1.00 -115 imp:p=1 imp:e=1 \$
 detector sphere 15
 116 3 -1.00 -116 imp:p=1 imp:e=1 \$
 detector sphere 16
 117 3 -1.00 -117 imp:p=1 imp:e=1 \$
 detector sphere 17
 118 3 -1.00 -118 imp:p=1 imp:e=1 \$
 detector sphere 18
 119 3 -1.00 -119 imp:p=1 imp:e=1 \$
 detector sphere 19
 120 3 -1.00 -120 imp:p=1 imp:e=1 \$
 detector sphere 20
 121 3 -1.00 -121 imp:p=1 imp:e=1 \$
 detector sphere 21
 122 3 -1.00 -122 imp:p=1 imp:e=1 \$
 detector sphere 22
 123 3 -1.00 -123 imp:p=1 imp:e=1 \$
 detector sphere 23
 124 3 -1.00 -124 imp:p=1 imp:e=1 \$
 detector sphere 24
 125 3 -1.00 -125 imp:p=1 imp:e=1 \$
 detector sphere 25
 126 3 -1.00 -126 imp:p=1 imp:e=1 \$
 detector sphere 26
 127 3 -1.00 -127 imp:p=1 imp:e=1 \$
 detector sphere 27
 128 3 -1.00 -128 imp:p=1 imp:e=1 \$
 detector sphere 28
 129 3 -1.00 -129 imp:p=1 imp:e=1 \$
 detector sphere 29
 130 3 -1.00 -130 imp:p=1 imp:e=1 \$
 detector sphere 30
 131 3 -1.00 -131 imp:p=1 imp:e=1 \$
 detector sphere 31
 132 3 -1.00 -132 imp:p=1 imp:e=1 \$
 detector sphere 32
 133 3 -1.00 -133 imp:p=1 imp:e=1 \$
 detector sphere 33
 134 3 -1.00 -134 imp:p=1 imp:e=1 \$
 detector sphere 34

135 3 -1.00 -135 imp:p=1 imp:e=1 \$
 detector sphere 35
 136 3 -1.00 -136 imp:p=1 imp:e=1 \$
 detector sphere 36
 137 3 -1.00 -137 imp:p=1 imp:e=1 \$
 detector sphere 37
 138 3 -1.00 -138 imp:p=1 imp:e=1 \$
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 139 3 -1.00 -139 imp:p=1 imp:e=1 \$
 detector sphere 39
 140 3 -1.00 -140 imp:p=1 imp:e=1 \$
 detector sphere 40
 141 3 -1.00 -141 imp:p=1 imp:e=1 \$
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 142 3 -1.00 -142 imp:p=1 imp:e=1 \$
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 143 3 -1.00 -143 imp:p=1 imp:e=1 \$
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 144 3 -1.00 -144 imp:p=1 imp:e=1 \$
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 145 3 -1.00 -145 imp:p=1 imp:e=1 \$
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 146 3 -1.00 -146 imp:p=1 imp:e=1 \$
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 147 3 -1.00 -147 imp:p=1 imp:e=1 \$
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 148 3 -1.00 -148 imp:p=1 imp:e=1 \$
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 149 3 -1.00 -149 imp:p=1 imp:e=1 \$
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 150 3 -1.00 -150 imp:p=1 imp:e=1 \$
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 151 3 -1.00 -151 imp:p=1 imp:e=1 \$
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 152 3 -1.00 -152 imp:p=1 imp:e=1 \$
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 153 3 -1.00 -153 imp:p=1 imp:e=1 \$
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 154 3 -1.00 -154 imp:p=1 imp:e=1 \$
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155 3 -1.00 -155 imp:p=1 imp:e=1 \$
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 156 3 -1.00 -156 imp:p=1 imp:e=1 \$
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 157 3 -1.00 -157 imp:p=1 imp:e=1 \$
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 158 3 -1.00 -158 imp:p=1 imp:e=1 \$
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 159 3 -1.00 -159 imp:p=1 imp:e=1 \$
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 160 3 -1.00 -160 imp:p=1 imp:e=1 \$
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 161 3 -1.00 -161 imp:p=1 imp:e=1 \$
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 162 3 -1.00 -162 imp:p=1 imp:e=1 \$
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 163 3 -1.00 -163 imp:p=1 imp:e=1 \$
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 164 3 -1.00 -164 imp:p=1 imp:e=1 \$
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 165 3 -1.00 -165 imp:p=1 imp:e=1 \$
 detector sphere 65
 166 3 -1.00 -166 imp:p=1 imp:e=1 \$
 detector sphere 66
 167 3 -1.00 -167 imp:p=1 imp:e=1 \$
 detector sphere 67
 168 3 -1.00 -168 imp:p=1 imp:e=1 \$
 detector sphere 68
 169 3 -1.00 -169 imp:p=1 imp:e=1 \$
 detector sphere 69
 170 3 -1.00 -170 imp:p=1 imp:e=1 \$
 detector sphere 70
 171 3 -1.00 -171 imp:p=1 imp:e=1 \$
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 172 3 -1.00 -172 imp:p=1 imp:e=1 \$
 detector sphere 72
 173 3 -1.00 -173 imp:p=1 imp:e=1 \$
 detector sphere 73
 174 3 -1.00 -174 imp:p=1 imp:e=1 \$
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175 3 -1.00 -175 imp:p=1 imp:e=1 \$
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 176 3 -1.00 -176 imp:p=1 imp:e=1 \$
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 177 3 -1.00 -177 imp:p=1 imp:e=1 \$
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 178 3 -1.00 -178 imp:p=1 imp:e=1 \$
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 179 3 -1.00 -179 imp:p=1 imp:e=1 \$
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 188 3 -1.00 -188 imp:p=1 imp:e=1 \$
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 193 3 -1.00 -193 imp:p=1 imp:e=1 \$
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 194 3 -1.00 -194 imp:p=1 imp:e=1 \$
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195 3 -1.00 -195 imp:p=1 imp:e=1 \$
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 196 3 -1.00 -196 imp:p=1 imp:e=1 \$
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 197 3 -1.00 -197 imp:p=1 imp:e=1 \$
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 198 3 -1.00 -198 imp:p=1 imp:e=1 \$
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 199 3 -1.00 -199 imp:p=1 imp:e=1 \$
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 201 3 -1.00 -201 imp:p=1 imp:e=1 \$
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 202 3 -1.00 -202 imp:p=1 imp:e=1 \$
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 203 3 -1.00 -203 imp:p=1 imp:e=1 \$
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 204 3 -1.00 -204 imp:p=1 imp:e=1 \$
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 205 3 -1.00 -205 imp:p=1 imp:e=1 \$
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 206 3 -1.00 -206 imp:p=1 imp:e=1 \$
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 207 3 -1.00 -207 imp:p=1 imp:e=1 \$
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 212 3 -1.00 -212 imp:p=1 imp:e=1 \$
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 213 3 -1.00 -213 imp:p=1 imp:e=1 \$
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215 3 -1.00 -215 imp:p=1 imp:e=1 \$
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 216 3 -1.00 -216 imp:p=1 imp:e=1 \$
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 217 3 -1.00 -217 imp:p=1 imp:e=1 \$
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 226 3 -1.00 -226 imp:p=1 imp:e=1 \$
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 227 3 -1.00 -227 imp:p=1 imp:e=1 \$
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 228 3 -1.00 -228 imp:p=1 imp:e=1 \$
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 229 3 -1.00 -229 imp:p=1 imp:e=1 \$
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 230 3 -1.00 -230 imp:p=1 imp:e=1 \$
 detector sphere 130
 231 3 -1.00 -231 imp:p=1 imp:e=1 \$
 detector sphere 131
 232 3 -1.00 -232 imp:p=1 imp:e=1 \$
 detector sphere 132
 233 3 -1.00 -233 imp:p=1 imp:e=1 \$
 detector sphere 133
 234 3 -1.00 -234 imp:p=1 imp:e=1 \$
 detector sphere 134

235 3 -1.00 -235 imp:p=1 imp:e=1 \$
 detector sphere 135
 236 3 -1.00 -236 imp:p=1 imp:e=1 \$
 detector sphere 136
 237 3 -1.00 -237 imp:p=1 imp:e=1 \$
 detector sphere 137
 238 3 -1.00 -238 imp:p=1 imp:e=1 \$
 detector sphere 138
 239 3 -1.00 -239 imp:p=1 imp:e=1 \$
 detector sphere 139
 240 3 -1.00 -240 imp:p=1 imp:e=1 \$
 detector sphere 140
 241 3 -1.00 -241 imp:p=1 imp:e=1 \$
 detector sphere 141
 242 3 -1.00 -242 imp:p=1 imp:e=1 \$
 detector sphere 142
 243 3 -1.00 -243 imp:p=1 imp:e=1 \$
 detector sphere 143
 244 3 -1.00 -244 imp:p=1 imp:e=1 \$
 detector sphere 144
 245 3 -1.00 -245 imp:p=1 imp:e=1 \$
 detector sphere 145
 246 3 -1.00 -246 imp:p=1 imp:e=1 \$
 detector sphere 146
 247 3 -1.00 -247 imp:p=1 imp:e=1 \$
 detector sphere 147
 248 3 -1.00 -248 imp:p=1 imp:e=1 \$
 detector sphere 148
 249 3 -1.00 -249 imp:p=1 imp:e=1 \$
 detector sphere 149
 250 3 -1.00 -250 imp:p=1 imp:e=1 \$
 detector sphere 150
 251 3 -1.00 -251 imp:p=1 imp:e=1 \$
 detector sphere 151
 252 3 -1.00 -252 imp:p=1 imp:e=1 \$
 detector sphere 152
 253 3 -1.00 -253 imp:p=1 imp:e=1 \$
 detector sphere 153
 254 3 -1.00 -254 imp:p=1 imp:e=1 \$
 detector sphere 154

255 3 -1.00 -255 imp:p=1 imp:e=1 \$
 detector sphere 155
 256 3 -1.00 -256 imp:p=1 imp:e=1 \$
 detector sphere 156
 257 3 -1.00 -257 imp:p=1 imp:e=1 \$
 detector sphere 157
 258 3 -1.00 -258 imp:p=1 imp:e=1 \$
 detector sphere 158
 259 3 -1.00 -259 imp:p=1 imp:e=1 \$
 detector sphere 159
 260 3 -1.00 -260 imp:p=1 imp:e=1 \$
 detector sphere 160
 261 3 -1.00 -261 imp:p=1 imp:e=1 \$
 detector sphere 161
 262 3 -1.00 -262 imp:p=1 imp:e=1 \$
 detector sphere 162
 263 3 -1.00 -263 imp:p=1 imp:e=1 \$
 detector sphere 163
 264 3 -1.00 -264 imp:p=1 imp:e=1 \$
 detector sphere 164
 265 3 -1.00 -265 imp:p=1 imp:e=1 \$
 detector sphere 165
 266 3 -1.00 -266 imp:p=1 imp:e=1 \$
 detector sphere 166
 267 3 -1.00 -267 imp:p=1 imp:e=1 \$
 detector sphere 167
 268 3 -1.00 -268 imp:p=1 imp:e=1 \$
 detector sphere 168
 269 3 -1.00 -269 imp:p=1 imp:e=1 \$
 detector sphere 169
 270 3 -1.00 -270 imp:p=1 imp:e=1 \$
 detector sphere 170
 271 3 -1.00 -271 imp:p=1 imp:e=1 \$
 detector sphere 171
 272 3 -1.00 -272 imp:p=1 imp:e=1 \$
 detector sphere 172
 273 3 -1.00 -273 imp:p=1 imp:e=1 \$
 detector sphere 173
 274 3 -1.00 -274 imp:p=1 imp:e=1 \$
 detector sphere 174

275 3 -1.00 -275 imp:p=1 imp:e=1 \$
 detector sphere 175
 276 3 -1.00 -276 imp:p=1 imp:e=1 \$
 detector sphere 176
 277 3 -1.00 -277 imp:p=1 imp:e=1 \$
 detector sphere 177
 278 3 -1.00 -278 imp:p=1 imp:e=1 \$
 detector sphere 178
 279 3 -1.00 -279 imp:p=1 imp:e=1 \$
 detector sphere 179
 280 3 -1.00 -280 imp:p=1 imp:e=1 \$
 detector sphere 180
 281 3 -1.00 -281 imp:p=1 imp:e=1 \$
 detector sphere 181
 282 3 -1.00 -282 imp:p=1 imp:e=1 \$
 detector sphere 182
 283 3 -1.00 -283 imp:p=1 imp:e=1 \$
 detector sphere 183
 284 3 -1.00 -284 imp:p=1 imp:e=1 \$
 detector sphere 184
 285 3 -1.00 -285 imp:p=1 imp:e=1 \$
 detector sphere 185
 286 3 -1.00 -286 imp:p=1 imp:e=1 \$
 detector sphere 186
 287 3 -1.00 -287 imp:p=1 imp:e=1 \$
 detector sphere 187
 288 3 -1.00 -288 imp:p=1 imp:e=1 \$
 detector sphere 188
 289 3 -1.00 -289 imp:p=1 imp:e=1 \$
 detector sphere 189
 290 3 -1.00 -290 imp:p=1 imp:e=1 \$
 detector sphere 190
 291 3 -1.00 -291 imp:p=1 imp:e=1 \$
 detector sphere 191
 292 3 -1.00 -292 imp:p=1 imp:e=1 \$
 detector sphere 192
 293 3 -1.00 -293 imp:p=1 imp:e=1 \$
 detector sphere 193
 294 3 -1.00 -294 imp:p=1 imp:e=1 \$
 detector sphere 194

295 3 -1.00 -295 imp:p=1 imp:e=1 \$
 detector sphere 195
 296 3 -1.00 -296 imp:p=1 imp:e=1 \$
 detector sphere 196
 297 3 -1.00 -297 imp:p=1 imp:e=1 \$
 detector sphere 197
 298 3 -1.00 -298 imp:p=1 imp:e=1 \$
 detector sphere 198
 299 3 -1.00 -299 imp:p=1 imp:e=1 \$
 detector sphere 199
 300 3 -1.00 -300 imp:p=1 imp:e=1 \$
 detector sphere 200
 999 0 +30 imp:p=0 imp:e=0 \$ outside
 world / void

c **BLOCK 2: SURFACE CARDS **

c soft tissue sphere r=11.24
 c scales sphere r=11.54
 10 sph 0 0 0 11.24 \$ pangolin
 soft tissue
 20 sph 0 0 0 11.54 \$ pangolin
 keratin scales
 30 rpp -15 15 -15 15 -15 15 \$ universe
 bounds
 c whole body detector sphere depth at 0.402
 cm
 101 sph 6.736 -7.714 4.379 0.0134 \$
 detector sphere 1
 102 sph 7.401 -7.079 4.379 0.0134 \$
 detector sphere 2
 103 sph 8.006 -6.387 4.379 0.0134 \$
 detector sphere 3
 104 sph 8.546 -5.643 4.379 0.0134 \$
 detector sphere 4
 105 sph 9.018 -4.854 4.379 0.0134 \$
 detector sphere 5
 106 sph 9.417 -4.026 4.379 0.0134 \$
 detector sphere 6
 107 sph 9.740 -3.166 4.379 0.0134 \$
 detector sphere 7

108 sph 9.984 -2.279 4.379 0.0134 \$
 detector sphere 8
 109 sph 10.149 -1.375 4.379 0.0134 \$
 detector sphere 9
 110 sph 10.231 -0.460 4.379 0.0134 \$
 detector sphere 10
 111 sph 10.231 0.460 4.379 0.0134 \$
 detector sphere 11
 112 sph 10.149 1.375 4.379 0.0134 \$
 detector sphere 12
 113 sph 9.984 2.279 4.379 0.0134 \$ detector
 sphere 13
 114 sph 9.740 3.166 4.379 0.0134 \$ detector
 sphere 14
 115 sph 9.417 4.026 4.379 0.0134 \$ detector
 sphere 15
 116 sph 9.018 4.854 4.379 0.0134 \$ detector
 sphere 16
 117 sph 8.546 5.643 4.379 0.0134 \$ detector
 sphere 17
 118 sph 8.006 6.387 4.379 0.0134 \$ detector
 sphere 18
 119 sph 7.401 7.079 4.379 0.0134 \$ detector
 sphere 19
 120 sph 6.736 7.714 4.379 0.0134 \$ detector
 sphere 20
 121 sph 6.968 -7.978 3.443 0.0134 \$
 detector sphere 21
 122 sph 7.655 -7.322 3.443 0.0134 \$
 detector sphere 22
 123 sph 8.280 -6.606 3.443 0.0134 \$
 detector sphere 23
 124 sph 8.839 -5.837 3.443 0.0134 \$
 detector sphere 24
 125 sph 9.327 -5.021 3.443 0.0134 \$
 detector sphere 25
 126 sph 9.740 -4.164 3.443 0.0134 \$
 detector sphere 26
 127 sph 10.074 -3.274 3.443 0.0134 \$
 detector sphere 27

128 sph 10.327 -2.358 3.443 0.0134 \$
 detector sphere 28
 129 sph 10.497 -1.422 3.443 0.0134 \$
 detector sphere 29
 130 sph 10.582 -0.475 3.443 0.0134 \$
 detector sphere 30
 131 sph 10.582 0.475 3.443 0.0134 \$
 detector sphere 31
 132 sph 10.497 1.422 3.443 0.0134 \$
 detector sphere 32
 133 sph 10.327 2.358 3.443 0.0134 \$
 detector sphere 33
 134 sph 10.074 3.274 3.443 0.0134 \$
 detector sphere 34
 135 sph 9.740 4.164 3.443 0.0134 \$ detector
 sphere 35
 136 sph 9.327 5.021 3.443 0.0134 \$ detector
 sphere 36
 137 sph 8.839 5.837 3.443 0.0134 \$ detector
 sphere 37
 138 sph 8.280 6.606 3.443 0.0134 \$ detector
 sphere 38
 139 sph 7.655 7.322 3.443 0.0134 \$ detector
 sphere 39
 140 sph 6.968 7.978 3.443 0.0134 \$ detector
 sphere 40
 141 sph 7.143 -8.179 2.479 0.0134 \$
 detector sphere 41
 142 sph 7.847 -7.506 2.479 0.0134 \$
 detector sphere 42
 143 sph 8.488 -6.772 2.479 0.0134 \$
 detector sphere 43
 144 sph 9.061 -5.983 2.479 0.0134 \$
 detector sphere 44
 145 sph 9.561 -5.147 2.479 0.0134 \$
 detector sphere 45
 146 sph 9.984 -4.269 2.479 0.0134 \$
 detector sphere 46
 147 sph 10.327 -3.356 2.479 0.0134 \$
 detector sphere 47

148 sph 10.586 -2.417 2.479 0.0134 \$
 detector sphere 48
 149 sph 10.760 -1.458 2.479 0.0134 \$
 detector sphere 49
 150 sph 10.848 -0.487 2.479 0.0134 \$
 detector sphere 50
 151 sph 10.848 0.487 2.479 0.0134 \$
 detector sphere 51
 152 sph 10.760 1.458 2.479 0.0134 \$
 detector sphere 52
 153 sph 10.586 2.417 2.479 0.0134 \$
 detector sphere 53
 154 sph 10.327 3.356 2.479 0.0134 \$
 detector sphere 54
 155 sph 9.984 4.269 2.479 0.0134 \$ detector
 sphere 55
 156 sph 9.561 5.147 2.479 0.0134 \$ detector
 sphere 56
 157 sph 9.061 5.983 2.479 0.0134 \$ detector
 sphere 57
 158 sph 8.488 6.772 2.479 0.0134 \$ detector
 sphere 58
 159 sph 7.847 7.506 2.479 0.0134 \$ detector
 sphere 59
 160 sph 7.143 8.179 2.479 0.0134 \$ detector
 sphere 60
 161 sph 7.260 -8.313 1.495 0.0134 \$
 detector sphere 61
 162 sph 7.976 -7.629 1.495 0.0134 \$
 detector sphere 62
 163 sph 8.628 -6.883 1.495 0.0134 \$
 detector sphere 63
 164 sph 9.210 -6.082 1.495 0.0134 \$
 detector sphere 64
 165 sph 9.719 -5.231 1.495 0.0134 \$
 detector sphere 65
 166 sph 10.149 -4.339 1.495 0.0134 \$
 detector sphere 66
 167 sph 10.497 -3.412 1.495 0.0134 \$
 detector sphere 67

168 sph 10.760 -2.457 1.495 0.0134 \$
 detector sphere 68
 169 sph 10.937 -1.482 1.495 0.0134 \$
 detector sphere 69
 170 sph 11.026 -0.495 1.495 0.0134 \$
 detector sphere 70
 171 sph 11.026 0.495 1.495 0.0134 \$
 detector sphere 71
 172 sph 10.937 1.482 1.495 0.0134 \$
 detector sphere 72
 173 sph 10.760 2.457 1.495 0.0134 \$
 detector sphere 73
 174 sph 10.497 3.412 1.495 0.0134 \$
 detector sphere 74
 175 sph 10.149 4.339 1.495 0.0134 \$
 detector sphere 75
 176 sph 9.719 5.231 1.495 0.0134 \$ detector
 sphere 76
 177 sph 9.210 6.082 1.495 0.0134 \$ detector
 sphere 77
 178 sph 8.628 6.883 1.495 0.0134 \$ detector
 sphere 78
 179 sph 7.976 7.629 1.495 0.0134 \$ detector
 sphere 79
 180 sph 7.260 8.313 1.495 0.0134 \$ detector
 sphere 80
 181 sph 7.319 -8.381 0.500 0.0134 \$
 detector sphere 81
 182 sph 8.041 -7.691 0.500 0.0134 \$
 detector sphere 82
 183 sph 8.698 -6.939 0.500 0.0134 \$
 detector sphere 83
 184 sph 9.285 -6.131 0.500 0.0134 \$
 detector sphere 84
 185 sph 9.798 -5.274 0.500 0.0134 \$
 detector sphere 85
 186 sph 10.231 -4.374 0.500 0.0134 \$
 detector sphere 86
 187 sph 10.582 -3.439 0.500 0.0134 \$
 detector sphere 87

188 sph 10.848 -2.477 0.500 0.0134 \$
 detector sphere 88
 189 sph 11.026 -1.494 0.500 0.0134 \$
 detector sphere 89
 190 sph 11.116 -0.499 0.500 0.0134 \$
 detector sphere 90
 191 sph 11.116 0.499 0.500 0.0134 \$
 detector sphere 91
 192 sph 11.026 1.494 0.500 0.0134 \$
 detector sphere 92
 193 sph 10.848 2.477 0.500 0.0134 \$
 detector sphere 93
 194 sph 10.582 3.439 0.500 0.0134 \$
 detector sphere 94
 195 sph 10.231 4.374 0.500 0.0134 \$
 detector sphere 95
 196 sph 9.798 5.274 0.500 0.0134 \$ detector
 sphere 96
 197 sph 9.285 6.131 0.500 0.0134 \$ detector
 sphere 97
 198 sph 8.698 6.939 0.500 0.0134 \$ detector
 sphere 98
 199 sph 8.041 7.691 0.500 0.0134 \$ detector
 sphere 99
 200 sph 7.319 8.381 0.500 0.0134 \$ detector
 sphere 100
 201 sph 7.319 -8.381 -0.500 0.0134 \$
 detector sphere 101
 202 sph 8.041 -7.691 -0.500 0.0134 \$
 detector sphere 102
 203 sph 8.698 -6.939 -0.500 0.0134 \$
 detector sphere 103
 204 sph 9.285 -6.131 -0.500 0.0134 \$
 detector sphere 104
 205 sph 9.798 -5.274 -0.500 0.0134 \$
 detector sphere 105
 206 sph 10.231 -4.374 -0.500 0.0134 \$
 detector sphere 106
 207 sph 10.582 -3.439 -0.500 0.0134 \$
 detector sphere 107

208 sph 10.848 -2.477 -0.500 0.0134 \$
 detector sphere 108
 209 sph 11.026 -1.494 -0.500 0.0134 \$
 detector sphere 109
 210 sph 11.116 -0.499 -0.500 0.0134 \$
 detector sphere 110
 211 sph 11.116 0.499 -0.500 0.0134 \$
 detector sphere 111
 212 sph 11.026 1.494 -0.500 0.0134 \$
 detector sphere 112
 213 sph 10.848 2.477 -0.500 0.0134 \$
 detector sphere 113
 214 sph 10.582 3.439 -0.500 0.0134 \$
 detector sphere 114
 215 sph 10.231 4.374 -0.500 0.0134 \$
 detector sphere 115
 216 sph 9.798 5.274 -0.500 0.0134 \$
 detector sphere 116
 217 sph 9.285 6.131 -0.500 0.0134 \$
 detector sphere 117
 218 sph 8.698 6.939 -0.500 0.0134 \$
 detector sphere 118
 219 sph 8.041 7.691 -0.500 0.0134 \$
 detector sphere 119
 220 sph 7.319 8.381 -0.500 0.0134 \$
 detector sphere 120
 221 sph 7.260 -8.313 -1.495 0.0134 \$
 detector sphere 121
 222 sph 7.976 -7.629 -1.495 0.0134 \$
 detector sphere 122
 223 sph 8.628 -6.883 -1.495 0.0134 \$
 detector sphere 123
 224 sph 9.210 -6.082 -1.495 0.0134 \$
 detector sphere 124
 225 sph 9.719 -5.231 -1.495 0.0134 \$
 detector sphere 125
 226 sph 10.149 -4.339 -1.495 0.0134 \$
 detector sphere 126
 227 sph 10.497 -3.412 -1.495 0.0134 \$
 detector sphere 127

228 sph 10.760 -2.457 -1.495 0.0134 \$
 detector sphere 128
 229 sph 10.937 -1.482 -1.495 0.0134 \$
 detector sphere 129
 230 sph 11.026 -0.495 -1.495 0.0134 \$
 detector sphere 130
 231 sph 11.026 0.495 -1.495 0.0134 \$
 detector sphere 131
 232 sph 10.937 1.482 -1.495 0.0134 \$
 detector sphere 132
 233 sph 10.760 2.457 -1.495 0.0134 \$
 detector sphere 133
 234 sph 10.497 3.412 -1.495 0.0134 \$
 detector sphere 134
 235 sph 10.149 4.339 -1.495 0.0134 \$
 detector sphere 135
 236 sph 9.719 5.231 -1.495 0.0134 \$
 detector sphere 136
 237 sph 9.210 6.082 -1.495 0.0134 \$
 detector sphere 137
 238 sph 8.628 6.883 -1.495 0.0134 \$
 detector sphere 138
 239 sph 7.976 7.629 -1.495 0.0134 \$
 detector sphere 139
 240 sph 7.260 8.313 -1.495 0.0134 \$
 detector sphere 140
 241 sph 7.143 -8.179 -2.479 0.0134 \$
 detector sphere 141
 242 sph 7.847 -7.506 -2.479 0.0134 \$
 detector sphere 142
 243 sph 8.488 -6.772 -2.479 0.0134 \$
 detector sphere 143
 244 sph 9.061 -5.983 -2.479 0.0134 \$
 detector sphere 144
 245 sph 9.561 -5.147 -2.479 0.0134 \$
 detector sphere 145
 246 sph 9.984 -4.269 -2.479 0.0134 \$
 detector sphere 146
 247 sph 10.327 -3.356 -2.479 0.0134 \$
 detector sphere 147

248 sph 10.586 -2.417 -2.479 0.0134 \$
 detector sphere 148
 249 sph 10.760 -1.458 -2.479 0.0134 \$
 detector sphere 149
 250 sph 10.848 -0.487 -2.479 0.0134 \$
 detector sphere 150
 251 sph 10.848 0.487 -2.479 0.0134 \$
 detector sphere 151
 252 sph 10.760 1.458 -2.479 0.0134 \$
 detector sphere 152
 253 sph 10.586 2.417 -2.479 0.0134 \$
 detector sphere 153
 254 sph 10.327 3.356 -2.479 0.0134 \$
 detector sphere 154
 255 sph 9.984 4.269 -2.479 0.0134 \$
 detector sphere 155
 256 sph 9.561 5.147 -2.479 0.0134 \$
 detector sphere 156
 257 sph 9.061 5.983 -2.479 0.0134 \$
 detector sphere 157
 258 sph 8.488 6.772 -2.479 0.0134 \$
 detector sphere 158
 259 sph 7.847 7.506 -2.479 0.0134 \$
 detector sphere 159
 260 sph 7.143 8.179 -2.479 0.0134 \$
 detector sphere 160
 261 sph 6.968 -7.978 -3.443 0.0134 \$
 detector sphere 161
 262 sph 7.655 -7.322 -3.443 0.0134 \$
 detector sphere 162
 263 sph 8.280 -6.606 -3.443 0.0134 \$
 detector sphere 163
 264 sph 8.839 -5.837 -3.443 0.0134 \$
 detector sphere 164
 265 sph 9.327 -5.021 -3.443 0.0134 \$
 detector sphere 165
 266 sph 9.740 -4.164 -3.443 0.0134 \$
 detector sphere 166
 267 sph 10.074 -3.274 -3.443 0.0134 \$
 detector sphere 167

268 sph 10.327 -2.358 -3.443 0.0134 \$
 detector sphere 168
 269 sph 10.497 -1.422 -3.443 0.0134 \$
 detector sphere 169
 270 sph 10.582 -0.475 -3.443 0.0134 \$
 detector sphere 170
 271 sph 10.582 0.475 -3.443 0.0134 \$
 detector sphere 171
 272 sph 10.497 1.422 -3.443 0.0134 \$
 detector sphere 172
 273 sph 10.327 2.358 -3.443 0.0134 \$
 detector sphere 173
 274 sph 10.074 3.274 -3.443 0.0134 \$
 detector sphere 174
 275 sph 9.740 4.164 -3.443 0.0134 \$
 detector sphere 175
 276 sph 9.327 5.021 -3.443 0.0134 \$
 detector sphere 176
 277 sph 8.839 5.837 -3.443 0.0134 \$
 detector sphere 177
 278 sph 8.280 6.606 -3.443 0.0134 \$
 detector sphere 178
 279 sph 7.655 7.322 -3.443 0.0134 \$
 detector sphere 179
 280 sph 6.968 7.978 -3.443 0.0134 \$
 detector sphere 180
 281 sph 6.736 -7.714 -4.379 0.0134 \$
 detector sphere 181
 282 sph 7.401 -7.079 -4.379 0.0134 \$
 detector sphere 182
 283 sph 8.006 -6.387 -4.379 0.0134 \$
 detector sphere 183
 284 sph 8.546 -5.643 -4.379 0.0134 \$
 detector sphere 184
 285 sph 9.018 -4.854 -4.379 0.0134 \$
 detector sphere 185
 286 sph 9.417 -4.026 -4.379 0.0134 \$
 detector sphere 186
 287 sph 9.740 -3.166 -4.379 0.0134 \$
 detector sphere 187

288 sph 9.984 -2.279 -4.379 0.0134 \$
 detector sphere 188
 289 sph 10.149 -1.375 -4.379 0.0134 \$
 detector sphere 189
 290 sph 10.231 -0.460 -4.379 0.0134 \$
 detector sphere 190
 291 sph 10.231 0.460 -4.379 0.0134 \$
 detector sphere 191
 292 sph 10.149 1.375 -4.379 0.0134 \$
 detector sphere 192
 293 sph 9.984 2.279 -4.379 0.0134 \$
 detector sphere 193
 294 sph 9.740 3.166 -4.379 0.0134 \$
 detector sphere 194
 295 sph 9.417 4.026 -4.379 0.0134 \$
 detector sphere 195
 296 sph 9.018 4.854 -4.379 0.0134 \$
 detector sphere 196
 297 sph 8.546 5.643 -4.379 0.0134 \$
 detector sphere 197
 298 sph 8.006 6.387 -4.379 0.0134 \$
 detector sphere 198
 299 sph 7.401 7.079 -4.379 0.0134 \$
 detector sphere 199
 300 sph 6.736 7.714 -4.379 0.0134 \$
 detector sphere 200

 c ** BLOCK 3: DATA CARDS **
 c --- Material Definitions ---
 c Air (mass fractions)
 m1 6000 -0.000151 7000 -0.784437 8000 -
 0.210750 18000
 -0.004671 \$ C, N, O, Ar
 c Fingernail / keratin-like (mass fractions)
 m2 1000 -0.108355 6000 -0.438425 7000 -
 0.143325 8000
 -0.278820 16000 -0.031075 \$ H,
 C, N, O, S
 c ICRU 4-tissue (mass fractions)

m3 1000 -0.101172 6000 -0.111000 7000 -
 0.026000 8000
 -0.761828 \$ H, C, N, O
 c --- Source Definition ---
 SDEF pos=d2 erg=d1 par=2
 si1 1 1.173 1.332 \$ discrete
 Co-60 energies in MeV
 sp1 1 1 \$ equally
 probable
 si2 1 7.250 -7.826 4.387
 7.901 -7.169 4.387
 8.492 -6.458 4.387
 9.019 -5.698 4.387
 9.478 -4.896 4.387
 9.867 -4.057 4.387
 10.181 -3.188 4.387
 10.419 -2.294 4.387
 10.578 -1.383 4.387
 10.658 -0.462 4.387
 10.658 0.462 4.387
 10.578 1.383 4.387
 10.419 2.294 4.387
 10.181 3.188 4.387
 9.867 4.057 4.387
 9.478 4.896 4.387
 9.019 5.698 4.387
 8.492 6.458 4.387
 7.901 7.169 4.387
 7.250 7.826 4.387
 7.481 -8.075 3.447
 8.152 -7.397 3.447
 8.762 -6.664 3.447
 9.306 -5.880 3.447
 9.780 -5.052 3.447
 10.181 -4.186 3.447
 10.505 -3.289 3.447
 10.751 -2.367 3.447
 10.915 -1.427 3.447
 10.998 -0.477 3.447
 10.998 0.477 3.447

10.915 1.427 3.447	11.341 1.483 1.496
10.751 2.367 3.447	11.170 2.460 1.496
10.505 3.289 3.447	10.915 3.417 1.496
10.181 4.186 3.447	10.578 4.350 1.496
9.780 5.052 3.447	10.162 5.249 1.496
9.306 5.880 3.447	9.669 6.109 1.496
8.762 6.664 3.447	9.104 6.924 1.496
8.152 7.397 3.447	8.470 7.686 1.496
7.481 8.075 3.447	7.773 8.390 1.496
7.656 -8.264 2.480	7.832 -8.454 0.500
8.343 -7.570 2.480	8.534 -7.744 0.500
8.967 -6.819 2.480	9.173 -6.976 0.500
9.523 -6.017 2.480	9.742 -6.156 0.500
10.009 -5.170 2.480	10.239 -5.289 0.500
10.419 -4.284 2.480	10.658 -4.383 0.500
10.751 -3.366 2.480	10.998 -3.443 0.500
11.002 -2.422 2.480	11.255 -2.478 0.500
11.170 -1.461 2.480	11.427 -1.494 0.500
11.255 -0.488 2.480	11.513 -0.499 0.500
11.255 0.488 2.480	11.513 0.499 0.500
11.170 1.461 2.480	11.427 1.494 0.500
11.002 2.422 2.480	11.255 2.478 0.500
10.751 3.366 2.480	10.998 3.443 0.500
10.419 4.284 2.480	10.658 4.383 0.500
10.009 5.170 2.480	10.239 5.289 0.500
9.523 6.017 2.480	9.742 6.156 0.500
8.967 6.819 2.480	9.173 6.976 0.500
8.343 7.570 2.480	8.534 7.744 0.500
7.656 8.264 2.480	7.832 8.454 0.500
7.773 -8.390 1.496	7.832 -8.454 -0.500
8.470 -7.686 1.496	8.534 -7.744 -0.500
9.104 -6.924 1.496	9.173 -6.976 -0.500
9.669 -6.109 1.496	9.742 -6.156 -0.500
10.162 -5.249 1.496	10.239 -5.289 -0.500
10.578 -4.350 1.496	10.658 -4.383 -0.500
10.915 -3.417 1.496	10.998 -3.443 -0.500
11.170 -2.460 1.496	11.255 -2.478 -0.500
11.341 -1.483 1.496	11.427 -1.494 -0.500
11.427 -0.496 1.496	11.513 -0.499 -0.500
11.427 0.496 1.496	11.513 0.499 -0.500

11.427 1.494 -0.500
11.255 2.478 -0.500
10.998 3.443 -0.500
10.658 4.383 -0.500
10.239 5.289 -0.500
9.742 6.156 -0.500
9.173 6.976 -0.500
8.534 7.744 -0.500
7.832 8.454 -0.500
7.773 -8.390 -1.496
8.470 -7.686 -1.496
9.104 -6.924 -1.496
9.669 -6.109 -1.496
10.162 -5.249 -1.496
10.578 -4.350 -1.496
10.915 -3.417 -1.496
11.170 -2.460 -1.496
11.341 -1.483 -1.496
11.427 -0.496 -1.496
11.427 0.496 -1.496
11.341 1.483 -1.496
11.170 2.460 -1.496
10.915 3.417 -1.496
10.578 4.350 -1.496
10.162 5.249 -1.496
9.669 6.109 -1.496
9.104 6.924 -1.496
8.470 7.686 -1.496
7.773 8.390 -1.496
7.656 -8.264 -2.480
8.343 -7.570 -2.480
8.967 -6.819 -2.480
9.523 -6.017 -2.480
10.009 -5.170 -2.480
10.419 -4.284 -2.480
10.751 -3.366 -2.480
11.002 -2.422 -2.480
11.170 -1.461 -2.480
11.255 -0.488 -2.480
11.255 0.488 -2.480

11.170 1.461 -2.480
11.002 2.422 -2.480
10.751 3.366 -2.480
10.419 4.284 -2.480
10.009 5.170 -2.480
9.523 6.017 -2.480
8.967 6.819 -2.480
8.343 7.570 -2.480
7.656 8.264 -2.480
7.481 -8.075 -3.447
8.152 -7.397 -3.447
8.762 -6.664 -3.447
9.306 -5.880 -3.447
9.780 -5.052 -3.447
10.181 -4.186 -3.447
10.505 -3.289 -3.447
10.751 -2.367 -3.447
10.915 -1.427 -3.447
10.998 -0.477 -3.447
10.998 0.477 -3.447
10.915 1.427 -3.447
10.751 2.367 -3.447
10.505 3.289 -3.447
10.181 4.186 -3.447
9.780 5.052 -3.447
9.306 5.880 -3.447
8.762 6.664 -3.447
8.152 7.397 -3.447
7.481 8.075 -3.447
7.250 -7.826 -4.387
7.901 -7.169 -4.387
8.492 -6.458 -4.387
9.019 -5.698 -4.387
9.478 -4.896 -4.387
9.867 -4.057 -4.387
10.181 -3.188 -4.387
10.419 -2.294 -4.387
10.578 -1.383 -4.387
10.658 -0.462 -4.387
10.658 0.462 -4.387

10.578 1.383 -4.387	+F286 129
10.419 2.294 -4.387	+F296 130
10.181 3.188 -4.387	+F306 131
9.867 4.057 -4.387	+F316 132
9.478 4.896 -4.387	+F326 133
9.019 5.698 -4.387	+F336 134
8.492 6.458 -4.387	+F346 135
7.901 7.169 -4.387	+F356 136
7.250 7.826 -4.387	+F366 137
sp2 1 199R	+F376 138
c --- Tally Definition ---	+F386 139
c --- 200 Detectors at 0.402 cm depth ---	+F396 140
+F6 101	+F406 141
+F16 102	+F416 142
+F26 103	+F426 143
+F36 104	+F436 144
+F46 105	+F446 145
+F56 106	+F456 146
+F66 107	+F466 147
+F76 108	+F476 148
+F86 109	+F486 149
+F96 110	+F496 150
+F106 111	+F506 151
+F116 112	+F516 152
+F126 113	+F526 153
+F136 114	+F536 154
+F146 115	+F546 155
+F156 116	+F556 156
+F166 117	+F566 157
+F176 118	+F576 158
+F186 119	+F586 159
+F196 120	+F596 160
+F206 121	+F606 161
+F216 122	+F616 162
+F226 123	+F626 163
+F236 124	+F636 164
+F246 125	+F646 165
+F256 126	+F656 166
+F266 127	+F666 167
+F276 128	+F676 168

+F686 169	+F1086 209
+F696 170	+F1096 210
+F706 171	+F1106 211
+F716 172	+F1116 212
+F726 173	+F1126 213
+F736 174	+F1136 214
+F746 175	+F1146 215
+F756 176	+F1156 216
+F766 177	+F1166 217
+F776 178	+F1176 218
+F786 179	+F1186 219
+F796 180	+F1196 220
+F806 181	+F1206 221
+F816 182	+F1216 222
+F826 183	+F1226 223
+F836 184	+F1236 224
+F846 185	+F1246 225
+F856 186	+F1256 226
+F866 187	+F1266 227
+F876 188	+F1276 228
+F886 189	+F1286 229
+F896 190	+F1296 230
+F906 191	+F1306 231
+F916 192	+F1316 232
+F926 193	+F1326 233
+F936 194	+F1336 234
+F946 195	+F1346 235
+F956 196	+F1356 236
+F966 197	+F1366 237
+F976 198	+F1376 238
+F986 199	+F1386 239
+F996 200	+F1396 240
+F1006 201	+F1406 241
+F1016 202	+F1416 242
+F1026 203	+F1426 243
+F1036 204	+F1436 244
+F1046 205	+F1446 245
+F1056 206	+F1456 246
+F1066 207	+F1466 247
+F1076 208	+F1476 248

+F1486 249
 +F1496 250
 +F1506 251
 +F1516 252
 +F1526 253
 +F1536 254
 +F1546 255
 +F1556 256
 +F1566 257
 +F1576 258
 +F1586 259
 +F1596 260
 +F1606 261
 +F1616 262
 +F1626 263
 +F1636 264
 +F1646 265
 +F1656 266
 +F1666 267
 +F1676 268
 +F1686 269
 +F1696 270
 +F1706 271
 +F1716 272
 +F1726 273
 +F1736 274
 +F1746 275
 +F1756 276
 +F1766 277
 +F1776 278
 +F1786 279
 +F1796 280
 +F1806 281
 +F1816 282
 +F1826 283
 +F1836 284
 +F1846 285
 +F1856 286
 +F1866 287
 +F1876 288

+F1886 289
 +F1896 290
 +F1906 291
 +F1916 292
 +F1926 293
 +F1936 294
 +F1946 295
 +F1956 296
 +F1966 297
 +F1976 298
 +F1986 299
 +F1996 300
 +F2006 (101 102 103 104 105 106 107 108
 109 110 111 112 113 114 115 116 117
 118 119 120 121 122 123 124 125 126
 127 128 129 130 131 132 133 134
 135 136 137 138 139 140 141 142 143
 144 145 146 147 148 149 150 151
 152 153 154 155 156 157 158 159 160
 161 162 163 164 165 166 167 168
 169 170 171 172 173 174 175 176 177
 178 179 180 181 182 183 184 185
 186 187 188 189 190 191 192 193 194
 195 196 197 198 199 200 201 202
 203 204 205 206 207 208 209 210 211
 212 213 214 215 216 217 218 219
 220 221 222 223 224 225 226 227 228
 229 230 231 232 233 234 235 236
 237 238 239 240 241 242 243 244 245
 246 247 248 249 250 251 252 253
 254 255 256 257 258 259 260 261 262
 263 264 265 266 267 268 269 270
 271 272 273 274 275 276 277 278 279
 280 281 282 283 284 285 286 287
 288 289 290 291 292 293 294 295 296
 297 298 299 300)
 +F2016 (101 102 103 104 105 121 122 123
 124 125 141 142 143 144 145 161 162
 163 164 165 181 182 183 184 185) \$
 SQ1: Top-Left

+F2026 (106 107 108 109 110 126 127 128
 129 130 146 147 148 149 150 166 167
 168 169 170 186 187 188 189 190) \$
 SQ2: Top-MidLeft
 +F2036 (111 112 113 114 115 131 132 133
 134 135 151 152 153 154 155 171 172
 173 174 175 191 192 193 194 195) \$
 SQ3: Top-MidRight
 +F2046 (116 117 118 119 120 136 137 138
 139 140 156 157 158 159 160 176 177
 178 179 180 196 197 198 199 200) \$
 SQ4: Top-Right
 +F2056 (201 202 203 204 205 221 222 223
 224 225 241 242 243 244 245 261 262
 263 264 265 281 282 283 284 285) \$
 SQ5: Bottom-Left
 +F2066 (206 207 208 209 210 226 227 228
 229 230 246 247 248 249 250 266 267

268 269 270 286 287 288 289 290) \$
 SQ6: Bottom-MidLeft
 +F2076 (211 212 213 214 215 231 232 233
 234 235 251 252 253 254 255 271 272
 273 274 275 291 292 293 294 295) \$
 SQ7: Bottom-MidRight
 +F2086 (216 217 218 219 220 236 237 238
 239 240 256 257 258 259 260 276 277
 278 279 280 296 297 298 299 300) \$
 SQ8: Bottom-Right
 c --- Physics Parameters ---
 mode p e \$ photon mode &
 secondary e mode
 PRDMP 4J 10000000
 nps 1E10 \$ Add more as
 needed

+F6 Basal Layer of the Skin Dose for Disc Detectors from a Planar Source

c Isotropic Co-60 source on pangolin scales

c **BLOCK 1: CELL CARDS **

1 1 -0.001205 +20 -30 imp:p=1 imp:e=1 \$
universe air

2 3 -1.00 -10 +101 +102 +103 +104 +105
+106 +107 +108 +109 +110 +111 +112
+113

+114 +115 +116 +117 +118 +119 +120
+121 +122 +123 +124 +125 +126 +127
+128

+129 +130 +131 +132 +133 +134 +135
+136 +137 +138 +139 +140 +141 +142
+143

+144 +145 +146 +147 +148 +149 +150
+151 +152 +153 +154 +155 +156 +157
+158

+159 +160 +161 +162 +163 +164 +165
+166 +167 +168 +169 +170 +171 +172
+173

+174 +175 +176 +177 +178 +179 +180
+181 +182 +183 +184 +185 +186 +187
+188

+189 +190 +191 +192 +193 +194 +195
+196 +197 +198 +199 +200 +201 +202
+203

+204 +205 +206 +207 +208 +209 +210
+211 +212 +213 +214 +215 +216 +217
+218

+219 +220 +221 +222 +223 +224 +225
+226 +227 +228 +229 +230 +231 +232
+233

+234 +235 +236 +237 +238 +239 +240
+241 +242 +243 +244 +245 +246 +247
+248

+249 +250 +251 +252 +253 +254 +255
+256 +257 +258 +259 +260 +261 +262
+263

+264 +265 +266 +267 +268 +269 +270
+271 +272 +273 +274 +275 +276 +277
+278

+279 +280 +281 +282 +283 +284 +285
+286 +287 +288 +289 +290 +291 +292
+293

+294 +295 +296 +297 +298 +299 +300

imp:p=1 imp:e=1 \$ soft tissue sphere

3 2 -1.35 -20 +10 +101 +102 +103 +104
+105 +106 +107 +108 +109 +110 +111
+112

+113 +114 +115 +116 +117 +118 +119
+120 +121 +122 +123 +124 +125 +126
+127

+128 +129 +130 +131 +132 +133 +134
+135 +136 +137 +138 +139 +140 +141
+142

+143 +144 +145 +146 +147 +148 +149
+150 +151 +152 +153 +154 +155 +156
+157

+158 +159 +160 +161 +162 +163 +164
+165 +166 +167 +168 +169 +170 +171
+172

+173 +174 +175 +176 +177 +178 +179
+180 +181 +182 +183 +184 +185 +186
+187

+188 +189 +190 +191 +192 +193 +194
+195 +196 +197 +198 +199 +200 +201
+202

+203 +204 +205 +206 +207 +208 +209
+210 +211 +212 +213 +214 +215 +216
+217

+218 +219 +220 +221 +222 +223 +224
+225 +226 +227 +228 +229 +230 +231
+232

+233 +234 +235 +236 +237 +238 +239
+240 +241 +242 +243 +244 +245 +246
+247

+248 +249 +250 +251 +252 +253 +254
+255 +256 +257 +258 +259 +260 +261
+262

+263 +264 +265 +266 +267 +268 +269
+270 +271 +272 +273 +274 +275 +276
+277

+278 +279 +280 +281 +282 +283 +284
+285 +286 +287 +288 +289 +290 +291
+292

+293 +294 +295 +296 +297 +298 +299
+300 imp:p=1 imp:e=1 \$ keratin sphere

101 3 -1.00 -101 imp:p=1 imp:e=1 \$
detector disc 1
102 3 -1.00 -102 imp:p=1 imp:e=1 \$
detector disc 2
103 3 -1.00 -103 imp:p=1 imp:e=1 \$
detector disc 3
104 3 -1.00 -104 imp:p=1 imp:e=1 \$
detector disc 4
105 3 -1.00 -105 imp:p=1 imp:e=1 \$
detector disc 5
106 3 -1.00 -106 imp:p=1 imp:e=1 \$
detector disc 6
107 3 -1.00 -107 imp:p=1 imp:e=1 \$
detector disc 7
108 3 -1.00 -108 imp:p=1 imp:e=1 \$
detector disc 8
109 3 -1.00 -109 imp:p=1 imp:e=1 \$
detector disc 9
110 3 -1.00 -110 imp:p=1 imp:e=1 \$
detector disc 10
111 3 -1.00 -111 imp:p=1 imp:e=1 \$ detector
disc 11
112 3 -1.00 -112 imp:p=1 imp:e=1 \$
detector disc 12
113 3 -1.00 -113 imp:p=1 imp:e=1 \$
detector disc 13
114 3 -1.00 -114 imp:p=1 imp:e=1 \$
detector disc 14
115 3 -1.00 -115 imp:p=1 imp:e=1 \$
detector disc 15
116 3 -1.00 -116 imp:p=1 imp:e=1 \$
detector disc 16
117 3 -1.00 -117 imp:p=1 imp:e=1 \$
detector disc 17
118 3 -1.00 -118 imp:p=1 imp:e=1 \$
detector disc 18
119 3 -1.00 -119 imp:p=1 imp:e=1 \$
detector disc 19
120 3 -1.00 -120 imp:p=1 imp:e=1 \$
detector disc 20
121 3 -1.00 -121 imp:p=1 imp:e=1 \$
detector disc 21
122 3 -1.00 -122 imp:p=1 imp:e=1 \$
detector disc 22
123 3 -1.00 -123 imp:p=1 imp:e=1 \$
detector disc 23

124 3 -1.00 -124 imp:p=1 imp:e=1 \$
detector disc 24
125 3 -1.00 -125 imp:p=1 imp:e=1 \$
detector disc 25
126 3 -1.00 -126 imp:p=1 imp:e=1 \$
detector disc 26
127 3 -1.00 -127 imp:p=1 imp:e=1 \$
detector disc 27
128 3 -1.00 -128 imp:p=1 imp:e=1 \$
detector disc 28
129 3 -1.00 -129 imp:p=1 imp:e=1 \$
detector disc 29
130 3 -1.00 -130 imp:p=1 imp:e=1 \$
detector disc 30
131 3 -1.00 -131 imp:p=1 imp:e=1 \$
detector disc 31
132 3 -1.00 -132 imp:p=1 imp:e=1 \$
detector disc 32
133 3 -1.00 -133 imp:p=1 imp:e=1 \$
detector disc 33
134 3 -1.00 -134 imp:p=1 imp:e=1 \$
detector disc 34
135 3 -1.00 -135 imp:p=1 imp:e=1 \$
detector disc 35
136 3 -1.00 -136 imp:p=1 imp:e=1 \$
detector disc 36
137 3 -1.00 -137 imp:p=1 imp:e=1 \$
detector disc 37
138 3 -1.00 -138 imp:p=1 imp:e=1 \$
detector disc 38
139 3 -1.00 -139 imp:p=1 imp:e=1 \$
detector disc 39
140 3 -1.00 -140 imp:p=1 imp:e=1 \$
detector disc 40
141 3 -1.00 -141 imp:p=1 imp:e=1 \$
detector disc 41
142 3 -1.00 -142 imp:p=1 imp:e=1 \$
detector disc 42
143 3 -1.00 -143 imp:p=1 imp:e=1 \$
detector disc 43
144 3 -1.00 -144 imp:p=1 imp:e=1 \$
detector disc 44
145 3 -1.00 -145 imp:p=1 imp:e=1 \$
detector disc 45
146 3 -1.00 -146 imp:p=1 imp:e=1 \$
detector disc 46

147 3 -1.00 -147 imp:p=1 imp:e=1 \$
detector disc 47
148 3 -1.00 -148 imp:p=1 imp:e=1 \$
detector disc 48
149 3 -1.00 -149 imp:p=1 imp:e=1 \$
detector disc 49
150 3 -1.00 -150 imp:p=1 imp:e=1 \$
detector disc 50
151 3 -1.00 -151 imp:p=1 imp:e=1 \$
detector disc 51
152 3 -1.00 -152 imp:p=1 imp:e=1 \$
detector disc 52
153 3 -1.00 -153 imp:p=1 imp:e=1 \$
detector disc 53
154 3 -1.00 -154 imp:p=1 imp:e=1 \$
detector disc 54
155 3 -1.00 -155 imp:p=1 imp:e=1 \$
detector disc 55
156 3 -1.00 -156 imp:p=1 imp:e=1 \$
detector disc 56
157 3 -1.00 -157 imp:p=1 imp:e=1 \$
detector disc 57
158 3 -1.00 -158 imp:p=1 imp:e=1 \$
detector disc 58
159 3 -1.00 -159 imp:p=1 imp:e=1 \$
detector disc 59
160 3 -1.00 -160 imp:p=1 imp:e=1 \$
detector disc 60
161 3 -1.00 -161 imp:p=1 imp:e=1 \$
detector disc 61
162 3 -1.00 -162 imp:p=1 imp:e=1 \$
detector disc 62
163 3 -1.00 -163 imp:p=1 imp:e=1 \$
detector disc 63
164 3 -1.00 -164 imp:p=1 imp:e=1 \$
detector disc 64
165 3 -1.00 -165 imp:p=1 imp:e=1 \$
detector disc 65
166 3 -1.00 -166 imp:p=1 imp:e=1 \$
detector disc 66
167 3 -1.00 -167 imp:p=1 imp:e=1 \$
detector disc 67
168 3 -1.00 -168 imp:p=1 imp:e=1 \$
detector disc 68
169 3 -1.00 -169 imp:p=1 imp:e=1 \$
detector disc 69

170 3 -1.00 -170 imp:p=1 imp:e=1 \$
detector disc 70
171 3 -1.00 -171 imp:p=1 imp:e=1 \$
detector disc 71
172 3 -1.00 -172 imp:p=1 imp:e=1 \$
detector disc 72
173 3 -1.00 -173 imp:p=1 imp:e=1 \$
detector disc 73
174 3 -1.00 -174 imp:p=1 imp:e=1 \$
detector disc 74
175 3 -1.00 -175 imp:p=1 imp:e=1 \$
detector disc 75
176 3 -1.00 -176 imp:p=1 imp:e=1 \$
detector disc 76
177 3 -1.00 -177 imp:p=1 imp:e=1 \$
detector disc 77
178 3 -1.00 -178 imp:p=1 imp:e=1 \$
detector disc 78
179 3 -1.00 -179 imp:p=1 imp:e=1 \$
detector disc 79
180 3 -1.00 -180 imp:p=1 imp:e=1 \$
detector disc 80
181 3 -1.00 -181 imp:p=1 imp:e=1 \$
detector disc 81
182 3 -1.00 -182 imp:p=1 imp:e=1 \$
detector disc 82
183 3 -1.00 -183 imp:p=1 imp:e=1 \$
detector disc 83
184 3 -1.00 -184 imp:p=1 imp:e=1 \$
detector disc 84
185 3 -1.00 -185 imp:p=1 imp:e=1 \$
detector disc 85
186 3 -1.00 -186 imp:p=1 imp:e=1 \$
detector disc 86
187 3 -1.00 -187 imp:p=1 imp:e=1 \$
detector disc 87
188 3 -1.00 -188 imp:p=1 imp:e=1 \$
detector disc 88
189 3 -1.00 -189 imp:p=1 imp:e=1 \$
detector disc 89
190 3 -1.00 -190 imp:p=1 imp:e=1 \$
detector disc 90
191 3 -1.00 -191 imp:p=1 imp:e=1 \$
detector disc 91
192 3 -1.00 -192 imp:p=1 imp:e=1 \$
detector disc 92

193 3 -1.00 -193 imp:p=1 imp:e=1 \$
detector disc 93
194 3 -1.00 -194 imp:p=1 imp:e=1 \$
detector disc 94
195 3 -1.00 -195 imp:p=1 imp:e=1 \$
detector disc 95
196 3 -1.00 -196 imp:p=1 imp:e=1 \$
detector disc 96
197 3 -1.00 -197 imp:p=1 imp:e=1 \$
detector disc 97
198 3 -1.00 -198 imp:p=1 imp:e=1 \$
detector disc 98
199 3 -1.00 -199 imp:p=1 imp:e=1 \$
detector disc 99
200 3 -1.00 -200 imp:p=1 imp:e=1 \$
detector disc 100
201 3 -1.00 -201 imp:p=1 imp:e=1 \$
detector disc 101
202 3 -1.00 -202 imp:p=1 imp:e=1 \$
detector disc 102
203 3 -1.00 -203 imp:p=1 imp:e=1 \$
detector disc 103
204 3 -1.00 -204 imp:p=1 imp:e=1 \$
detector disc 104
205 3 -1.00 -205 imp:p=1 imp:e=1 \$
detector disc 105
206 3 -1.00 -206 imp:p=1 imp:e=1 \$
detector disc 106
207 3 -1.00 -207 imp:p=1 imp:e=1 \$
detector disc 107
208 3 -1.00 -208 imp:p=1 imp:e=1 \$
detector disc 108
209 3 -1.00 -209 imp:p=1 imp:e=1 \$
detector disc 109
210 3 -1.00 -210 imp:p=1 imp:e=1 \$
detector disc 110
211 3 -1.00 -211 imp:p=1 imp:e=1 \$
detector disc 111
212 3 -1.00 -212 imp:p=1 imp:e=1 \$
detector disc 112
213 3 -1.00 -213 imp:p=1 imp:e=1 \$
detector disc 113
214 3 -1.00 -214 imp:p=1 imp:e=1 \$
detector disc 114
215 3 -1.00 -215 imp:p=1 imp:e=1 \$
detector disc 115

216 3 -1.00 -216 imp:p=1 imp:e=1 \$
detector disc 116
217 3 -1.00 -217 imp:p=1 imp:e=1 \$
detector disc 117
218 3 -1.00 -218 imp:p=1 imp:e=1 \$
detector disc 118
219 3 -1.00 -219 imp:p=1 imp:e=1 \$
detector disc 119
220 3 -1.00 -220 imp:p=1 imp:e=1 \$
detector disc 120
221 3 -1.00 -221 imp:p=1 imp:e=1 \$
detector disc 121
222 3 -1.00 -222 imp:p=1 imp:e=1 \$
detector disc 122
223 3 -1.00 -223 imp:p=1 imp:e=1 \$
detector disc 123
224 3 -1.00 -224 imp:p=1 imp:e=1 \$
detector disc 124
225 3 -1.00 -225 imp:p=1 imp:e=1 \$
detector disc 125
226 3 -1.00 -226 imp:p=1 imp:e=1 \$
detector disc 126
227 3 -1.00 -227 imp:p=1 imp:e=1 \$
detector disc 127
228 3 -1.00 -228 imp:p=1 imp:e=1 \$
detector disc 128
229 3 -1.00 -229 imp:p=1 imp:e=1 \$
detector disc 129
230 3 -1.00 -230 imp:p=1 imp:e=1 \$
detector disc 130
231 3 -1.00 -231 imp:p=1 imp:e=1 \$
detector disc 131
232 3 -1.00 -232 imp:p=1 imp:e=1 \$
detector disc 132
233 3 -1.00 -233 imp:p=1 imp:e=1 \$
detector disc 133
234 3 -1.00 -234 imp:p=1 imp:e=1 \$
detector disc 134
235 3 -1.00 -235 imp:p=1 imp:e=1 \$
detector disc 135
236 3 -1.00 -236 imp:p=1 imp:e=1 \$
detector disc 136
237 3 -1.00 -237 imp:p=1 imp:e=1 \$
detector disc 137
238 3 -1.00 -238 imp:p=1 imp:e=1 \$
detector disc 138

239 3 -1.00 -239 imp:p=1 imp:e=1 \$
 detector disc 139
 240 3 -1.00 -240 imp:p=1 imp:e=1 \$
 detector disc 140
 241 3 -1.00 -241 imp:p=1 imp:e=1 \$
 detector disc 141
 242 3 -1.00 -242 imp:p=1 imp:e=1 \$
 detector disc 142
 243 3 -1.00 -243 imp:p=1 imp:e=1 \$
 detector disc 143
 244 3 -1.00 -244 imp:p=1 imp:e=1 \$
 detector disc 144
 245 3 -1.00 -245 imp:p=1 imp:e=1 \$
 detector disc 145
 246 3 -1.00 -246 imp:p=1 imp:e=1 \$
 detector disc 146
 247 3 -1.00 -247 imp:p=1 imp:e=1 \$
 detector disc 147
 248 3 -1.00 -248 imp:p=1 imp:e=1 \$
 detector disc 148
 249 3 -1.00 -249 imp:p=1 imp:e=1 \$
 detector disc 149
 250 3 -1.00 -250 imp:p=1 imp:e=1 \$
 detector disc 150
 251 3 -1.00 -251 imp:p=1 imp:e=1 \$
 detector disc 151
 252 3 -1.00 -252 imp:p=1 imp:e=1 \$
 detector disc 152
 253 3 -1.00 -253 imp:p=1 imp:e=1 \$
 detector disc 153
 254 3 -1.00 -254 imp:p=1 imp:e=1 \$
 detector disc 154
 255 3 -1.00 -255 imp:p=1 imp:e=1 \$
 detector disc 155
 256 3 -1.00 -256 imp:p=1 imp:e=1 \$
 detector disc 156
 257 3 -1.00 -257 imp:p=1 imp:e=1 \$
 detector disc 157
 258 3 -1.00 -258 imp:p=1 imp:e=1 \$
 detector disc 158
 259 3 -1.00 -259 imp:p=1 imp:e=1 \$
 detector disc 159
 260 3 -1.00 -260 imp:p=1 imp:e=1 \$
 detector disc 160
 261 3 -1.00 -261 imp:p=1 imp:e=1 \$
 detector disc 161

262 3 -1.00 -262 imp:p=1 imp:e=1 \$
 detector disc 162
 263 3 -1.00 -263 imp:p=1 imp:e=1 \$
 detector disc 163
 264 3 -1.00 -264 imp:p=1 imp:e=1 \$
 detector disc 164
 265 3 -1.00 -265 imp:p=1 imp:e=1 \$
 detector disc 165
 266 3 -1.00 -266 imp:p=1 imp:e=1 \$
 detector disc 166
 267 3 -1.00 -267 imp:p=1 imp:e=1 \$
 detector disc 167
 268 3 -1.00 -268 imp:p=1 imp:e=1 \$
 detector disc 168
 269 3 -1.00 -269 imp:p=1 imp:e=1 \$
 detector disc 169
 270 3 -1.00 -270 imp:p=1 imp:e=1 \$
 detector disc 170
 271 3 -1.00 -271 imp:p=1 imp:e=1 \$
 detector disc 171
 272 3 -1.00 -272 imp:p=1 imp:e=1 \$
 detector disc 172
 273 3 -1.00 -273 imp:p=1 imp:e=1 \$
 detector disc 173
 274 3 -1.00 -274 imp:p=1 imp:e=1 \$
 detector disc 174
 275 3 -1.00 -275 imp:p=1 imp:e=1 \$
 detector disc 175
 276 3 -1.00 -276 imp:p=1 imp:e=1 \$
 detector disc 176
 277 3 -1.00 -277 imp:p=1 imp:e=1 \$
 detector disc 177
 278 3 -1.00 -278 imp:p=1 imp:e=1 \$
 detector disc 178
 279 3 -1.00 -279 imp:p=1 imp:e=1 \$
 detector disc 179
 280 3 -1.00 -280 imp:p=1 imp:e=1 \$
 detector disc 180
 281 3 -1.00 -281 imp:p=1 imp:e=1 \$
 detector disc 181
 282 3 -1.00 -282 imp:p=1 imp:e=1 \$
 detector disc 182
 283 3 -1.00 -283 imp:p=1 imp:e=1 \$
 detector disc 183
 284 3 -1.00 -284 imp:p=1 imp:e=1 \$
 detector disc 184

285 3 -1.00 -285 imp:p=1 imp:e=1 \$
 detector disc 185
 286 3 -1.00 -286 imp:p=1 imp:e=1 \$
 detector disc 186
 287 3 -1.00 -287 imp:p=1 imp:e=1 \$
 detector disc 187
 288 3 -1.00 -288 imp:p=1 imp:e=1 \$
 detector disc 188
 289 3 -1.00 -289 imp:p=1 imp:e=1 \$
 detector disc 189
 290 3 -1.00 -290 imp:p=1 imp:e=1 \$
 detector disc 190
 291 3 -1.00 -291 imp:p=1 imp:e=1 \$
 detector disc 191
 292 3 -1.00 -292 imp:p=1 imp:e=1 \$
 detector disc 192
 293 3 -1.00 -293 imp:p=1 imp:e=1 \$
 detector disc 193
 294 3 -1.00 -294 imp:p=1 imp:e=1 \$
 detector disc 194
 295 3 -1.00 -295 imp:p=1 imp:e=1 \$
 detector disc 195
 296 3 -1.00 -296 imp:p=1 imp:e=1 \$
 detector disc 196
 297 3 -1.00 -297 imp:p=1 imp:e=1 \$
 detector disc 197
 298 3 -1.00 -298 imp:p=1 imp:e=1 \$
 detector disc 198
 299 3 -1.00 -299 imp:p=1 imp:e=1 \$
 detector disc 199
 300 3 -1.00 -300 imp:p=1 imp:e=1 \$
 detector disc 200
 999 0 +30 imp:p=0 imp:e=0 \$ outside
 world / void

 c **BLOCK 2: SURFACE CARDS**
 c soft tissue sphere r=11.24
 c scales sphere r=11.54
 10 sph 0 0 0 11.24 \$ pangolin
 soft tissue
 20 sph 0 0 0 11.54 \$ pangolin
 keratin scales
 30 rpp -15 15 -15 15 -15 15 \$ universe
 bounds
 c basal layer detectors, r=11.133 at 0.407 cm
 depth base

c height of rcc = 0.01cm, center of rcc at
 0.402 cm depth
 101 rcc 6.730 -7.712 4.378 0.00605 -
 0.00693 0.00393 0.45
 102 rcc 7.395 -7.078 4.378 0.00664 -
 0.00636 0.00393 0.45
 103 rcc 8.000 -6.386 4.378 0.00719 -
 0.00574 0.00393 0.45
 104 rcc 8.540 -5.642 4.378 0.00767 -
 0.00507 0.00393 0.45
 105 rcc 9.012 -4.854 4.378 0.00809 -
 0.00436 0.00393 0.45
 106 rcc 9.411 -4.026 4.378 0.00845 -
 0.00362 0.00393 0.45
 107 rcc 9.734 -3.165 4.378 0.00874 -
 0.00284 0.00393 0.45
 108 rcc 9.979 -2.279 4.378 0.00896 -
 0.00205 0.00393 0.45
 109 rcc 10.143 -1.375 4.378 0.00911 -
 0.00124 0.00393 0.45
 110 rcc 10.226 -0.460 4.378 0.00918 -
 0.00041 0.00393 0.45
 111 rcc 10.226 0.460 4.378 0.00918 0.00041
 0.00393 0.45
 112 rcc 10.143 1.375 4.378 0.00911 0.00124
 0.00393 0.45
 113 rcc 9.979 2.279 4.378 0.00896 0.00205
 0.00393 0.45
 114 rcc 9.734 3.165 4.378 0.00874 0.00284
 0.00393 0.45
 115 rcc 9.411 4.026 4.378 0.00845 0.00362
 0.00393 0.45
 116 rcc 9.012 4.854 4.378 0.00809 0.00436
 0.00393 0.45
 117 rcc 8.540 5.642 4.378 0.00767 0.00507
 0.00393 0.45
 118 rcc 8.000 6.386 4.378 0.00719 0.00574
 0.00393 0.45
 119 rcc 7.395 7.078 4.378 0.00664 0.00636
 0.00393 0.45
 120 rcc 6.730 7.712 4.378 0.00605 0.00693
 0.00393 0.45
 121 rcc 6.961 -7.977 3.443 0.00625 -
 0.00717 0.00309 0.45
 122 rcc 7.649 -7.321 3.443 0.00687 -
 0.00658 0.00309 0.45

123 rcc 8.274 -6.605 3.443 0.00743 -	146 rcc 9.979 -4.269 2.479 0.00896 -
0.00593 0.00309 0.45	0.00383 0.00223 0.45
124 rcc 8.834 -5.836 3.443 0.00793 -	147 rcc 10.322 -3.356 2.479 0.00927 -
0.00524 0.00309 0.45	0.00301 0.00223 0.45
125 rcc 9.321 -5.020 3.443 0.00837 -	148 rcc 10.581 -2.417 2.479 0.00950 -
0.00451 0.00309 0.45	0.00217 0.00223 0.45
126 rcc 9.734 -4.164 3.443 0.00874 -	149 rcc 10.755 -1.458 2.479 0.00966 -
0.00374 0.00309 0.45	0.00131 0.00223 0.45
127 rcc 10.068 -3.274 3.443 0.00904 -	150 rcc 10.843 -0.487 2.479 0.00974 -
0.00294 0.00309 0.45	0.00044 0.00223 0.45
128 rcc 10.322 -2.358 3.443 0.00927 -	151 rcc 10.843 0.487 2.479 0.00974 0.00044
0.00212 0.00309 0.45	0.00223 0.45
129 rcc 10.491 -1.422 3.443 0.00942 -	152 rcc 10.755 1.458 2.479 0.00966 0.00131
0.00128 0.00309 0.45	0.00223 0.45
130 rcc 10.577 -0.475 3.443 0.00950 -	153 rcc 10.581 2.417 2.479 0.00950 0.00217
0.00043 0.00309 0.45	0.00223 0.45
131 rcc 10.577 0.475 3.443 0.00950 0.00043	154 rcc 10.322 3.356 2.479 0.00927 0.00301
0.00309 0.45	0.00223 0.45
132 rcc 10.491 1.422 3.443 0.00942 0.00128	155 rcc 9.979 4.269 2.479 0.00896 0.00383
0.00309 0.45	0.00223 0.45
133 rcc 10.322 2.358 3.443 0.00927 0.00212	156 rcc 9.556 5.146 2.479 0.00858 0.00462
0.00309 0.45	0.00223 0.45
134 rcc 10.068 3.274 3.443 0.00904 0.00294	157 rcc 9.056 5.983 2.479 0.00813 0.00537
0.00309 0.45	0.00223 0.45
135 rcc 9.734 4.164 3.443 0.00874 0.00374	158 rcc 8.482 6.771 2.479 0.00762 0.00608
0.00309 0.45	0.00223 0.45
136 rcc 9.321 5.020 3.443 0.00837 0.00451	159 rcc 7.841 7.505 2.479 0.00704 0.00674
0.00309 0.45	0.00223 0.45
137 rcc 8.834 5.836 3.443 0.00793 0.00524	160 rcc 7.136 8.178 2.479 0.00641 0.00735
0.00309 0.45	0.00223 0.45
138 rcc 8.274 6.605 3.443 0.00743 0.00593	161 rcc 7.253 -8.312 1.495 0.00652 -
0.00309 0.45	0.00747 0.00134 0.45
139 rcc 7.649 7.321 3.443 0.00687 0.00658	162 rcc 7.970 -7.628 1.495 0.00716 -
0.00309 0.45	0.00685 0.00134 0.45
140 rcc 6.961 7.977 3.443 0.00625 0.00717	163 rcc 8.622 -6.882 1.495 0.00774 -
0.00309 0.45	0.00618 0.00134 0.45
141 rcc 7.136 -8.178 2.479 0.00641 -	164 rcc 9.205 -6.081 1.495 0.00827 -
0.00735 0.00223 0.45	0.00546 0.00134 0.45
142 rcc 7.841 -7.505 2.479 0.00704 -	165 rcc 9.713 -5.231 1.495 0.00872 -
0.00674 0.00223 0.45	0.00470 0.00134 0.45
143 rcc 8.482 -6.771 2.479 0.00762 -	166 rcc 10.143 -4.339 1.495 0.00911 -
0.00608 0.00223 0.45	0.00390 0.00134 0.45
144 rcc 9.056 -5.983 2.479 0.00813 -	167 rcc 10.491 -3.411 1.495 0.00942 -
0.00537 0.00223 0.45	0.00306 0.00134 0.45
145 rcc 9.556 -5.146 2.479 0.00858 -	168 rcc 10.755 -2.457 1.495 0.00966 -
0.00462 0.00223 0.45	0.00221 0.00134 0.45

169 rcc 10.932 -1.482 1.495 0.00982 -
 0.00133 0.00134 0.45
 170 rcc 11.021 -0.495 1.495 0.00990 -
 0.00044 0.00134 0.45
 171 rcc 11.021 0.495 1.495 0.00990 0.00044
 0.00134 0.45
 172 rcc 10.932 1.482 1.495 0.00982 0.00133
 0.00134 0.45
 173 rcc 10.755 2.457 1.495 0.00966 0.00221
 0.00134 0.45
 174 rcc 10.491 3.411 1.495 0.00942 0.00306
 0.00134 0.45
 175 rcc 10.143 4.339 1.495 0.00911 0.00390
 0.00134 0.45
 176 rcc 9.713 5.231 1.495 0.00872 0.00470
 0.00134 0.45
 177 rcc 9.205 6.081 1.495 0.00827 0.00546
 0.00134 0.45
 178 rcc 8.622 6.882 1.495 0.00774 0.00618
 0.00134 0.45
 179 rcc 7.970 7.628 1.495 0.00716 0.00685
 0.00134 0.45
 180 rcc 7.253 8.312 1.495 0.00652 0.00747
 0.00134 0.45
 181 rcc 7.312 -8.380 0.500 0.00657 -
 0.00753 0.00045 0.45
 182 rcc 8.035 -7.690 0.500 0.00722 -
 0.00691 0.00045 0.45
 183 rcc 8.692 -6.938 0.500 0.00781 -
 0.00623 0.00045 0.45
 184 rcc 9.279 -6.131 0.500 0.00834 -
 0.00551 0.00045 0.45
 185 rcc 9.792 -5.274 0.500 0.00880 -
 0.00474 0.00045 0.45
 186 rcc 10.226 -4.374 0.500 0.00918 -
 0.00393 0.00045 0.45
 187 rcc 10.577 -3.439 0.500 0.00950 -
 0.00309 0.00045 0.45
 188 rcc 10.843 -2.477 0.500 0.00974 -
 0.00222 0.00045 0.45
 189 rcc 11.021 -1.494 0.500 0.00990 -
 0.00134 0.00045 0.45
 190 rcc 11.111 -0.499 0.500 0.00998 -
 0.00045 0.00045 0.45
 191 rcc 11.111 0.499 0.500 0.00998 0.00045
 0.00045 0.45

192 rcc 11.021 1.494 0.500 0.00990 0.00134
 0.00045 0.45
 193 rcc 10.843 2.477 0.500 0.00974 0.00222
 0.00045 0.45
 194 rcc 10.577 3.439 0.500 0.00950 0.00309
 0.00045 0.45
 195 rcc 10.226 4.374 0.500 0.00918 0.00393
 0.00045 0.45
 196 rcc 9.792 5.274 0.500 0.00880 0.00474
 0.00045 0.45
 197 rcc 9.279 6.131 0.500 0.00834 0.00551
 0.00045 0.45
 198 rcc 8.692 6.938 0.500 0.00781 0.00623
 0.00045 0.45
 199 rcc 8.035 7.690 0.500 0.00722 0.00691
 0.00045 0.45
 200 rcc 7.312 8.380 0.500 0.00657 0.00753
 0.00045 0.45
 201 rcc 7.312 -8.380 -0.500 0.00657 -
 0.00753 -0.00045 0.45
 202 rcc 8.035 -7.690 -0.500 0.00722 -
 0.00691 -0.00045 0.45
 203 rcc 8.692 -6.938 -0.500 0.00781 -
 0.00623 -0.00045 0.45
 204 rcc 9.279 -6.131 -0.500 0.00834 -
 0.00551 -0.00045 0.45
 205 rcc 9.792 -5.274 -0.500 0.00880 -
 0.00474 -0.00045 0.45
 206 rcc 10.226 -4.374 -0.500 0.00918 -
 0.00393 -0.00045 0.45
 207 rcc 10.577 -3.439 -0.500 0.00950 -
 0.00309 -0.00045 0.45
 208 rcc 10.843 -2.477 -0.500 0.00974 -
 0.00222 -0.00045 0.45
 209 rcc 11.021 -1.494 -0.500 0.00990 -
 0.00134 -0.00045 0.45
 210 rcc 11.111 -0.499 -0.500 0.00998 -
 0.00045 -0.00045 0.45
 211 rcc 11.111 0.499 -0.500 0.00998
 0.00045 -0.00045 0.45
 212 rcc 11.021 1.494 -0.500 0.00990
 0.00134 -0.00045 0.45
 213 rcc 10.843 2.477 -0.500 0.00974
 0.00222 -0.00045 0.45
 214 rcc 10.577 3.439 -0.500 0.00950
 0.00309 -0.00045 0.45

215 rcc 10.226 4.374 -0.500 0.00918
 0.00393 -0.00045 0.45
 216 rcc 9.792 5.274 -0.500 0.00880 0.00474
 -0.00045 0.45
 217 rcc 9.279 6.131 -0.500 0.00834 0.00551
 -0.00045 0.45
 218 rcc 8.692 6.938 -0.500 0.00781 0.00623
 -0.00045 0.45
 219 rcc 8.035 7.690 -0.500 0.00722 0.00691
 -0.00045 0.45
 220 rcc 7.312 8.380 -0.500 0.00657 0.00753
 -0.00045 0.45
 221 rcc 7.253 -8.312 -1.495 0.00652 -
 0.00747 -0.00134 0.45
 222 rcc 7.970 -7.628 -1.495 0.00716 -
 0.00685 -0.00134 0.45
 223 rcc 8.622 -6.882 -1.495 0.00774 -
 0.00618 -0.00134 0.45
 224 rcc 9.205 -6.081 -1.495 0.00827 -
 0.00546 -0.00134 0.45
 225 rcc 9.713 -5.231 -1.495 0.00872 -
 0.00470 -0.00134 0.45
 226 rcc 10.143 -4.339 -1.495 0.00911 -
 0.00390 -0.00134 0.45
 227 rcc 10.491 -3.411 -1.495 0.00942 -
 0.00306 -0.00134 0.45
 228 rcc 10.755 -2.457 -1.495 0.00966 -
 0.00221 -0.00134 0.45
 229 rcc 10.932 -1.482 -1.495 0.00982 -
 0.00133 -0.00134 0.45
 230 rcc 11.021 -0.495 -1.495 0.00990 -
 0.00044 -0.00134 0.45
 231 rcc 11.021 0.495 -1.495 0.00990
 0.00044 -0.00134 0.45
 232 rcc 10.932 1.482 -1.495 0.00982
 0.00133 -0.00134 0.45
 233 rcc 10.755 2.457 -1.495 0.00966
 0.00221 -0.00134 0.45
 234 rcc 10.491 3.411 -1.495 0.00942
 0.00306 -0.00134 0.45
 235 rcc 10.143 4.339 -1.495 0.00911
 0.00390 -0.00134 0.45
 236 rcc 9.713 5.231 -1.495 0.00872 0.00470
 -0.00134 0.45
 237 rcc 9.205 6.081 -1.495 0.00827 0.00546
 -0.00134 0.45

238 rcc 8.622 6.882 -1.495 0.00774 0.00618
 -0.00134 0.45
 239 rcc 7.970 7.628 -1.495 0.00716 0.00685
 -0.00134 0.45
 240 rcc 7.253 8.312 -1.495 0.00652 0.00747
 -0.00134 0.45
 241 rcc 7.136 -8.178 -2.479 0.00641 -
 0.00735 -0.00223 0.45
 242 rcc 7.841 -7.505 -2.479 0.00704 -
 0.00674 -0.00223 0.45
 243 rcc 8.482 -6.771 -2.479 0.00762 -
 0.00608 -0.00223 0.45
 244 rcc 9.056 -5.983 -2.479 0.00813 -
 0.00537 -0.00223 0.45
 245 rcc 9.556 -5.146 -2.479 0.00858 -
 0.00462 -0.00223 0.45
 246 rcc 9.979 -4.269 -2.479 0.00896 -
 0.00383 -0.00223 0.45
 247 rcc 10.322 -3.356 -2.479 0.00927 -
 0.00301 -0.00223 0.45
 248 rcc 10.581 -2.417 -2.479 0.00950 -
 0.00217 -0.00223 0.45
 249 rcc 10.755 -1.458 -2.479 0.00966 -
 0.00131 -0.00223 0.45
 250 rcc 10.843 -0.487 -2.479 0.00974 -
 0.00044 -0.00223 0.45
 251 rcc 10.843 0.487 -2.479 0.00974
 0.00044 -0.00223 0.45
 252 rcc 10.755 1.458 -2.479 0.00966
 0.00131 -0.00223 0.45
 253 rcc 10.581 2.417 -2.479 0.00950
 0.00217 -0.00223 0.45
 254 rcc 10.322 3.356 -2.479 0.00927
 0.00301 -0.00223 0.45
 255 rcc 9.979 4.269 -2.479 0.00896 0.00383
 -0.00223 0.45
 256 rcc 9.556 5.146 -2.479 0.00858 0.00462
 -0.00223 0.45
 257 rcc 9.056 5.983 -2.479 0.00813 0.00537
 -0.00223 0.45
 258 rcc 8.482 6.771 -2.479 0.00762 0.00608
 -0.00223 0.45
 259 rcc 7.841 7.505 -2.479 0.00704 0.00674
 -0.00223 0.45
 260 rcc 7.136 8.178 -2.479 0.00641 0.00735
 -0.00223 0.45

261 rcc 6.961 -7.977 -3.443 0.00625 -
 0.00717 -0.00309 0.45
 262 rcc 7.649 -7.321 -3.443 0.00687 -
 0.00658 -0.00309 0.45
 263 rcc 8.274 -6.605 -3.443 0.00743 -
 0.00593 -0.00309 0.45
 264 rcc 8.834 -5.836 -3.443 0.00793 -
 0.00524 -0.00309 0.45
 265 rcc 9.321 -5.020 -3.443 0.00837 -
 0.00451 -0.00309 0.45
 266 rcc 9.734 -4.164 -3.443 0.00874 -
 0.00374 -0.00309 0.45
 267 rcc 10.068 -3.274 -3.443 0.00904 -
 0.00294 -0.00309 0.45
 268 rcc 10.322 -2.358 -3.443 0.00927 -
 0.00212 -0.00309 0.45
 269 rcc 10.491 -1.422 -3.443 0.00942 -
 0.00128 -0.00309 0.45
 270 rcc 10.577 -0.475 -3.443 0.00950 -
 0.00043 -0.00309 0.45
 271 rcc 10.577 0.475 -3.443 0.00950
 0.00043 -0.00309 0.45
 272 rcc 10.491 1.422 -3.443 0.00942
 0.00128 -0.00309 0.45
 273 rcc 10.322 2.358 -3.443 0.00927
 0.00212 -0.00309 0.45
 274 rcc 10.068 3.274 -3.443 0.00904
 0.00294 -0.00309 0.45
 275 rcc 9.734 4.164 -3.443 0.00874 0.00374
 -0.00309 0.45
 276 rcc 9.321 5.020 -3.443 0.00837 0.00451
 -0.00309 0.45
 277 rcc 8.834 5.836 -3.443 0.00793 0.00524
 -0.00309 0.45
 278 rcc 8.274 6.605 -3.443 0.00743 0.00593
 -0.00309 0.45
 279 rcc 7.649 7.321 -3.443 0.00687 0.00658
 -0.00309 0.45
 280 rcc 6.961 7.977 -3.443 0.00625 0.00717
 -0.00309 0.45
 281 rcc 6.730 -7.712 -4.378 0.00605 -
 0.00693 -0.00393 0.45
 282 rcc 7.395 -7.078 -4.378 0.00664 -
 0.00636 -0.00393 0.45
 283 rcc 8.000 -6.386 -4.378 0.00719 -
 0.00574 -0.00393 0.45

284 rcc 8.540 -5.642 -4.378 0.00767 -
 0.00507 -0.00393 0.45
 285 rcc 9.012 -4.854 -4.378 0.00809 -
 0.00436 -0.00393 0.45
 286 rcc 9.411 -4.026 -4.378 0.00845 -
 0.00362 -0.00393 0.45
 287 rcc 9.734 -3.165 -4.378 0.00874 -
 0.00284 -0.00393 0.45
 288 rcc 9.979 -2.279 -4.378 0.00896 -
 0.00205 -0.00393 0.45
 289 rcc 10.143 -1.375 -4.378 0.00911 -
 0.00124 -0.00393 0.45
 290 rcc 10.226 -0.460 -4.378 0.00918 -
 0.00041 -0.00393 0.45
 291 rcc 10.226 0.460 -4.378 0.00918
 0.00041 -0.00393 0.45
 292 rcc 10.143 1.375 -4.378 0.00911
 0.00124 -0.00393 0.45
 293 rcc 9.979 2.279 -4.378 0.00896 0.00205
 -0.00393 0.45
 294 rcc 9.734 3.165 -4.378 0.00874 0.00284
 -0.00393 0.45
 295 rcc 9.411 4.026 -4.378 0.00845 0.00362
 -0.00393 0.45
 296 rcc 9.012 4.854 -4.378 0.00809 0.00436
 -0.00393 0.45
 297 rcc 8.540 5.642 -4.378 0.00767 0.00507
 -0.00393 0.45
 298 rcc 8.000 6.386 -4.378 0.00719 0.00574
 -0.00393 0.45
 299 rcc 7.395 7.078 -4.378 0.00664 0.00636
 -0.00393 0.45
 300 rcc 6.730 7.712 -4.378 0.00605 0.00693
 -0.00393 0.45

c **BLOCK 3: DATA CARDS **

c --- Material Definitions ---

c Air (mass fractions)

m1 6000 -0.000151 7000 -0.784437 8000 -
 0.210750 18000

-0.004671 \$ C, N, O, Ar

c Fingernail / keratin-like (mass fractions)

m2 1000 -0.108355 6000 -0.438425 7000 -
 0.143325 8000

-0.278820 16000 -0.031075 \$ H,

C, N, O, S

c ICRU 4-tissue (mass fractions)	9.306 5.880 3.447
m3 1000 -0.101172 6000 -0.111000 7000 -	8.762 6.664 3.447
0.026000 8000	8.152 7.397 3.447
-0.761828 \$ H, C, N, O	7.481 8.075 3.447
c --- Source Definition ---	7.656 -8.264 2.480
SDEF pos=d2 erg=d1 par=2	8.343 -7.570 2.480
si1 1 1.173 1.332 \$ discrete	8.967 -6.819 2.480
Co-60 energies in MeV	9.523 -6.017 2.480
sp1 1 1 \$ equally	10.009 -5.170 2.480
probable	10.419 -4.284 2.480
si2 1 7.250 -7.826 4.387	10.751 -3.366 2.480
7.901 -7.169 4.387	11.002 -2.422 2.480
8.492 -6.458 4.387	11.170 -1.461 2.480
9.019 -5.698 4.387	11.255 -0.488 2.480
9.478 -4.896 4.387	11.255 0.488 2.480
9.867 -4.057 4.387	11.170 1.461 2.480
10.181 -3.188 4.387	11.002 2.422 2.480
10.419 -2.294 4.387	10.751 3.366 2.480
10.578 -1.383 4.387	10.419 4.284 2.480
10.658 -0.462 4.387	10.009 5.170 2.480
10.658 0.462 4.387	9.523 6.017 2.480
10.578 1.383 4.387	8.967 6.819 2.480
10.419 2.294 4.387	8.343 7.570 2.480
10.181 3.188 4.387	7.656 8.264 2.480
9.867 4.057 4.387	7.773 -8.390 1.496
9.478 4.896 4.387	8.470 -7.686 1.496
9.019 5.698 4.387	9.104 -6.924 1.496
8.492 6.458 4.387	9.669 -6.109 1.496
7.901 7.169 4.387	10.162 -5.249 1.496
7.250 7.826 4.387	10.578 -4.350 1.496
7.481 -8.075 3.447	10.915 -3.417 1.496
8.152 -7.397 3.447	11.170 -2.460 1.496
8.762 -6.664 3.447	11.341 -1.483 1.496
9.306 -5.880 3.447	11.427 -0.496 1.496
9.780 -5.052 3.447	11.427 0.496 1.496
10.181 -4.186 3.447	11.341 1.483 1.496
10.505 -3.289 3.447	11.170 2.460 1.496
10.751 -2.367 3.447	10.915 3.417 1.496
10.915 -1.427 3.447	10.578 4.350 1.496
10.998 -0.477 3.447	10.162 5.249 1.496
10.998 0.477 3.447	9.669 6.109 1.496
10.915 1.427 3.447	9.104 6.924 1.496
10.751 2.367 3.447	8.470 7.686 1.496
10.505 3.289 3.447	7.773 8.390 1.496
10.181 4.186 3.447	7.832 -8.454 0.500
9.780 5.052 3.447	8.534 -7.744 0.500

9.173 -6.976 0.500	11.341 -1.483 -1.496
9.742 -6.156 0.500	11.427 -0.496 -1.496
10.239 -5.289 0.500	11.427 0.496 -1.496
10.658 -4.383 0.500	11.341 1.483 -1.496
10.998 -3.443 0.500	11.170 2.460 -1.496
11.255 -2.478 0.500	10.915 3.417 -1.496
11.427 -1.494 0.500	10.578 4.350 -1.496
11.513 -0.499 0.500	10.162 5.249 -1.496
11.513 0.499 0.500	9.669 6.109 -1.496
11.427 1.494 0.500	9.104 6.924 -1.496
11.255 2.478 0.500	8.470 7.686 -1.496
10.998 3.443 0.500	7.773 8.390 -1.496
10.658 4.383 0.500	7.656 -8.264 -2.480
10.239 5.289 0.500	8.343 -7.570 -2.480
9.742 6.156 0.500	8.967 -6.819 -2.480
9.173 6.976 0.500	9.523 -6.017 -2.480
8.534 7.744 0.500	10.009 -5.170 -2.480
7.832 8.454 0.500	10.419 -4.284 -2.480
7.832 -8.454 -0.500	10.751 -3.366 -2.480
8.534 -7.744 -0.500	11.002 -2.422 -2.480
9.173 -6.976 -0.500	11.170 -1.461 -2.480
9.742 -6.156 -0.500	11.255 -0.488 -2.480
10.239 -5.289 -0.500	11.255 0.488 -2.480
10.658 -4.383 -0.500	11.170 1.461 -2.480
10.998 -3.443 -0.500	11.002 2.422 -2.480
11.255 -2.478 -0.500	10.751 3.366 -2.480
11.427 -1.494 -0.500	10.419 4.284 -2.480
11.513 -0.499 -0.500	10.009 5.170 -2.480
11.513 0.499 -0.500	9.523 6.017 -2.480
11.427 1.494 -0.500	8.967 6.819 -2.480
11.255 2.478 -0.500	8.343 7.570 -2.480
10.998 3.443 -0.500	7.656 8.264 -2.480
10.658 4.383 -0.500	7.481 -8.075 -3.447
10.239 5.289 -0.500	8.152 -7.397 -3.447
9.742 6.156 -0.500	8.762 -6.664 -3.447
9.173 6.976 -0.500	9.306 -5.880 -3.447
8.534 7.744 -0.500	9.780 -5.052 -3.447
7.832 8.454 -0.500	10.181 -4.186 -3.447
7.773 -8.390 -1.496	10.505 -3.289 -3.447
8.470 -7.686 -1.496	10.751 -2.367 -3.447
9.104 -6.924 -1.496	10.915 -1.427 -3.447
9.669 -6.109 -1.496	10.998 -0.477 -3.447
10.162 -5.249 -1.496	10.998 0.477 -3.447
10.578 -4.350 -1.496	10.915 1.427 -3.447
10.915 -3.417 -1.496	10.751 2.367 -3.447
11.170 -2.460 -1.496	10.505 3.289 -3.447

10.181 4.186 -3.447	+F176 118
9.780 5.052 -3.447	+F186 119
9.306 5.880 -3.447	+F196 120
8.762 6.664 -3.447	+F206 121
8.152 7.397 -3.447	+F216 122
7.481 8.075 -3.447	+F226 123
7.250 -7.826 -4.387	+F236 124
7.901 -7.169 -4.387	+F246 125
8.492 -6.458 -4.387	+F256 126
9.019 -5.698 -4.387	+F266 127
9.478 -4.896 -4.387	+F276 128
9.867 -4.057 -4.387	+F286 129
10.181 -3.188 -4.387	+F296 130
10.419 -2.294 -4.387	+F306 131
10.578 -1.383 -4.387	+F316 132
10.658 -0.462 -4.387	+F326 133
10.658 0.462 -4.387	+F336 134
10.578 1.383 -4.387	+F346 135
10.419 2.294 -4.387	+F356 136
10.181 3.188 -4.387	+F366 137
9.867 4.057 -4.387	+F376 138
9.478 4.896 -4.387	+F386 139
9.019 5.698 -4.387	+F396 140
8.492 6.458 -4.387	+F406 141
7.901 7.169 -4.387	+F416 142
7.250 7.826 -4.387	+F426 143
sp2 1 199R	+F436 144
c --- Tally Definition ---	+F446 145
c --- 200 Detectors at 0.402 cm depth ---	+F456 146
+F6 101	+F466 147
+F16 102	+F476 148
+F26 103	+F486 149
+F36 104	+F496 150
+F46 105	+F506 151
+F56 106	+F516 152
+F66 107	+F526 153
+F76 108	+F536 154
+F86 109	+F546 155
+F96 110	+F556 156
+F106 111	+F566 157
+F116 112	+F576 158
+F126 113	+F586 159
+F136 114	+F596 160
+F146 115	+F606 161
+F156 116	+F616 162
+F166 117	+F626 163

+F636 164	+F1096 210
+F646 165	+F1106 211
+F656 166	+F1116 212
+F666 167	+F1126 213
+F676 168	+F1136 214
+F686 169	+F1146 215
+F696 170	+F1156 216
+F706 171	+F1166 217
+F716 172	+F1176 218
+F726 173	+F1186 219
+F736 174	+F1196 220
+F746 175	+F1206 221
+F756 176	+F1216 222
+F766 177	+F1226 223
+F776 178	+F1236 224
+F786 179	+F1246 225
+F796 180	+F1256 226
+F806 181	+F1266 227
+F816 182	+F1276 228
+F826 183	+F1286 229
+F836 184	+F1296 230
+F846 185	+F1306 231
+F856 186	+F1316 232
+F866 187	+F1326 233
+F876 188	+F1336 234
+F886 189	+F1346 235
+F896 190	+F1356 236
+F906 191	+F1366 237
+F916 192	+F1376 238
+F926 193	+F1386 239
+F936 194	+F1396 240
+F946 195	+F1406 241
+F956 196	+F1416 242
+F966 197	+F1426 243
+F976 198	+F1436 244
+F986 199	+F1446 245
+F996 200	+F1456 246
+F1006 201	+F1466 247
+F1016 202	+F1476 248
+F1026 203	+F1486 249
+F1036 204	+F1496 250
+F1046 205	+F1506 251
+F1056 206	+F1516 252
+F1066 207	+F1526 253
+F1076 208	+F1536 254
+F1086 209	+F1546 255

+F1556 256	+F2006 (101 102 103 104 105 106 107 108
+F1566 257	109 110 111 112 113 114 115 116 117
+F1576 258	118 119 120 121 122 123 124 125 126
+F1586 259	127 128 129 130 131 132 133 134
+F1596 260	135 136 137 138 139 140 141 142 143
+F1606 261	144 145 146 147 148 149 150 151
+F1616 262	152 153 154 155 156 157 158 159 160
+F1626 263	161 162 163 164 165 166 167 168
+F1636 264	169 170 171 172 173 174 175 176 177
+F1646 265	178 179 180 181 182 183 184 185
+F1656 266	186 187 188 189 190 191 192 193 194
+F1666 267	195 196 197 198 199 200 201 202
+F1676 268	203 204 205 206 207 208 209 210 211
+F1686 269	212 213 214 215 216 217 218 219
+F1696 270	220 221 222 223 224 225 226 227 228
+F1706 271	229 230 231 232 233 234 235 236
+F1716 272	237 238 239 240 241 242 243 244 245
+F1726 273	246 247 248 249 250 251 252 253
+F1736 274	254 255 256 257 258 259 260 261 262
+F1746 275	263 264 265 266 267 268 269 270
+F1756 276	271 272 273 274 275 276 277 278 279
+F1766 277	280 281 282 283 284 285 286 287
+F1776 278	288 289 290 291 292 293 294 295 296
+F1786 279	297 298 299 300)
+F1796 280	+F2016 (101 102 103 104 105 121 122 123
+F1806 281	124 125 141 142 143 144 145 161 162
+F1816 282	163 164 165 181 182 183 184 185) \$
+F1826 283	SQ1: Top-Left
+F1836 284	+F2026 (106 107 108 109 110 126 127 128
+F1846 285	129 130 146 147 148 149 150 166 167
+F1856 286	168 169 170 186 187 188 189 190) \$
+F1866 287	SQ2: Top-MidLeft
+F1876 288	+F2036 (111 112 113 114 115 131 132 133
+F1886 289	134 135 151 152 153 154 155 171 172
+F1896 290	173 174 175 191 192 193 194 195) \$
+F1906 291	SQ3: Top-MidRight
+F1916 292	+F2046 (116 117 118 119 120 136 137 138
+F1926 293	139 140 156 157 158 159 160 176 177
+F1936 294	178 179 180 196 197 198 199 200) \$
+F1946 295	SQ4: Top-Right
+F1956 296	+F2056 (201 202 203 204 205 221 222 223
+F1966 297	224 225 241 242 243 244 245 261 262
+F1976 298	263 264 265 281 282 283 284 285) \$
+F1986 299	SQ5: Bottom-Left
+F1996 300	+F2066 (206 207 208 209 210 226 227 228
	229 230 246 247 248 249 250 266 267

268 269 270 286 287 288 289 290) \$
 SQ6: Bottom-MidLeft
 +F2076 (211 212 213 214 215 231 232 233
 234 235 251 252 253 254 255 271 272
 273 274 275 291 292 293 294 295) \$
 SQ7: Bottom-MidRight
 +F2086 (216 217 218 219 220 236 237 238
 239 240 256 257 258 259 260 276 277
 278 279 280 296 297 298 299 300) \$
 SQ8: Bottom-Right

c --- Volume Calculation ---
 VOL 3J 0.0063617 199R 1J
 c --- Physics Parameters ---
 mode p e \$ photon mode &
 secondary e mode
 PRDMP 4J 10000000
 nps 1E10 \$ Add more as
 needed

F6 MIRD Method Comparison from a Point Source

c Isotropic Co-60 source on pangolin scales

c ***** BLOCK 1: CELL CARDS *****

```
1 1 -0.001205 +20 -30 imp:p=1 imp:e=1 $ universe air
2 3 -1.00 -10 imp:p=1 imp:e=1 $ soft tissue ellipsoid
3 2 -1.35 -20 +10 imp:p=1 imp:e=1 $ keratin ellipsoid
999 0 +30 imp:p=0 imp:e=0 $ outside world / void
```

c ***** BLOCK 2: SURFACE CARDS *****

c soft tissue sphere r=11.24

c scales sphere r=11.54

```
10 sph 0 0 0 11.24 $ pangolin soft tissue
20 sph 0 0 0 11.54 $ pangolin keratin scales
30 rpp -15 15 -15 15 -15 15 $ universe bounds
```

c ***** BLOCK 3: DATA CARDS *****

c --- Material Definitions ---

c Air (mass fractions)

```
m1 6000 -0.000151 7000 -0.784437 8000 -0.210750 18000 &
-0.004671 $ C, N, O, Ar
```

c Fingernail / keratin-like (mass fractions)

```
m2 1000 -0.108355 6000 -0.438425 7000 -0.143325 8000 &
-0.278820 16000 -0.031075 $ H, C, N, O, S
```

c ICRU 4-tissue (mass fractions)

```
m3 1000 -0.101172 6000 -0.111000 7000 -0.026000 8000 &
-0.761828 $ H, C, N, O
```

c --- Source Definition ---

SDEF pos=0 -11.535 0 erg=d1 par=2

si1 l 1.173 1.332 \$ discrete Co-60 energies in MeV

sp1 d 1.0 1.0 \$ equally probable

c --- Tally Definition ---

F6:p,e 2

c --- Physics Parameters ---

```
mode p e $ photon and secondary electron mode
nps 1E8 $ Add more as needed
```

F4 Beta Particle Penetration Depth in Keratin

Co-60 Beta Range in Keratin Scale - 30 x 0.1mm Nestled Spheres

c ***** BLOCK 1: CELL CARDS *****

```
1 1 -1.30 -101      imp:e=1 $ Sphere 1
2 1 -1.30 101 -102   imp:e=1 $ Sphere 2
3 1 -1.30 102 -103   imp:e=1 $ Sphere 3
4 1 -1.30 103 -104   imp:e=1 $ Sphere 4
5 1 -1.30 104 -105   imp:e=1 $ Sphere 5
6 1 -1.30 105 -106   imp:e=1 $ Sphere 6
7 1 -1.30 106 -107   imp:e=1 $ Sphere 7
8 1 -1.30 107 -108   imp:e=1 $ Sphere 8
9 1 -1.30 108 -109   imp:e=1 $ Sphere 9
10 1 -1.30 109 -110  imp:e=1 $ Sphere 10
11 1 -1.30 110 -111  imp:e=1 $ Sphere 11
12 1 -1.30 111 -112  imp:e=1 $ Sphere 12
13 1 -1.30 112 -113  imp:e=1 $ Sphere 13
14 1 -1.30 113 -114  imp:e=1 $ Sphere 14
15 1 -1.30 114 -115  imp:e=1 $ Sphere 15
16 1 -1.30 115 -116  imp:e=1 $ Sphere 16
17 1 -1.30 116 -117  imp:e=1 $ Sphere 17
18 1 -1.30 117 -118  imp:e=1 $ Sphere 18
19 1 -1.30 118 -119  imp:e=1 $ Sphere 19
20 1 -1.30 119 -120  imp:e=1 $ Sphere 20
21 1 -1.30 120 -121  imp:e=1 $ Sphere 21
22 1 -1.30 121 -122  imp:e=1 $ Sphere 22
23 1 -1.30 122 -123  imp:e=1 $ Sphere 23
24 1 -1.30 123 -124  imp:e=1 $ Sphere 24
25 1 -1.30 124 -125  imp:e=1 $ Sphere 25
26 1 -1.30 125 -126  imp:e=1 $ Sphere 26
27 1 -1.30 126 -127  imp:e=1 $ Sphere 27
28 1 -1.30 127 -128  imp:e=1 $ Sphere 28
29 1 -1.30 128 -129  imp:e=1 $ Sphere 29
30 1 -1.30 129 -130  imp:e=1 $ Sphere 30
31 0      130      imp:e=0 $ Kill particles past 3mm
```

c ***** BLOCK 2: SURFACE CARDS *****

c Nestled spheres at 0.1mm intervals (0.01 cm)

```
101 sph 0 0 0 0.01
102 sph 0 0 0 0.02
103 sph 0 0 0 0.03
104 sph 0 0 0 0.04
105 sph 0 0 0 0.05
106 sph 0 0 0 0.06
107 sph 0 0 0 0.07
108 sph 0 0 0 0.08
```

109 sph 0 0 0 0.09
 110 sph 0 0 0 0.10
 111 sph 0 0 0 0.11
 112 sph 0 0 0 0.12
 113 sph 0 0 0 0.13
 114 sph 0 0 0 0.14
 115 sph 0 0 0 0.15
 116 sph 0 0 0 0.16
 117 sph 0 0 0 0.17
 118 sph 0 0 0 0.18
 119 sph 0 0 0 0.19
 120 sph 0 0 0 0.20
 121 sph 0 0 0 0.21
 122 sph 0 0 0 0.22
 123 sph 0 0 0 0.23
 124 sph 0 0 0 0.24
 125 sph 0 0 0 0.25
 126 sph 0 0 0 0.26
 127 sph 0 0 0 0.27
 128 sph 0 0 0 0.28
 129 sph 0 0 0 0.29
 130 sph 0 0 0 0.30

c ***** BLOCK 3: DATA CARDS *****

c Keratin/Fingernail Material (mass fraction)

ml 1000 -0.108355 6000 -0.438425 7000 -0.143325 8000 &
 -0.278820 16000 -0.031075 \$ H, C, N, O, S

c Co-60 Beta Source at x=0 emitting in 4-pi

sdef pos=0 0 0 erg=d1 par=3

si1 L 0.00 0.03 0.06 0.09 0.12 0.15 0.18 0.21 0.24 0.27 0.30 0.318

sp1 0.000 0.030 0.085 0.150 0.200 0.220 0.195 0.105 0.050 0.025 0.020 0.020

c Flux Tally

f4:e 1 2 3 4 5 6 7 8 9 10 &

11 12 13 14 15 16 17 18 19 20 &

21 22 23 24 25 26 27 28 29 30

c Energy Bins

e4 0.05 0.10 0.15 0.20 0.25 0.318

mode e

nps 1E7 \$ increase if necessary

APPENDIX E

Appendix E lists supporting calculations used in MCNP simulations and the calculations used to determine radiation dose to the pangolin.

Keratin Composition

Table E-1 below lists the sex-averaged and finger-averaged elemental composition by mass of human fingernails (Schumacher et al. 2009). The remaining mass is assumed to be from water; no other trace elements were considered for this study.

Table E-1, Calculated Elemental Composition of Human Fingernails by Percent Mass Fraction

Element	Male Index	Male Little	Female Index	Female Little	Average
C	43.6	43.85	43.83	44.09	43.8425
H	7.36	7.28	7.36	7.29	7.3225
N	14.18	14.44	14.35	14.36	14.3325
S	3	3.02	3.36	3.05	3.1075
H (from water)	-	-	-	-	3.513
O (from water)	-	-	-	-	27.882
Total	-	-	-	-	100

The total percent composition by mass of the carbon, hydrogen, nitrogen, and sulfur was 68.605%. The remaining 31.395% was assumed to be water. The percent composition by mass of the hydrogen and oxygen from water were found by the equations below.

$$\text{Mass Fraction of Oxygen in Water} = \frac{\text{Molar Mass of Oxygen}}{\text{Molar Mass of H}_2\text{O}} = \frac{15.999 \text{ g}}{18.015 \text{ g}} = 0.8809$$

$$\text{Mass Fraction of Oxygen in Water in Fingernails} = 31.395 * 0.8809 = 27.882$$

$$\text{Mass Fraction of Hydrogen in Water} = \frac{\text{Molar Mass of Hydrogen}}{\text{Molar Mass of H}_2\text{O}} = \frac{1.008 \text{ g}}{18.015 \text{ g}} = 0.11191$$

$$\text{Mass Fraction of Hydrogen in Water in Fingernails} = 31.395 * .11191 = 3.513$$

Table E-2 shows the updated elemental composition by mass of human fingernails including the fraction lost to water from the initial study.

Table E-2, Corrected Elemental Percentage Mass Fraction of Human Fingernails

Element	Male Index	Male Little	Female Index	Female Little	Average
C	43.6	43.85	43.83	44.09	43.8425
H	7.36	7.28	7.36	7.29	10.8355
N	14.18	14.44	14.35	14.36	14.3325
S	3	3.02	3.36	3.05	3.1075
O	-	-	-	-	27.882
Total	-	-	-	-	100

Based on the calculated elemental composition of the human fingernails used as an analogue for pangolin scales in the MCNP simulation, the percent mass fraction of each element was divided by one hundred to give the decimal mass fraction in Table E-3 below.

Table E-3, Calculated Elemental Mass Fraction of Human Fingernails

Element	Mass Fraction
H	0.108355
C	0.438425
N	0.143325
O	0.27882
S	0.031075

Point Source Locations

The phantom sphere for the point sources was defined as having a radius of 11.535 cm to account for the proposed DMSO penetration depth. The 20 cm x 10 cm grid was centered on the equator of the sphere at $z = 0$. The 20 cm direction was defined along the azimuthal angle (φ) around the x-axis, and the 10 cm direction was defined along the polar angle (θ) from north to south. The center of the grid was defined at cartesian coordinates (11.535 cm, 0 cm, 0 cm), corresponding to $\theta_0 = \frac{\pi}{2}$ and $\varphi_0 = 0$.

On a sphere, the relationship between arc length (s) and the angle is defined as $angle = \frac{s}{r}$. The full span of the grid is thus:

$$\Delta\theta_{total} = \frac{L_{\theta}}{r} = \frac{10 \text{ cm}}{11.535 \text{ cm}} = 0.867 \text{ rad}$$

$$\Delta\varphi_{total} = \frac{L_\theta}{r} = \frac{20 \text{ cm}}{11.535 \text{ cm}} = 1.734 \text{ rad}$$

The full span of the grid was divided into 1 cm x 1 cm patches, corresponding to $N_\theta = 10$ columns and $N_\varphi = 20$ rows. The angular width of each patch is found by:

$$\Delta\theta = \frac{\Delta\theta_{total}}{N_\theta} = \frac{0.867 \text{ rad}}{10} = 0.0867 \text{ rad}$$

$$\Delta\varphi = \frac{\Delta\varphi_{total}}{N_\varphi} = \frac{1.734 \text{ rad}}{20} = 0.0867 \text{ rad}$$

The angular width of each 1 cm x 1 cm patch is approximately equal. The center for each patch in the grid is found by:

$$\theta_i = \theta_0 + \left((i - 1) - \left(\frac{N_\theta - 1}{2} \right) \right) \Delta\theta, \text{ where } i = 1, 2, \dots, 10$$

$$\varphi_j = \varphi_0 + \left((j - 1) - \left(\frac{N_\varphi - 1}{2} \right) \right) \Delta\varphi, \text{ where } j = 1, 2, \dots, 20$$

The center for each patch is where $\theta_0 = \frac{\pi}{2} = 1.571 \text{ rad}$ and $\varphi_0 = 0$.

The cartesian coordinates for each center of the patch in the grid are then found by:

$$x = r \sin\theta \cos\varphi$$

$$y = r \sin\theta \sin\varphi$$

$$z = r \cos\theta$$

The area of each patch was calculated to ensure each cell was approximately 1 cm². The cell curvature varies slightly with changes in θ , which is why areas only approximate 1 cm². The formula is:

$$area_{patch} = r^2 \sin\theta \Delta\theta_{patch} \Delta\varphi_{patch}$$

The following is an example calculation for the coordinates listed in Table E-4 below using patch $j = 1$ and $i = 1$.

$$\theta_1 = 1.571 \text{ rad} + \left((1 - 1) - \left(\frac{10 - 1}{2} \right) \right) \times 0.0867 \text{ rad} = 1.181 \text{ rad}$$

$$\varphi_1 = 0 \text{ rad} + \left((1 - 1) - \left(\frac{20-1}{2} \right) \right) \times 0.0867 \text{ rad} = -0.824 \text{ rad}$$

$$x = (11.535 \text{ cm}) \sin(1.181 \text{ rad}) \cos(-0.824 \text{ rad}) = 7.250 \text{ cm}$$

$$y = (11.535 \text{ cm}) \sin(1.181 \text{ rad}) \sin(-0.824 \text{ rad}) = -7.826 \text{ cm}$$

$$z = (11.535 \text{ cm}) \cos(1.1807 \text{ rad}) = 4.387 \text{ cm}$$

$$area_{patch} = (11.535 \text{ cm})^2 \sin(1.181 \text{ rad}) (0.0867 \text{ rad}) (0.0867 \text{ rad}) = 0.925 \text{ cm}^2$$

Table E-4 below lists all 200-point source locations for the planar source calculation.

Table E-4, Source Coordinates for the Point Source Grid

Point #	i (Col)	j (Row)	Φ (rad)	ϑ (rad)	x (cm)	y (cm)	z (cm)	Area (cm ²)
1	1	1	1.181	-0.824	7.250	-7.826	4.387	0.925
2	1	2	1.181	-0.737	7.901	-7.169	4.387	0.925
3	1	3	1.181	-0.650	8.492	-6.458	4.387	0.925
4	1	4	1.181	-0.564	9.019	-5.698	4.387	0.925
5	1	5	1.181	-0.477	9.478	-4.896	4.387	0.925
6	1	6	1.181	-0.390	9.867	-4.057	4.387	0.925
7	1	7	1.181	-0.303	10.181	-3.188	4.387	0.925
8	1	8	1.181	-0.217	10.419	-2.294	4.387	0.925
9	1	9	1.181	-0.130	10.578	-1.383	4.387	0.925
10	1	10	1.181	-0.043	10.658	-0.462	4.387	0.925
11	1	11	1.181	0.043	10.658	0.462	4.387	0.925
12	1	12	1.181	0.130	10.578	1.383	4.387	0.925
13	1	13	1.181	0.217	10.419	2.294	4.387	0.925
14	1	14	1.181	0.303	10.181	3.188	4.387	0.925
15	1	15	1.181	0.390	9.867	4.057	4.387	0.925
16	1	16	1.181	0.477	9.478	4.896	4.387	0.925
17	1	17	1.181	0.564	9.019	5.698	4.387	0.925
18	1	18	1.181	0.650	8.492	6.458	4.387	0.925
19	1	19	1.181	0.737	7.901	7.169	4.387	0.925
20	1	20	1.181	0.824	7.250	7.826	4.387	0.925
21	2	1	1.267	-0.824	7.481	-8.075	3.447	0.954
22	2	2	1.267	-0.737	8.152	-7.397	3.447	0.954
23	2	3	1.267	-0.650	8.762	-6.664	3.447	0.954
24	2	4	1.267	-0.564	9.306	-5.880	3.447	0.954
25	2	5	1.267	-0.477	9.780	-5.052	3.447	0.954
26	2	6	1.267	-0.390	10.181	-4.186	3.447	0.954
27	2	7	1.267	-0.303	10.505	-3.289	3.447	0.954
28	2	8	1.267	-0.217	10.751	-2.367	3.447	0.954
29	2	9	1.267	-0.130	10.915	-1.427	3.447	0.954
30	2	10	1.267	-0.043	10.998	-0.477	3.447	0.954
31	2	11	1.267	0.043	10.998	0.477	3.447	0.954
32	2	12	1.267	0.130	10.915	1.427	3.447	0.954
33	2	13	1.267	0.217	10.751	2.367	3.447	0.954
34	2	14	1.267	0.303	10.505	3.289	3.447	0.954
35	2	15	1.267	0.390	10.181	4.186	3.447	0.954
36	2	16	1.267	0.477	9.780	5.052	3.447	0.954
37	2	17	1.267	0.564	9.306	5.880	3.447	0.954
38	2	18	1.267	0.650	8.762	6.664	3.447	0.954
39	2	19	1.267	0.737	8.152	7.397	3.447	0.954

40	2	20	1.267	0.824	7.481	8.075	3.447	0.954
41	3	1	1.354	-0.824	7.656	-8.264	2.480	0.977
42	3	2	1.354	-0.737	8.343	-7.570	2.480	0.977
43	3	3	1.354	-0.650	8.967	-6.819	2.480	0.977
44	3	4	1.354	-0.564	9.523	-6.017	2.480	0.977
45	3	5	1.354	-0.477	10.009	-5.170	2.480	0.977
46	3	6	1.354	-0.390	10.419	-4.284	2.480	0.977
47	3	7	1.354	-0.303	10.751	-3.366	2.480	0.977
48	3	8	1.354	-0.217	11.002	-2.422	2.480	0.977
49	3	9	1.354	-0.130	11.170	-1.461	2.480	0.977
50	3	10	1.354	-0.043	11.255	-0.488	2.480	0.977
51	3	11	1.354	0.043	11.255	0.488	2.480	0.977
52	3	12	1.354	0.130	11.170	1.461	2.480	0.977
53	3	13	1.354	0.217	11.002	2.422	2.480	0.977
54	3	14	1.354	0.303	10.751	3.366	2.480	0.977
55	3	15	1.354	0.390	10.419	4.284	2.480	0.977
56	3	16	1.354	0.477	10.009	5.170	2.480	0.977
57	3	17	1.354	0.564	9.523	6.017	2.480	0.977
58	3	18	1.354	0.650	8.967	6.819	2.480	0.977
59	3	19	1.354	0.737	8.343	7.570	2.480	0.977
60	3	20	1.354	0.824	7.656	8.264	2.480	0.977
61	4	1	1.441	-0.824	7.773	-8.390	1.496	0.992
62	4	2	1.441	-0.737	8.470	-7.686	1.496	0.992
63	4	3	1.441	-0.650	9.104	-6.924	1.496	0.992
64	4	4	1.441	-0.564	9.669	-6.109	1.496	0.992
65	4	5	1.441	-0.477	10.162	-5.249	1.496	0.992
66	4	6	1.441	-0.390	10.578	-4.350	1.496	0.992
67	4	7	1.441	-0.303	10.915	-3.417	1.496	0.992
68	4	8	1.441	-0.217	11.170	-2.460	1.496	0.992
69	4	9	1.441	-0.130	11.341	-1.483	1.496	0.992
70	4	10	1.441	-0.043	11.427	-0.496	1.496	0.992
71	4	11	1.441	0.043	11.427	0.496	1.496	0.992
72	4	12	1.441	0.130	11.341	1.483	1.496	0.992
73	4	13	1.441	0.217	11.170	2.460	1.496	0.992
74	4	14	1.441	0.303	10.915	3.417	1.496	0.992
75	4	15	1.441	0.390	10.578	4.350	1.496	0.992
76	4	16	1.441	0.477	10.162	5.249	1.496	0.992
77	4	17	1.441	0.564	9.669	6.109	1.496	0.992
78	4	18	1.441	0.650	9.104	6.924	1.496	0.992
79	4	19	1.441	0.737	8.470	7.686	1.496	0.992
80	4	20	1.441	0.824	7.773	8.390	1.496	0.992
81	5	1	1.527	-0.824	7.832	-8.454	0.500	0.999
82	5	2	1.527	-0.737	8.534	-7.744	0.500	0.999

83	5	3	1.527	-0.650	9.173	-6.976	0.500	0.999
84	5	4	1.527	-0.564	9.742	-6.156	0.500	0.999
85	5	5	1.527	-0.477	10.239	-5.289	0.500	0.999
86	5	6	1.527	-0.390	10.658	-4.383	0.500	0.999
87	5	7	1.527	-0.303	10.998	-3.443	0.500	0.999
88	5	8	1.527	-0.217	11.255	-2.478	0.500	0.999
89	5	9	1.527	-0.130	11.427	-1.494	0.500	0.999
90	5	10	1.527	-0.043	11.513	-0.499	0.500	0.999
91	5	11	1.527	0.043	11.513	0.499	0.500	0.999
92	5	12	1.527	0.130	11.427	1.494	0.500	0.999
93	5	13	1.527	0.217	11.255	2.478	0.500	0.999
94	5	14	1.527	0.303	10.998	3.443	0.500	0.999
95	5	15	1.527	0.390	10.658	4.383	0.500	0.999
96	5	16	1.527	0.477	10.239	5.289	0.500	0.999
97	5	17	1.527	0.564	9.742	6.156	0.500	0.999
98	5	18	1.527	0.650	9.173	6.976	0.500	0.999
99	5	19	1.527	0.737	8.534	7.744	0.500	0.999
100	5	20	1.527	0.824	7.832	8.454	0.500	0.999
101	6	1	1.614	-0.824	7.832	-8.454	-0.500	0.999
102	6	2	1.614	-0.737	8.534	-7.744	-0.500	0.999
103	6	3	1.614	-0.650	9.173	-6.976	-0.500	0.999
104	6	4	1.614	-0.564	9.742	-6.156	-0.500	0.999
105	6	5	1.614	-0.477	10.239	-5.289	-0.500	0.999
106	6	6	1.614	-0.390	10.658	-4.383	-0.500	0.999
107	6	7	1.614	-0.303	10.998	-3.443	-0.500	0.999
108	6	8	1.614	-0.217	11.255	-2.478	-0.500	0.999
109	6	9	1.614	-0.130	11.427	-1.494	-0.500	0.999
110	6	10	1.614	-0.043	11.513	-0.499	-0.500	0.999
111	6	11	1.614	0.043	11.513	0.499	-0.500	0.999
112	6	12	1.614	0.130	11.427	1.494	-0.500	0.999
113	6	13	1.614	0.217	11.255	2.478	-0.500	0.999
114	6	14	1.614	0.303	10.998	3.443	-0.500	0.999
115	6	15	1.614	0.390	10.658	4.383	-0.500	0.999
116	6	16	1.614	0.477	10.239	5.289	-0.500	0.999
117	6	17	1.614	0.564	9.742	6.156	-0.500	0.999
118	6	18	1.614	0.650	9.173	6.976	-0.500	0.999
119	6	19	1.614	0.737	8.534	7.744	-0.500	0.999
120	6	20	1.614	0.824	7.832	8.454	-0.500	0.999
121	7	1	1.701	-0.824	7.773	-8.390	-1.496	0.992
122	7	2	1.701	-0.737	8.470	-7.686	-1.496	0.992
123	7	3	1.701	-0.650	9.104	-6.924	-1.496	0.992
124	7	4	1.701	-0.564	9.669	-6.109	-1.496	0.992
125	7	5	1.701	-0.477	10.162	-5.249	-1.496	0.992

126	7	6	1.701	-0.390	10.578	-4.350	-1.496	0.992
127	7	7	1.701	-0.303	10.915	-3.417	-1.496	0.992
128	7	8	1.701	-0.217	11.170	-2.460	-1.496	0.992
129	7	9	1.701	-0.130	11.341	-1.483	-1.496	0.992
130	7	10	1.701	-0.043	11.427	-0.496	-1.496	0.992
131	7	11	1.701	0.043	11.427	0.496	-1.496	0.992
132	7	12	1.701	0.130	11.341	1.483	-1.496	0.992
133	7	13	1.701	0.217	11.170	2.460	-1.496	0.992
134	7	14	1.701	0.303	10.915	3.417	-1.496	0.992
135	7	15	1.701	0.390	10.578	4.350	-1.496	0.992
136	7	16	1.701	0.477	10.162	5.249	-1.496	0.992
137	7	17	1.701	0.564	9.669	6.109	-1.496	0.992
138	7	18	1.701	0.650	9.104	6.924	-1.496	0.992
139	7	19	1.701	0.737	8.470	7.686	-1.496	0.992
140	7	20	1.701	0.824	7.773	8.390	-1.496	0.992
141	8	1	1.788	-0.824	7.656	-8.264	-2.480	0.977
142	8	2	1.788	-0.737	8.343	-7.570	-2.480	0.977
143	8	3	1.788	-0.650	8.967	-6.819	-2.480	0.977
144	8	4	1.788	-0.564	9.523	-6.017	-2.480	0.977
145	8	5	1.788	-0.477	10.009	-5.170	-2.480	0.977
146	8	6	1.788	-0.390	10.419	-4.284	-2.480	0.977
147	8	7	1.788	-0.303	10.751	-3.366	-2.480	0.977
148	8	8	1.788	-0.217	11.002	-2.422	-2.480	0.977
149	8	9	1.788	-0.130	11.170	-1.461	-2.480	0.977
150	8	10	1.788	-0.043	11.255	-0.488	-2.480	0.977
151	8	11	1.788	0.043	11.255	0.488	-2.480	0.977
152	8	12	1.788	0.130	11.170	1.461	-2.480	0.977
153	8	13	1.788	0.217	11.002	2.422	-2.480	0.977
154	8	14	1.788	0.303	10.751	3.366	-2.480	0.977
155	8	15	1.788	0.390	10.419	4.284	-2.480	0.977
156	8	16	1.788	0.477	10.009	5.170	-2.480	0.977
157	8	17	1.788	0.564	9.523	6.017	-2.480	0.977
158	8	18	1.788	0.650	8.967	6.819	-2.480	0.977
159	8	19	1.788	0.737	8.343	7.570	-2.480	0.977
160	8	20	1.788	0.824	7.656	8.264	-2.480	0.977
161	9	1	1.874	-0.824	7.481	-8.075	-3.447	0.954
162	9	2	1.874	-0.737	8.152	-7.397	-3.447	0.954
163	9	3	1.874	-0.650	8.762	-6.664	-3.447	0.954
164	9	4	1.874	-0.564	9.306	-5.880	-3.447	0.954
165	9	5	1.874	-0.477	9.780	-5.052	-3.447	0.954
166	9	6	1.874	-0.390	10.181	-4.186	-3.447	0.954
167	9	7	1.874	-0.303	10.505	-3.289	-3.447	0.954
168	9	8	1.874	-0.217	10.751	-2.367	-3.447	0.954

169	9	9	1.874	-0.130	10.915	-1.427	-3.447	0.954
170	9	10	1.874	-0.043	10.998	-0.477	-3.447	0.954
171	9	11	1.874	0.043	10.998	0.477	-3.447	0.954
172	9	12	1.874	0.130	10.915	1.427	-3.447	0.954
173	9	13	1.874	0.217	10.751	2.367	-3.447	0.954
174	9	14	1.874	0.303	10.505	3.289	-3.447	0.954
175	9	15	1.874	0.390	10.181	4.186	-3.447	0.954
176	9	16	1.874	0.477	9.780	5.052	-3.447	0.954
177	9	17	1.874	0.564	9.306	5.880	-3.447	0.954
178	9	18	1.874	0.650	8.762	6.664	-3.447	0.954
179	9	19	1.874	0.737	8.152	7.397	-3.447	0.954
180	9	20	1.874	0.824	7.481	8.075	-3.447	0.954
181	10	1	1.961	-0.824	7.250	-7.826	-4.387	0.925
182	10	2	1.961	-0.737	7.901	-7.169	-4.387	0.925
183	10	3	1.961	-0.650	8.492	-6.458	-4.387	0.925
184	10	4	1.961	-0.564	9.019	-5.698	-4.387	0.925
185	10	5	1.961	-0.477	9.478	-4.896	-4.387	0.925
186	10	6	1.961	-0.390	9.867	-4.057	-4.387	0.925
187	10	7	1.961	-0.303	10.181	-3.188	-4.387	0.925
188	10	8	1.961	-0.217	10.419	-2.294	-4.387	0.925
189	10	9	1.961	-0.130	10.578	-1.383	-4.387	0.925
190	10	10	1.961	-0.043	10.658	-0.462	-4.387	0.925
191	10	11	1.961	0.043	10.658	0.462	-4.387	0.925
192	10	12	1.961	0.130	10.578	1.383	-4.387	0.925
193	10	13	1.961	0.217	10.419	2.294	-4.387	0.925
194	10	14	1.961	0.303	10.181	3.188	-4.387	0.925
195	10	15	1.961	0.390	9.867	4.057	-4.387	0.925
196	10	16	1.961	0.477	9.478	4.896	-4.387	0.925
197	10	17	1.961	0.564	9.019	5.698	-4.387	0.925
198	10	18	1.961	0.650	8.492	6.458	-4.387	0.925
199	10	19	1.961	0.737	7.901	7.169	-4.387	0.925
200	10	20	1.961	0.824	7.250	7.826	-4.387	0.925

Whole-Body Dose Detector Locations

The center of each whole-body dose detector sphere was plotted by modeling an inner phantom sphere with a radius of 10.145 cm to model the 11.54 cm radius of the outer keratin scales minus the 1.395 cm whole-body dosimetric dose depth. The 20 cm x 10 cm grid was centered on the equator of the sphere at $z = 0$. The 20 cm direction was defined along the azimuthal angle (ϕ) around the x-axis, and the 10 cm direction was defined along the polar angle

(θ) from north to south. The center of the grid was defined at cartesian coordinates (10.145 cm, 0 cm, 0 cm), corresponding to $\theta_0 = \frac{\pi}{2}$ and $\varphi_0 = 0$.

The full span of the grid was:

$$\Delta\theta_{total} = \frac{L_\theta}{r} = \frac{10 \text{ cm}}{10.145 \text{ cm}} = 0.986 \text{ rad}$$

$$\Delta\varphi_{total} = \frac{L_\varphi}{r} = \frac{20 \text{ cm}}{10.145 \text{ cm}} = 1.971 \text{ rad}$$

The full span of the grid was divided into 1 cm x 1 cm patches, corresponding to $N_\theta = 10$ columns and $N_\varphi = 20$ rows. The angular width of each patch was:

$$\Delta\theta = \frac{\Delta\theta_{total}}{N_\theta} = \frac{0.986 \text{ rad}}{10} = 0.0986 \text{ rad}$$

$$\Delta\varphi = \frac{\Delta\varphi_{total}}{N_\varphi} = \frac{1.971 \text{ rad}}{20} = 0.0986 \text{ rad}$$

The angular width of each 1 cm x 1 cm patch is approximately equal. The center for each patch in the grid is found by:

$$\theta_i = \theta_0 + \left((i-1) - \left(\frac{N_\theta-1}{2} \right) \right) \Delta\theta, \text{ where } i = 1, 2, \dots, 10$$

$$\varphi_j = \varphi_0 + \left((j-1) - \left(\frac{N_\varphi-1}{2} \right) \right) \Delta\varphi, \text{ where } j = 1, 2, \dots, 20$$

The center for each patch is where $\theta_0 = \frac{\pi}{2} = 1.571 \text{ rad}$ and $\varphi_0 = 0$.

The cartesian coordinates for each center of the patch in the grid are then found by:

$$x = r \sin\theta \cos\varphi$$

$$y = r \sin\theta \sin\varphi$$

$$z = r \cos\theta$$

The area of each patch was calculated by:

$$area_{patch} = r^2 \sin\theta \Delta\theta_{patch} \Delta\varphi_{patch}$$

The following is an example calculation for the coordinates listed in Table E-5 below using patch $j = 1$ and $i = 1$.

$$\theta_1 = 1.571 \text{ rad} + \left((1 - 1) - \left(\frac{10-1}{2} \right) \right) \times 0.0986 \text{ rad} = 1.127 \text{ rad}$$

$$\varphi_1 = 0 \text{ rad} + \left((1 - 1) - \left(\frac{20-1}{2} \right) \right) \times 0.0986 \text{ rad} = -0.936 \text{ rad}$$

$$x = (10.145 \text{ cm}) \sin(1.127 \text{ rad}) \cos(-0.936 \text{ rad}) = 5.431 \text{ cm}$$

$$y = (10.145 \text{ cm}) \sin(1.127 \text{ rad}) \sin(-0.936 \text{ rad}) = -7.380 \text{ cm}$$

$$z = (10.145 \text{ cm}) \cos(1.127 \text{ rad}) = 4.354 \text{ cm}$$

$$area_{patch} = (10.145 \text{ cm})^2 \sin(1.127 \text{ rad}) (0.0986 \text{ rad}) (0.0986 \text{ rad}) = 0.903 \text{ cm}^2$$

Table E-5 below lists all two hundred spherical detector locations for the whole body.

Table E-5, Whole-Body Point Detector Coordinates for the Planar Source

Point #	i (Column)	j (Row)	Φ (rad)	ϑ (rad)	x (cm)	y (cm)	z (cm)	Area (cm ²)
1	1	1	1.127	-0.936	5.431	-7.380	4.354	0.903
2	1	2	1.127	-0.838	6.131	-6.810	4.354	0.903
3	1	3	1.127	-0.739	6.771	-6.174	4.354	0.903
4	1	4	1.127	-0.641	7.346	-5.477	4.354	0.903
5	1	5	1.127	-0.542	7.849	-4.728	4.354	0.903
6	1	6	1.127	-0.444	8.276	-3.933	4.354	0.903
7	1	7	1.127	-0.345	8.623	-3.099	4.354	0.903
8	1	8	1.127	-0.246	8.886	-2.235	4.354	0.903
9	1	9	1.127	-0.148	9.063	-1.350	4.354	0.903
10	1	10	1.127	-0.049	9.152	-0.451	4.354	0.903
11	1	11	1.127	0.049	9.152	0.451	4.354	0.903
12	1	12	1.127	0.148	9.063	1.350	4.354	0.903
13	1	13	1.127	0.246	8.886	2.235	4.354	0.903
14	1	14	1.127	0.345	8.623	3.099	4.354	0.903
15	1	15	1.127	0.444	8.276	3.933	4.354	0.903
16	1	16	1.127	0.542	7.849	4.728	4.354	0.903
17	1	17	1.127	0.641	7.346	5.477	4.354	0.903
18	1	18	1.127	0.739	6.771	6.174	4.354	0.903
19	1	19	1.127	0.838	6.131	6.810	4.354	0.903
20	1	20	1.127	0.936	5.431	7.380	4.354	0.903
21	2	1	1.226	-0.936	5.658	-7.690	3.431	0.941

22	2	2	1.226	-0.838	6.388	-7.096	3.431	0.941
23	2	3	1.226	-0.739	7.055	-6.432	3.431	0.941
24	2	4	1.226	-0.641	7.654	-5.707	3.431	0.941
25	2	5	1.226	-0.542	8.178	-4.926	3.431	0.941
26	2	6	1.226	-0.444	8.623	-4.097	3.431	0.941
27	2	7	1.226	-0.345	8.985	-3.229	3.431	0.941
28	2	8	1.226	-0.246	9.259	-2.329	3.431	0.941
29	2	9	1.226	-0.148	9.443	-1.406	3.431	0.941
30	2	10	1.226	-0.049	9.536	-0.470	3.431	0.941
31	2	11	1.226	0.049	9.536	0.470	3.431	0.941
32	2	12	1.226	0.148	9.443	1.406	3.431	0.941
33	2	13	1.226	0.246	9.259	2.329	3.431	0.941
34	2	14	1.226	0.345	8.985	3.229	3.431	0.941
35	2	15	1.226	0.444	8.623	4.097	3.431	0.941
36	2	16	1.226	0.542	8.178	4.926	3.431	0.941
37	2	17	1.226	0.641	7.654	5.707	3.431	0.941
38	2	18	1.226	0.739	7.055	6.432	3.431	0.941
39	2	19	1.226	0.838	6.388	7.096	3.431	0.941
40	2	20	1.226	0.936	5.658	7.690	3.431	0.941
41	3	1	1.324	-0.936	5.831	-7.924	2.475	0.970
42	3	2	1.324	-0.838	6.583	-7.312	2.475	0.970
43	3	3	1.324	-0.739	7.270	-6.629	2.475	0.970
44	3	4	1.324	-0.641	7.887	-5.881	2.475	0.970
45	3	5	1.324	-0.542	8.428	-5.076	2.475	0.970
46	3	6	1.324	-0.444	8.886	-4.222	2.475	0.970
47	3	7	1.324	-0.345	9.259	-3.327	2.475	0.970
48	3	8	1.324	-0.246	9.541	-2.400	2.475	0.970
49	3	9	1.324	-0.148	9.731	-1.449	2.475	0.970
50	3	10	1.324	-0.049	9.827	-0.485	2.475	0.970
51	3	11	1.324	0.049	9.827	0.485	2.475	0.970
52	3	12	1.324	0.148	9.731	1.449	2.475	0.970
53	3	13	1.324	0.246	9.541	2.400	2.475	0.970
54	3	14	1.324	0.345	9.259	3.327	2.475	0.970
55	3	15	1.324	0.444	8.886	4.222	2.475	0.970
56	3	16	1.324	0.542	8.428	5.076	2.475	0.970
57	3	17	1.324	0.641	7.887	5.881	2.475	0.970
58	3	18	1.324	0.739	7.270	6.629	2.475	0.970
59	3	19	1.324	0.838	6.583	7.312	2.475	0.970
60	3	20	1.324	0.936	5.831	7.924	2.475	0.970
61	4	1	1.423	-0.936	5.947	-8.082	1.495	0.989
62	4	2	1.423	-0.838	6.714	-7.458	1.495	0.989
63	4	3	1.423	-0.739	7.415	-6.761	1.495	0.989
64	4	4	1.423	-0.641	8.044	-5.998	1.495	0.989

65	4	5	1.423	-0.542	8.595	-5.177	1.495	0.989
66	4	6	1.423	-0.444	9.063	-4.306	1.495	0.989
67	4	7	1.423	-0.345	9.443	-3.394	1.495	0.989
68	4	8	1.423	-0.246	9.731	-2.448	1.495	0.989
69	4	9	1.423	-0.148	9.925	-1.478	1.495	0.989
70	4	10	1.423	-0.049	10.022	-0.494	1.495	0.989
71	4	11	1.423	0.049	10.022	0.494	1.495	0.989
72	4	12	1.423	0.148	9.925	1.478	1.495	0.989
73	4	13	1.423	0.246	9.731	2.448	1.495	0.989
74	4	14	1.423	0.345	9.443	3.394	1.495	0.989
75	4	15	1.423	0.444	9.063	4.306	1.495	0.989
76	4	16	1.423	0.542	8.595	5.177	1.495	0.989
77	4	17	1.423	0.641	8.044	5.998	1.495	0.989
78	4	18	1.423	0.739	7.415	6.761	1.495	0.989
79	4	19	1.423	0.838	6.714	7.458	1.495	0.989
80	4	20	1.423	0.936	5.947	8.082	1.495	0.989
81	5	1	1.522	-0.936	6.005	-8.161	0.500	0.999
82	5	2	1.522	-0.838	6.779	-7.531	0.500	0.999
83	5	3	1.522	-0.739	7.488	-6.827	0.500	0.999
84	5	4	1.522	-0.641	8.123	-6.057	0.500	0.999
85	5	5	1.522	-0.542	8.680	-5.228	0.500	0.999
86	5	6	1.522	-0.444	9.152	-4.349	0.500	0.999
87	5	7	1.522	-0.345	9.536	-3.427	0.500	0.999
88	5	8	1.522	-0.246	9.827	-2.472	0.500	0.999
89	5	9	1.522	-0.148	10.022	-1.493	0.500	0.999
90	5	10	1.522	-0.049	10.120	-0.499	0.500	0.999
91	5	11	1.522	0.049	10.120	0.499	0.500	0.999
92	5	12	1.522	0.148	10.022	1.493	0.500	0.999
93	5	13	1.522	0.246	9.827	2.472	0.500	0.999
94	5	14	1.522	0.345	9.536	3.427	0.500	0.999
95	5	15	1.522	0.444	9.152	4.349	0.500	0.999
96	5	16	1.522	0.542	8.680	5.228	0.500	0.999
97	5	17	1.522	0.641	8.123	6.057	0.500	0.999
98	5	18	1.522	0.739	7.488	6.827	0.500	0.999
99	5	19	1.522	0.838	6.779	7.531	0.500	0.999
100	5	20	1.522	0.936	6.005	8.161	0.500	0.999
101	6	1	1.620	-0.936	6.005	-8.161	-0.500	0.999
102	6	2	1.620	-0.838	6.779	-7.531	-0.500	0.999
103	6	3	1.620	-0.739	7.488	-6.827	-0.500	0.999
104	6	4	1.620	-0.641	8.123	-6.057	-0.500	0.999
105	6	5	1.620	-0.542	8.680	-5.228	-0.500	0.999
106	6	6	1.620	-0.444	9.152	-4.349	-0.500	0.999
107	6	7	1.620	-0.345	9.536	-3.427	-0.500	0.999

108	6	8	1.620	-0.246	9.827	-2.472	-0.500	0.999
109	6	9	1.620	-0.148	10.022	-1.493	-0.500	0.999
110	6	10	1.620	-0.049	10.120	-0.499	-0.500	0.999
111	6	11	1.620	0.049	10.120	0.499	-0.500	0.999
112	6	12	1.620	0.148	10.022	1.493	-0.500	0.999
113	6	13	1.620	0.246	9.827	2.472	-0.500	0.999
114	6	14	1.620	0.345	9.536	3.427	-0.500	0.999
115	6	15	1.620	0.444	9.152	4.349	-0.500	0.999
116	6	16	1.620	0.542	8.680	5.228	-0.500	0.999
117	6	17	1.620	0.641	8.123	6.057	-0.500	0.999
118	6	18	1.620	0.739	7.488	6.827	-0.500	0.999
119	6	19	1.620	0.838	6.779	7.531	-0.500	0.999
120	6	20	1.620	0.936	6.005	8.161	-0.500	0.999
121	7	1	1.719	-0.936	5.947	-8.082	-1.495	0.989
122	7	2	1.719	-0.838	6.714	-7.458	-1.495	0.989
123	7	3	1.719	-0.739	7.415	-6.761	-1.495	0.989
124	7	4	1.719	-0.641	8.044	-5.998	-1.495	0.989
125	7	5	1.719	-0.542	8.595	-5.177	-1.495	0.989
126	7	6	1.719	-0.444	9.063	-4.306	-1.495	0.989
127	7	7	1.719	-0.345	9.443	-3.394	-1.495	0.989
128	7	8	1.719	-0.246	9.731	-2.448	-1.495	0.989
129	7	9	1.719	-0.148	9.925	-1.478	-1.495	0.989
130	7	10	1.719	-0.049	10.022	-0.494	-1.495	0.989
131	7	11	1.719	0.049	10.022	0.494	-1.495	0.989
132	7	12	1.719	0.148	9.925	1.478	-1.495	0.989
133	7	13	1.719	0.246	9.731	2.448	-1.495	0.989
134	7	14	1.719	0.345	9.443	3.394	-1.495	0.989
135	7	15	1.719	0.444	9.063	4.306	-1.495	0.989
136	7	16	1.719	0.542	8.595	5.177	-1.495	0.989
137	7	17	1.719	0.641	8.044	5.998	-1.495	0.989
138	7	18	1.719	0.739	7.415	6.761	-1.495	0.989
139	7	19	1.719	0.838	6.714	7.458	-1.495	0.989
140	7	20	1.719	0.936	5.947	8.082	-1.495	0.989
141	8	1	1.817	-0.936	5.831	-7.924	-2.475	0.970
142	8	2	1.817	-0.838	6.583	-7.312	-2.475	0.970
143	8	3	1.817	-0.739	7.270	-6.629	-2.475	0.970
144	8	4	1.817	-0.641	7.887	-5.881	-2.475	0.970
145	8	5	1.817	-0.542	8.428	-5.076	-2.475	0.970
146	8	6	1.817	-0.444	8.886	-4.222	-2.475	0.970
147	8	7	1.817	-0.345	9.259	-3.327	-2.475	0.970
148	8	8	1.817	-0.246	9.541	-2.400	-2.475	0.970
149	8	9	1.817	-0.148	9.731	-1.449	-2.475	0.970
150	8	10	1.817	-0.049	9.827	-0.485	-2.475	0.970

151	8	11	1.817	0.049	9.827	0.485	-2.475	0.970
152	8	12	1.817	0.148	9.731	1.449	-2.475	0.970
153	8	13	1.817	0.246	9.541	2.400	-2.475	0.970
154	8	14	1.817	0.345	9.259	3.327	-2.475	0.970
155	8	15	1.817	0.444	8.886	4.222	-2.475	0.970
156	8	16	1.817	0.542	8.428	5.076	-2.475	0.970
157	8	17	1.817	0.641	7.887	5.881	-2.475	0.970
158	8	18	1.817	0.739	7.270	6.629	-2.475	0.970
159	8	19	1.817	0.838	6.583	7.312	-2.475	0.970
160	8	20	1.817	0.936	5.831	7.924	-2.475	0.970
161	9	1	1.916	-0.936	5.658	-7.690	-3.431	0.941
162	9	2	1.916	-0.838	6.388	-7.096	-3.431	0.941
163	9	3	1.916	-0.739	7.055	-6.432	-3.431	0.941
164	9	4	1.916	-0.641	7.654	-5.707	-3.431	0.941
165	9	5	1.916	-0.542	8.178	-4.926	-3.431	0.941
166	9	6	1.916	-0.444	8.623	-4.097	-3.431	0.941
167	9	7	1.916	-0.345	8.985	-3.229	-3.431	0.941
168	9	8	1.916	-0.246	9.259	-2.329	-3.431	0.941
169	9	9	1.916	-0.148	9.443	-1.406	-3.431	0.941
170	9	10	1.916	-0.049	9.536	-0.470	-3.431	0.941
171	9	11	1.916	0.049	9.536	0.470	-3.431	0.941
172	9	12	1.916	0.148	9.443	1.406	-3.431	0.941
173	9	13	1.916	0.246	9.259	2.329	-3.431	0.941
174	9	14	1.916	0.345	8.985	3.229	-3.431	0.941
175	9	15	1.916	0.444	8.623	4.097	-3.431	0.941
176	9	16	1.916	0.542	8.178	4.926	-3.431	0.941
177	9	17	1.916	0.641	7.654	5.707	-3.431	0.941
178	9	18	1.916	0.739	7.055	6.432	-3.431	0.941
179	9	19	1.916	0.838	6.388	7.096	-3.431	0.941
180	9	20	1.916	0.936	5.658	7.690	-3.431	0.941
181	10	1	2.014	-0.936	5.431	-7.380	-4.354	0.903
182	10	2	2.014	-0.838	6.131	-6.810	-4.354	0.903
183	10	3	2.014	-0.739	6.771	-6.174	-4.354	0.903
184	10	4	2.014	-0.641	7.346	-5.477	-4.354	0.903
185	10	5	2.014	-0.542	7.849	-4.728	-4.354	0.903
186	10	6	2.014	-0.444	8.276	-3.933	-4.354	0.903
187	10	7	2.014	-0.345	8.623	-3.099	-4.354	0.903
188	10	8	2.014	-0.246	8.886	-2.235	-4.354	0.903
189	10	9	2.014	-0.148	9.063	-1.350	-4.354	0.903
190	10	10	2.014	-0.049	9.152	-0.451	-4.354	0.903
191	10	11	2.014	0.049	9.152	0.451	-4.354	0.903
192	10	12	2.014	0.148	9.063	1.350	-4.354	0.903
193	10	13	2.014	0.246	8.886	2.235	-4.354	0.903

194	10	14	2.014	0.345	8.623	3.099	-4.354	0.903
195	10	15	2.014	0.444	8.276	3.933	-4.354	0.903
196	10	16	2.014	0.542	7.849	4.728	-4.354	0.903
197	10	17	2.014	0.641	7.346	5.477	-4.354	0.903
198	10	18	2.014	0.739	6.771	6.174	-4.354	0.903
199	10	19	2.014	0.838	6.131	6.810	-4.354	0.903
200	10	20	2.014	0.936	5.431	7.380	-4.354	0.903

Basal Layer of the Skin Point Detector Locations

The center of each detector sphere was plotted by modeling an inner phantom sphere with a radius of 11.138 cm to model the 11.54 cm radius of the outer keratin scales minus the 0.402 cm basal layer of the skin dosimetric dose depth. The 20 cm x 10 cm grid was centered on the equator of the sphere at $z = 0$. The 20 cm direction was defined along the azimuthal angle (φ) around the x-axis, and the 10 cm direction was defined along the polar angle (θ) from north to south. The center of the grid was defined at cartesian coordinates (11.138 cm, 0 cm, 0 cm), corresponding to $\theta_0 = \frac{\pi}{2}$ and $\varphi_0 = 0$.

The full span of the grid was:

$$\Delta\theta_{total} = \frac{L_\theta}{r} = \frac{10 \text{ cm}}{11.138 \text{ cm}} = 0.898 \text{ rad}$$

$$\Delta\varphi_{total} = \frac{L_\varphi}{r} = \frac{20 \text{ cm}}{11.138 \text{ cm}} = 1.796 \text{ rad}$$

The full span of the grid was divided into 1 cm x 1 cm patches, corresponding to $N_\theta = 10$ columns and $N_\varphi = 20$ rows. The angular width of each patch was:

$$\Delta\theta = \frac{\Delta\theta_{total}}{N_\theta} = \frac{0.8672 \text{ rad}}{10} = 0.0898 \text{ rad}$$

$$\Delta\varphi = \frac{\Delta\varphi_{total}}{N_\varphi} = \frac{1.7344 \text{ rad}}{20} = 0.0898 \text{ rad}$$

The angular width of each 1 cm x 1 cm patch is approximately equal. The center for each patch in the grid is found by:

$$\theta_i = \theta_0 + \left((i - 1) - \left(\frac{N_\theta - 1}{2} \right) \right) \Delta\theta, \text{ where } i = 1, 2, \dots, 10$$

$$\varphi_j = \varphi_0 + \left((j - 1) - \left(\frac{N_\varphi - 1}{2} \right) \right) \Delta\varphi, \text{ where } j = 1, 2, \dots, 20$$

The center for each patch is where $\theta_0 = \frac{\pi}{2} = 1.571 \text{ rad}$ and $\varphi_0 = 0$.

The cartesian coordinates for each center of the patch in the grid are then found by:

$$x = r \sin\theta \cos\varphi$$

$$y = r \sin\theta \sin\varphi$$

$$z = r \cos\theta$$

The area of each patch was calculated by:

$$area_{patch} = r^2 \sin\theta \Delta\theta_{patch} \Delta\varphi_{patch}$$

The following is an example calculation for the coordinates listed in Table E-6 below using patch $j = 1$ and $I = 1$.

$$\theta_1 = 1.571 \text{ rad} + \left((1 - 1) - \left(\frac{10 - 1}{2} \right) \right) \times 0.0898 \text{ rad} = 1.167 \text{ rad}$$

$$\varphi_1 = 0 \text{ rad} + \left((1 - 1) - \left(\frac{20 - 1}{2} \right) \right) \times 0.0898 \text{ rad} = -0.853 \text{ rad}$$

$$x = (11.138 \text{ cm}) \sin(1.167 \text{ rad}) \cos(-0.853 \text{ rad}) = 6.736 \text{ cm}$$

$$y = (11.138 \text{ cm}) \sin(1.167 \text{ rad}) \sin(-0.853 \text{ rad}) = -7.714 \text{ cm}$$

$$z = (11.138) \cos(1.167 \text{ rad}) = 4.379 \text{ cm}$$

$$area_{patch} = (11.138 \text{ cm})^2 \sin(1.167 \text{ rad}) (0.0898 \text{ rad}) (0.0898 \text{ rad}) = 0.919 \text{ cm}^2$$

Table E-6 below lists all two hundred basal layer of the skin spherical detector locations for the planar source calculation.

Table E-6, Basal Layer of the Skin Point Detector Coordinates for the Planar Source

Point #	i (Col)	j (Row)	Φ (rad)	ϑ (rad)	x (cm)	y (cm)	z (cm)	Area (cm ²)
1	1	1	1.167	-0.853	6.736	-7.714	4.379	0.919
2	1	2	1.167	-0.763	7.401	-7.079	4.379	0.919
3	1	3	1.167	-0.673	8.006	-6.387	4.379	0.919
4	1	4	1.167	-0.584	8.546	-5.643	4.379	0.919
5	1	5	1.167	-0.494	9.018	-4.854	4.379	0.919
6	1	6	1.167	-0.404	9.417	-4.026	4.379	0.919
7	1	7	1.167	-0.314	9.740	-3.166	4.379	0.919
8	1	8	1.167	-0.224	9.984	-2.279	4.379	0.919
9	1	9	1.167	-0.135	10.149	-1.375	4.379	0.919
10	1	10	1.167	-0.045	10.231	-0.460	4.379	0.919
11	1	11	1.167	0.045	10.231	0.460	4.379	0.919
12	1	12	1.167	0.135	10.149	1.375	4.379	0.919
13	1	13	1.167	0.224	9.984	2.279	4.379	0.919
14	1	14	1.167	0.314	9.740	3.166	4.379	0.919
15	1	15	1.167	0.404	9.417	4.026	4.379	0.919
16	1	16	1.167	0.494	9.018	4.854	4.379	0.919
17	1	17	1.167	0.584	8.546	5.643	4.379	0.919
18	1	18	1.167	0.673	8.006	6.387	4.379	0.919
19	1	19	1.167	0.763	7.401	7.079	4.379	0.919
20	1	20	1.167	0.853	6.736	7.714	4.379	0.919
21	2	1	1.257	-0.853	6.968	-7.978	3.443	0.951
22	2	2	1.257	-0.763	7.655	-7.322	3.443	0.951
23	2	3	1.257	-0.673	8.280	-6.606	3.443	0.951
24	2	4	1.257	-0.584	8.839	-5.837	3.443	0.951
25	2	5	1.257	-0.494	9.327	-5.021	3.443	0.951
26	2	6	1.257	-0.404	9.740	-4.164	3.443	0.951
27	2	7	1.257	-0.314	10.074	-3.274	3.443	0.951
28	2	8	1.257	-0.224	10.327	-2.358	3.443	0.951
29	2	9	1.257	-0.135	10.497	-1.422	3.443	0.951
30	2	10	1.257	-0.045	10.582	-0.475	3.443	0.951
31	2	11	1.257	0.045	10.582	0.475	3.443	0.951
32	2	12	1.257	0.135	10.497	1.422	3.443	0.951
33	2	13	1.257	0.224	10.327	2.358	3.443	0.951
34	2	14	1.257	0.314	10.074	3.274	3.443	0.951
35	2	15	1.257	0.404	9.740	4.164	3.443	0.951
36	2	16	1.257	0.494	9.327	5.021	3.443	0.951
37	2	17	1.257	0.584	8.839	5.837	3.443	0.951
38	2	18	1.257	0.673	8.280	6.606	3.443	0.951
39	2	19	1.257	0.763	7.655	7.322	3.443	0.951
40	2	20	1.257	0.853	6.968	7.978	3.443	0.951

41	3	1	1.346	-0.853	7.143	-8.179	2.479	0.975
42	3	2	1.346	-0.763	7.847	-7.506	2.479	0.975
43	3	3	1.346	-0.673	8.488	-6.772	2.479	0.975
44	3	4	1.346	-0.584	9.061	-5.983	2.479	0.975
45	3	5	1.346	-0.494	9.561	-5.147	2.479	0.975
46	3	6	1.346	-0.404	9.984	-4.269	2.479	0.975
47	3	7	1.346	-0.314	10.327	-3.356	2.479	0.975
48	3	8	1.346	-0.224	10.586	-2.417	2.479	0.975
49	3	9	1.346	-0.135	10.760	-1.458	2.479	0.975
50	3	10	1.346	-0.045	10.848	-0.487	2.479	0.975
51	3	11	1.346	0.045	10.848	0.487	2.479	0.975
52	3	12	1.346	0.135	10.760	1.458	2.479	0.975
53	3	13	1.346	0.224	10.586	2.417	2.479	0.975
54	3	14	1.346	0.314	10.327	3.356	2.479	0.975
55	3	15	1.346	0.404	9.984	4.269	2.479	0.975
56	3	16	1.346	0.494	9.561	5.147	2.479	0.975
57	3	17	1.346	0.584	9.061	5.983	2.479	0.975
58	3	18	1.346	0.673	8.488	6.772	2.479	0.975
59	3	19	1.346	0.763	7.847	7.506	2.479	0.975
60	3	20	1.346	0.853	7.143	8.179	2.479	0.975
61	4	1	1.436	-0.853	7.260	-8.313	1.495	0.991
62	4	2	1.436	-0.763	7.976	-7.629	1.495	0.991
63	4	3	1.436	-0.673	8.628	-6.883	1.495	0.991
64	4	4	1.436	-0.584	9.210	-6.082	1.495	0.991
65	4	5	1.436	-0.494	9.719	-5.231	1.495	0.991
66	4	6	1.436	-0.404	10.149	-4.339	1.495	0.991
67	4	7	1.436	-0.314	10.497	-3.412	1.495	0.991
68	4	8	1.436	-0.224	10.760	-2.457	1.495	0.991
69	4	9	1.436	-0.135	10.937	-1.482	1.495	0.991
70	4	10	1.436	-0.045	11.026	-0.495	1.495	0.991
71	4	11	1.436	0.045	11.026	0.495	1.495	0.991
72	4	12	1.436	0.135	10.937	1.482	1.495	0.991
73	4	13	1.436	0.224	10.760	2.457	1.495	0.991
74	4	14	1.436	0.314	10.497	3.412	1.495	0.991
75	4	15	1.436	0.404	10.149	4.339	1.495	0.991
76	4	16	1.436	0.494	9.719	5.231	1.495	0.991
77	4	17	1.436	0.584	9.210	6.082	1.495	0.991
78	4	18	1.436	0.673	8.628	6.883	1.495	0.991
79	4	19	1.436	0.763	7.976	7.629	1.495	0.991
80	4	20	1.436	0.853	7.260	8.313	1.495	0.991
81	5	1	1.526	-0.853	7.319	-8.381	0.500	0.999
82	5	2	1.526	-0.763	8.041	-7.691	0.500	0.999
83	5	3	1.526	-0.673	8.698	-6.939	0.500	0.999

84	5	4	1.526	-0.584	9.285	-6.131	0.500	0.999
85	5	5	1.526	-0.494	9.798	-5.274	0.500	0.999
86	5	6	1.526	-0.404	10.231	-4.374	0.500	0.999
87	5	7	1.526	-0.314	10.582	-3.439	0.500	0.999
88	5	8	1.526	-0.224	10.848	-2.477	0.500	0.999
89	5	9	1.526	-0.135	11.026	-1.494	0.500	0.999
90	5	10	1.526	-0.045	11.116	-0.499	0.500	0.999
91	5	11	1.526	0.045	11.116	0.499	0.500	0.999
92	5	12	1.526	0.135	11.026	1.494	0.500	0.999
93	5	13	1.526	0.224	10.848	2.477	0.500	0.999
94	5	14	1.526	0.314	10.582	3.439	0.500	0.999
95	5	15	1.526	0.404	10.231	4.374	0.500	0.999
96	5	16	1.526	0.494	9.798	5.274	0.500	0.999
97	5	17	1.526	0.584	9.285	6.131	0.500	0.999
98	5	18	1.526	0.673	8.698	6.939	0.500	0.999
99	5	19	1.526	0.763	8.041	7.691	0.500	0.999
100	5	20	1.526	0.853	7.319	8.381	0.500	0.999
101	6	1	1.616	-0.853	7.319	-8.381	-0.500	0.999
102	6	2	1.616	-0.763	8.041	-7.691	-0.500	0.999
103	6	3	1.616	-0.673	8.698	-6.939	-0.500	0.999
104	6	4	1.616	-0.584	9.285	-6.131	-0.500	0.999
105	6	5	1.616	-0.494	9.798	-5.274	-0.500	0.999
106	6	6	1.616	-0.404	10.231	-4.374	-0.500	0.999
107	6	7	1.616	-0.314	10.582	-3.439	-0.500	0.999
108	6	8	1.616	-0.224	10.848	-2.477	-0.500	0.999
109	6	9	1.616	-0.135	11.026	-1.494	-0.500	0.999
110	6	10	1.616	-0.045	11.116	-0.499	-0.500	0.999
111	6	11	1.616	0.045	11.116	0.499	-0.500	0.999
112	6	12	1.616	0.135	11.026	1.494	-0.500	0.999
113	6	13	1.616	0.224	10.848	2.477	-0.500	0.999
114	6	14	1.616	0.314	10.582	3.439	-0.500	0.999
115	6	15	1.616	0.404	10.231	4.374	-0.500	0.999
116	6	16	1.616	0.494	9.798	5.274	-0.500	0.999
117	6	17	1.616	0.584	9.285	6.131	-0.500	0.999
118	6	18	1.616	0.673	8.698	6.939	-0.500	0.999
119	6	19	1.616	0.763	8.041	7.691	-0.500	0.999
120	6	20	1.616	0.853	7.319	8.381	-0.500	0.999
121	7	1	1.705	-0.853	7.260	-8.313	-1.495	0.991
122	7	2	1.705	-0.763	7.976	-7.629	-1.495	0.991
123	7	3	1.705	-0.673	8.628	-6.883	-1.495	0.991
124	7	4	1.705	-0.584	9.210	-6.082	-1.495	0.991
125	7	5	1.705	-0.494	9.719	-5.231	-1.495	0.991
126	7	6	1.705	-0.404	10.149	-4.339	-1.495	0.991

127	7	7	1.705	-0.314	10.497	-3.412	-1.495	0.991
128	7	8	1.705	-0.224	10.760	-2.457	-1.495	0.991
129	7	9	1.705	-0.135	10.937	-1.482	-1.495	0.991
130	7	10	1.705	-0.045	11.026	-0.495	-1.495	0.991
131	7	11	1.705	0.045	11.026	0.495	-1.495	0.991
132	7	12	1.705	0.135	10.937	1.482	-1.495	0.991
133	7	13	1.705	0.224	10.760	2.457	-1.495	0.991
134	7	14	1.705	0.314	10.497	3.412	-1.495	0.991
135	7	15	1.705	0.404	10.149	4.339	-1.495	0.991
136	7	16	1.705	0.494	9.719	5.231	-1.495	0.991
137	7	17	1.705	0.584	9.210	6.082	-1.495	0.991
138	7	18	1.705	0.673	8.628	6.883	-1.495	0.991
139	7	19	1.705	0.763	7.976	7.629	-1.495	0.991
140	7	20	1.705	0.853	7.260	8.313	-1.495	0.991
141	8	1	1.795	-0.853	7.143	-8.179	-2.479	0.975
142	8	2	1.795	-0.763	7.847	-7.506	-2.479	0.975
143	8	3	1.795	-0.673	8.488	-6.772	-2.479	0.975
144	8	4	1.795	-0.584	9.061	-5.983	-2.479	0.975
145	8	5	1.795	-0.494	9.561	-5.147	-2.479	0.975
146	8	6	1.795	-0.404	9.984	-4.269	-2.479	0.975
147	8	7	1.795	-0.314	10.327	-3.356	-2.479	0.975
148	8	8	1.795	-0.224	10.586	-2.417	-2.479	0.975
149	8	9	1.795	-0.135	10.760	-1.458	-2.479	0.975
150	8	10	1.795	-0.045	10.848	-0.487	-2.479	0.975
151	8	11	1.795	0.045	10.848	0.487	-2.479	0.975
152	8	12	1.795	0.135	10.760	1.458	-2.479	0.975
153	8	13	1.795	0.224	10.586	2.417	-2.479	0.975
154	8	14	1.795	0.314	10.327	3.356	-2.479	0.975
155	8	15	1.795	0.404	9.984	4.269	-2.479	0.975
156	8	16	1.795	0.494	9.561	5.147	-2.479	0.975
157	8	17	1.795	0.584	9.061	5.983	-2.479	0.975
158	8	18	1.795	0.673	8.488	6.772	-2.479	0.975
159	8	19	1.795	0.763	7.847	7.506	-2.479	0.975
160	8	20	1.795	0.853	7.143	8.179	-2.479	0.975
161	9	1	1.885	-0.853	6.968	-7.978	-3.443	0.951
162	9	2	1.885	-0.763	7.655	-7.322	-3.443	0.951
163	9	3	1.885	-0.673	8.280	-6.606	-3.443	0.951
164	9	4	1.885	-0.584	8.839	-5.837	-3.443	0.951
165	9	5	1.885	-0.494	9.327	-5.021	-3.443	0.951
166	9	6	1.885	-0.404	9.740	-4.164	-3.443	0.951
167	9	7	1.885	-0.314	10.074	-3.274	-3.443	0.951
168	9	8	1.885	-0.224	10.327	-2.358	-3.443	0.951
169	9	9	1.885	-0.135	10.497	-1.422	-3.443	0.951

170	9	10	1.885	-0.045	10.582	-0.475	-3.443	0.951
171	9	11	1.885	0.045	10.582	0.475	-3.443	0.951
172	9	12	1.885	0.135	10.497	1.422	-3.443	0.951
173	9	13	1.885	0.224	10.327	2.358	-3.443	0.951
174	9	14	1.885	0.314	10.074	3.274	-3.443	0.951
175	9	15	1.885	0.404	9.740	4.164	-3.443	0.951
176	9	16	1.885	0.494	9.327	5.021	-3.443	0.951
177	9	17	1.885	0.584	8.839	5.837	-3.443	0.951
178	9	18	1.885	0.673	8.280	6.606	-3.443	0.951
179	9	19	1.885	0.763	7.655	7.322	-3.443	0.951
180	9	20	1.885	0.853	6.968	7.978	-3.443	0.951
181	10	1	1.975	-0.853	6.736	-7.714	-4.379	0.919
182	10	2	1.975	-0.763	7.401	-7.079	-4.379	0.919
183	10	3	1.975	-0.673	8.006	-6.387	-4.379	0.919
184	10	4	1.975	-0.584	8.546	-5.643	-4.379	0.919
185	10	5	1.975	-0.494	9.018	-4.854	-4.379	0.919
186	10	6	1.975	-0.404	9.417	-4.026	-4.379	0.919
187	10	7	1.975	-0.314	9.740	-3.166	-4.379	0.919
188	10	8	1.975	-0.224	9.984	-2.279	-4.379	0.919
189	10	9	1.975	-0.135	10.149	-1.375	-4.379	0.919
190	10	10	1.975	-0.045	10.231	-0.460	-4.379	0.919
191	10	11	1.975	0.045	10.231	0.460	-4.379	0.919
192	10	12	1.975	0.135	10.149	1.375	-4.379	0.919
193	10	13	1.975	0.224	9.984	2.279	-4.379	0.919
194	10	14	1.975	0.314	9.740	3.166	-4.379	0.919
195	10	15	1.975	0.404	9.417	4.026	-4.379	0.919
196	10	16	1.975	0.494	9.018	4.854	-4.379	0.919
197	10	17	1.975	0.584	8.546	5.643	-4.379	0.919
198	10	18	1.975	0.673	8.006	6.387	-4.379	0.919
199	10	19	1.975	0.763	7.401	7.079	-4.379	0.919
200	10	20	1.975	0.853	6.736	7.714	-4.379	0.919

Basal Layer of the Skin Disc Detector Locations

The center of each detector sphere was plotted by modeling an inner phantom sphere with a radius of 11.133 cm to model the 11.54 cm radius of the outer keratin scales minus the 0.402 cm basal layer of the skin dosimetric dose depth minus half the height of the disc detectors, 0.005 cm, to find the base coordinates and keep the dosimetric depth at the center of the disc detector. The 20 cm x 10 cm grid was centered on the equator of the sphere at $z = 0$. The

20 cm direction was defined along the azimuthal angle (φ) around the x-axis, and the 10 cm direction was defined along the polar angle (θ) from north to south. The center of the grid was defined at cartesian coordinates (11.133 cm, 0 cm, 0 cm), corresponding to $\theta_0 = \frac{\pi}{2}$ and $\varphi_0 = 0$.

The full span of the grid was:

$$\Delta\theta_{total} = \frac{L_\theta}{r} = \frac{10 \text{ cm}}{11.133 \text{ cm}} = 0.898 \text{ rad}$$

$$\Delta\varphi_{total} = \frac{L_\varphi}{r} = \frac{20 \text{ cm}}{11.133 \text{ cm}} = 1.796 \text{ rad}$$

The full span of the grid was divided into 1 cm x 1 cm patches, corresponding to $N_\theta = 10$ columns and $N_\varphi = 20$ rows. The angular width of each patch was:

$$\Delta\theta = \frac{\Delta\theta_{total}}{N_\theta} = \frac{0.898 \text{ rad}}{10} = 0.0898 \text{ rad}$$

$$\Delta\varphi = \frac{\Delta\varphi_{total}}{N_\varphi} = \frac{1.796 \text{ rad}}{20} = 0.0898 \text{ rad}$$

The angular width of each 1 cm x 1 cm patch is approximately equal. The center for each patch in the grid is found by:

$$\theta_i = \theta_0 + \left((i - 1) - \left(\frac{N_\theta - 1}{2} \right) \right) \Delta\theta, \text{ where } i = 1, 2, \dots, 10$$

$$\varphi_j = \varphi_0 + \left((j - 1) - \left(\frac{N_\varphi - 1}{2} \right) \right) \Delta\varphi, \text{ where } j = 1, 2, \dots, 20$$

The center for each patch is where $\theta_0 = \frac{\pi}{2} = 1.571 \text{ rad}$ and $\varphi_0 = 0$.

The cartesian coordinates for each center of the patch in the grid are then found by:

$$x = r \sin\theta \cos\varphi$$

$$y = r \sin\theta \sin\varphi$$

$$z = r \cos\theta$$

The area of each patch was calculated by:

$$area_{patch} = r^2 \sin\theta \Delta\theta_{patch} \Delta\varphi_{patch}$$

The following is an example calculation for the coordinates listed in Table E-7 below using patch $j = 1$ and $I = 1$.

$$\theta_1 = 1.571 \text{ rad} + \left((1 - 1) - \left(\frac{10-1}{2} \right) \right) \times 0.0898 \text{ rad} = 1.167 \text{ rad}$$

$$\varphi_1 = 0 \text{ rad} + \left((1 - 1) - \left(\frac{20-1}{2} \right) \right) \times 0.0898 \text{ rad} = -0.853 \text{ rad}$$

$$x = (11.138 \text{ cm}) \sin(1.167 \text{ rad}) \cos(-0.853 \text{ rad}) = 6.730 \text{ cm}$$

$$y = (11.138 \text{ cm}) \sin(1.167 \text{ rad}) \sin(-0.853 \text{ rad}) = -7.712 \text{ cm}$$

$$z = (11.138) \cos(1.167 \text{ rad}) = 4.378 \text{ m}$$

$$area_{patch} = (11.133 \text{ cm})^2 \sin(1.167 \text{ rad}) (0.0898 \text{ rad})(0.0898 \text{ rad}) = 0.919 \text{ cm}^2$$

Table E-7 below lists all two hundred basal layer of the skin disc detector base locations for the planar source calculation.

Table E-7, Basal Layer of the Skin Disc Detector Coordinates for the Planar Source

Point #	i (Col)	j (Row)	Φ (rad)	ϑ (rad)	x (cm)	y (cm)	z (cm)	Area (cm ²)
1	1	1	1.167	-0.853	6.730	-7.712	4.378	0.919
2	1	2	1.167	-0.763	7.395	-7.078	4.378	0.919
3	1	3	1.167	-0.674	8.000	-6.386	4.378	0.919
4	1	4	1.167	-0.584	8.540	-5.642	4.378	0.919
5	1	5	1.167	-0.494	9.012	-4.854	4.378	0.919
6	1	6	1.167	-0.404	9.411	-4.026	4.378	0.919
7	1	7	1.167	-0.314	9.734	-3.165	4.378	0.919
8	1	8	1.167	-0.225	9.979	-2.279	4.378	0.919
9	1	9	1.167	-0.135	10.143	-1.375	4.378	0.919
10	1	10	1.167	-0.045	10.226	-0.460	4.378	0.919
11	1	11	1.167	0.045	10.226	0.460	4.378	0.919
12	1	12	1.167	0.135	10.143	1.375	4.378	0.919
13	1	13	1.167	0.225	9.979	2.279	4.378	0.919
14	1	14	1.167	0.314	9.734	3.165	4.378	0.919
15	1	15	1.167	0.404	9.411	4.026	4.378	0.919
16	1	16	1.167	0.494	9.012	4.854	4.378	0.919
17	1	17	1.167	0.584	8.540	5.642	4.378	0.919
18	1	18	1.167	0.674	8.000	6.386	4.378	0.919
19	1	19	1.167	0.763	7.395	7.078	4.378	0.919

20	1	20	1.167	0.853	6.730	7.712	4.378	0.919
21	2	1	1.256	-0.853	6.961	-7.977	3.443	0.951
22	2	2	1.256	-0.763	7.649	-7.321	3.443	0.951
23	2	3	1.256	-0.674	8.274	-6.605	3.443	0.951
24	2	4	1.256	-0.584	8.834	-5.836	3.443	0.951
25	2	5	1.256	-0.494	9.321	-5.020	3.443	0.951
26	2	6	1.256	-0.404	9.734	-4.164	3.443	0.951
27	2	7	1.256	-0.314	10.068	-3.274	3.443	0.951
28	2	8	1.256	-0.225	10.322	-2.358	3.443	0.951
29	2	9	1.256	-0.135	10.491	-1.422	3.443	0.951
30	2	10	1.256	-0.045	10.577	-0.475	3.443	0.951
31	2	11	1.256	0.045	10.577	0.475	3.443	0.951
32	2	12	1.256	0.135	10.491	1.422	3.443	0.951
33	2	13	1.256	0.225	10.322	2.358	3.443	0.951
34	2	14	1.256	0.314	10.068	3.274	3.443	0.951
35	2	15	1.256	0.404	9.734	4.164	3.443	0.951
36	2	16	1.256	0.494	9.321	5.020	3.443	0.951
37	2	17	1.256	0.584	8.834	5.836	3.443	0.951
38	2	18	1.256	0.674	8.274	6.605	3.443	0.951
39	2	19	1.256	0.763	7.649	7.321	3.443	0.951
40	2	20	1.256	0.853	6.961	7.977	3.443	0.951
41	3	1	1.346	-0.853	7.136	-8.178	2.479	0.975
42	3	2	1.346	-0.763	7.841	-7.505	2.479	0.975
43	3	3	1.346	-0.674	8.482	-6.771	2.479	0.975
44	3	4	1.346	-0.584	9.056	-5.983	2.479	0.975
45	3	5	1.346	-0.494	9.556	-5.146	2.479	0.975
46	3	6	1.346	-0.404	9.979	-4.269	2.479	0.975
47	3	7	1.346	-0.314	10.322	-3.356	2.479	0.975
48	3	8	1.346	-0.225	10.581	-2.417	2.479	0.975
49	3	9	1.346	-0.135	10.755	-1.458	2.479	0.975
50	3	10	1.346	-0.045	10.843	-0.487	2.479	0.975
51	3	11	1.346	0.045	10.843	0.487	2.479	0.975
52	3	12	1.346	0.135	10.755	1.458	2.479	0.975
53	3	13	1.346	0.225	10.581	2.417	2.479	0.975
54	3	14	1.346	0.314	10.322	3.356	2.479	0.975
55	3	15	1.346	0.404	9.979	4.269	2.479	0.975
56	3	16	1.346	0.494	9.556	5.146	2.479	0.975
57	3	17	1.346	0.584	9.056	5.983	2.479	0.975
58	3	18	1.346	0.674	8.482	6.771	2.479	0.975
59	3	19	1.346	0.763	7.841	7.505	2.479	0.975
60	3	20	1.346	0.853	7.136	8.178	2.479	0.975
61	4	1	1.436	-0.853	7.253	-8.312	1.495	0.991
62	4	2	1.436	-0.763	7.970	-7.628	1.495	0.991

63	4	3	1.436	-0.674	8.622	-6.882	1.495	0.991
64	4	4	1.436	-0.584	9.205	-6.081	1.495	0.991
65	4	5	1.436	-0.494	9.713	-5.231	1.495	0.991
66	4	6	1.436	-0.404	10.143	-4.339	1.495	0.991
67	4	7	1.436	-0.314	10.491	-3.411	1.495	0.991
68	4	8	1.436	-0.225	10.755	-2.457	1.495	0.991
69	4	9	1.436	-0.135	10.932	-1.482	1.495	0.991
70	4	10	1.436	-0.045	11.021	-0.495	1.495	0.991
71	4	11	1.436	0.045	11.021	0.495	1.495	0.991
72	4	12	1.436	0.135	10.932	1.482	1.495	0.991
73	4	13	1.436	0.225	10.755	2.457	1.495	0.991
74	4	14	1.436	0.314	10.491	3.411	1.495	0.991
75	4	15	1.436	0.404	10.143	4.339	1.495	0.991
76	4	16	1.436	0.494	9.713	5.231	1.495	0.991
77	4	17	1.436	0.584	9.205	6.081	1.495	0.991
78	4	18	1.436	0.674	8.622	6.882	1.495	0.991
79	4	19	1.436	0.763	7.970	7.628	1.495	0.991
80	4	20	1.436	0.853	7.253	8.312	1.495	0.991
81	5	1	1.526	-0.853	7.312	-8.380	0.500	0.999
82	5	2	1.526	-0.763	8.035	-7.690	0.500	0.999
83	5	3	1.526	-0.674	8.692	-6.938	0.500	0.999
84	5	4	1.526	-0.584	9.279	-6.131	0.500	0.999
85	5	5	1.526	-0.494	9.792	-5.274	0.500	0.999
86	5	6	1.526	-0.404	10.226	-4.374	0.500	0.999
87	5	7	1.526	-0.314	10.577	-3.439	0.500	0.999
88	5	8	1.526	-0.225	10.843	-2.477	0.500	0.999
89	5	9	1.526	-0.135	11.021	-1.494	0.500	0.999
90	5	10	1.526	-0.045	11.111	-0.499	0.500	0.999
91	5	11	1.526	0.045	11.111	0.499	0.500	0.999
92	5	12	1.526	0.135	11.021	1.494	0.500	0.999
93	5	13	1.526	0.225	10.843	2.477	0.500	0.999
94	5	14	1.526	0.314	10.577	3.439	0.500	0.999
95	5	15	1.526	0.404	10.226	4.374	0.500	0.999
96	5	16	1.526	0.494	9.792	5.274	0.500	0.999
97	5	17	1.526	0.584	9.279	6.131	0.500	0.999
98	5	18	1.526	0.674	8.692	6.938	0.500	0.999
99	5	19	1.526	0.763	8.035	7.690	0.500	0.999
100	5	20	1.526	0.853	7.312	8.380	0.500	0.999
101	6	1	1.616	-0.853	7.312	-8.380	-0.500	0.999
102	6	2	1.616	-0.763	8.035	-7.690	-0.500	0.999
103	6	3	1.616	-0.674	8.692	-6.938	-0.500	0.999
104	6	4	1.616	-0.584	9.279	-6.131	-0.500	0.999
105	6	5	1.616	-0.494	9.792	-5.274	-0.500	0.999

106	6	6	1.616	-0.404	10.226	-4.374	-0.500	0.999
107	6	7	1.616	-0.314	10.577	-3.439	-0.500	0.999
108	6	8	1.616	-0.225	10.843	-2.477	-0.500	0.999
109	6	9	1.616	-0.135	11.021	-1.494	-0.500	0.999
110	6	10	1.616	-0.045	11.111	-0.499	-0.500	0.999
111	6	11	1.616	0.045	11.111	0.499	-0.500	0.999
112	6	12	1.616	0.135	11.021	1.494	-0.500	0.999
113	6	13	1.616	0.225	10.843	2.477	-0.500	0.999
114	6	14	1.616	0.314	10.577	3.439	-0.500	0.999
115	6	15	1.616	0.404	10.226	4.374	-0.500	0.999
116	6	16	1.616	0.494	9.792	5.274	-0.500	0.999
117	6	17	1.616	0.584	9.279	6.131	-0.500	0.999
118	6	18	1.616	0.674	8.692	6.938	-0.500	0.999
119	6	19	1.616	0.763	8.035	7.690	-0.500	0.999
120	6	20	1.616	0.853	7.312	8.380	-0.500	0.999
121	7	1	1.706	-0.853	7.253	-8.312	-1.495	0.991
122	7	2	1.706	-0.763	7.970	-7.628	-1.495	0.991
123	7	3	1.706	-0.674	8.622	-6.882	-1.495	0.991
124	7	4	1.706	-0.584	9.205	-6.081	-1.495	0.991
125	7	5	1.706	-0.494	9.713	-5.231	-1.495	0.991
126	7	6	1.706	-0.404	10.143	-4.339	-1.495	0.991
127	7	7	1.706	-0.314	10.491	-3.411	-1.495	0.991
128	7	8	1.706	-0.225	10.755	-2.457	-1.495	0.991
129	7	9	1.706	-0.135	10.932	-1.482	-1.495	0.991
130	7	10	1.706	-0.045	11.021	-0.495	-1.495	0.991
131	7	11	1.706	0.045	11.021	0.495	-1.495	0.991
132	7	12	1.706	0.135	10.932	1.482	-1.495	0.991
133	7	13	1.706	0.225	10.755	2.457	-1.495	0.991
134	7	14	1.706	0.314	10.491	3.411	-1.495	0.991
135	7	15	1.706	0.404	10.143	4.339	-1.495	0.991
136	7	16	1.706	0.494	9.713	5.231	-1.495	0.991
137	7	17	1.706	0.584	9.205	6.081	-1.495	0.991
138	7	18	1.706	0.674	8.622	6.882	-1.495	0.991
139	7	19	1.706	0.763	7.970	7.628	-1.495	0.991
140	7	20	1.706	0.853	7.253	8.312	-1.495	0.991
141	8	1	1.795	-0.853	7.136	-8.178	-2.479	0.975
142	8	2	1.795	-0.763	7.841	-7.505	-2.479	0.975
143	8	3	1.795	-0.674	8.482	-6.771	-2.479	0.975
144	8	4	1.795	-0.584	9.056	-5.983	-2.479	0.975
145	8	5	1.795	-0.494	9.556	-5.146	-2.479	0.975
146	8	6	1.795	-0.404	9.979	-4.269	-2.479	0.975
147	8	7	1.795	-0.314	10.322	-3.356	-2.479	0.975
148	8	8	1.795	-0.225	10.581	-2.417	-2.479	0.975

149	8	9	1.795	-0.135	10.755	-1.458	-2.479	0.975
150	8	10	1.795	-0.045	10.843	-0.487	-2.479	0.975
151	8	11	1.795	0.045	10.843	0.487	-2.479	0.975
152	8	12	1.795	0.135	10.755	1.458	-2.479	0.975
153	8	13	1.795	0.225	10.581	2.417	-2.479	0.975
154	8	14	1.795	0.314	10.322	3.356	-2.479	0.975
155	8	15	1.795	0.404	9.979	4.269	-2.479	0.975
156	8	16	1.795	0.494	9.556	5.146	-2.479	0.975
157	8	17	1.795	0.584	9.056	5.983	-2.479	0.975
158	8	18	1.795	0.674	8.482	6.771	-2.479	0.975
159	8	19	1.795	0.763	7.841	7.505	-2.479	0.975
160	8	20	1.795	0.853	7.136	8.178	-2.479	0.975
161	9	1	1.885	-0.853	6.961	-7.977	-3.443	0.951
162	9	2	1.885	-0.763	7.649	-7.321	-3.443	0.951
163	9	3	1.885	-0.674	8.274	-6.605	-3.443	0.951
164	9	4	1.885	-0.584	8.834	-5.836	-3.443	0.951
165	9	5	1.885	-0.494	9.321	-5.020	-3.443	0.951
166	9	6	1.885	-0.404	9.734	-4.164	-3.443	0.951
167	9	7	1.885	-0.314	10.068	-3.274	-3.443	0.951
168	9	8	1.885	-0.225	10.322	-2.358	-3.443	0.951
169	9	9	1.885	-0.135	10.491	-1.422	-3.443	0.951
170	9	10	1.885	-0.045	10.577	-0.475	-3.443	0.951
171	9	11	1.885	0.045	10.577	0.475	-3.443	0.951
172	9	12	1.885	0.135	10.491	1.422	-3.443	0.951
173	9	13	1.885	0.225	10.322	2.358	-3.443	0.951
174	9	14	1.885	0.314	10.068	3.274	-3.443	0.951
175	9	15	1.885	0.404	9.734	4.164	-3.443	0.951
176	9	16	1.885	0.494	9.321	5.020	-3.443	0.951
177	9	17	1.885	0.584	8.834	5.836	-3.443	0.951
178	9	18	1.885	0.674	8.274	6.605	-3.443	0.951
179	9	19	1.885	0.763	7.649	7.321	-3.443	0.951
180	9	20	1.885	0.853	6.961	7.977	-3.443	0.951
181	10	1	1.975	-0.853	6.730	-7.712	-4.378	0.919
182	10	2	1.975	-0.763	7.395	-7.078	-4.378	0.919
183	10	3	1.975	-0.674	8.000	-6.386	-4.378	0.919
184	10	4	1.975	-0.584	8.540	-5.642	-4.378	0.919
185	10	5	1.975	-0.494	9.012	-4.854	-4.378	0.919
186	10	6	1.975	-0.404	9.411	-4.026	-4.378	0.919
187	10	7	1.975	-0.314	9.734	-3.165	-4.378	0.919
188	10	8	1.975	-0.225	9.979	-2.279	-4.378	0.919
189	10	9	1.975	-0.135	10.143	-1.375	-4.378	0.919
190	10	10	1.975	-0.045	10.226	-0.460	-4.378	0.919
191	10	11	1.975	0.045	10.226	0.460	-4.378	0.919

192	10	12	1.975	0.135	10.143	1.375	-4.378	0.919
193	10	13	1.975	0.225	9.979	2.279	-4.378	0.919
194	10	14	1.975	0.314	9.734	3.165	-4.378	0.919
195	10	15	1.975	0.404	9.411	4.026	-4.378	0.919
196	10	16	1.975	0.494	9.012	4.854	-4.378	0.919
197	10	17	1.975	0.584	8.540	5.642	-4.378	0.919
198	10	18	1.975	0.674	8.000	6.386	-4.378	0.919
199	10	19	1.975	0.763	7.395	7.078	-4.378	0.919
200	10	20	1.975	0.853	6.730	7.712	-4.378	0.919

To input an RCC into MCNP, the height vector and radius are also required. To ensure the center of the bases of the RCCs were tangent to the inner 11.133 cm sphere, the cartesian coordinates for the centers of the bases were normalized to the unit radial vector of 11.133 and scaled by the disc thickness of 0.01 cm. This ensured the normal vector pointed radially outward, and the disc extended along this normal vector by 0.01 cm.

The height vectors were found by:

$$h_x = X \cdot \frac{0.01 \text{ cm}}{11.133 \text{ cm}}$$

$$h_y = Y \cdot \frac{0.01 \text{ cm}}{11.133 \text{ cm}}$$

$$h_z = Z \cdot \frac{0.01 \text{ cm}}{11.133 \text{ cm}}$$

The following is an example calculation for the height vectors listed in Table E-8 below using the cartesian coordinates for disc detector #1.

$$h_x = 6.730 \cdot \frac{0.01 \text{ cm}}{11.133 \text{ cm}} = 0.00605$$

$$h_y = -7.712 \cdot \frac{0.01 \text{ cm}}{11.133 \text{ cm}} = -0.00693$$

$$h_z = 4.378 \cdot \frac{0.01 \text{ cm}}{11.133 \text{ cm}} = 0.00393$$

Table E-8, Height Vectors for the Basal Layer of the Skin Disc Detectors for the Planar Source

Disc #	i (Col)	j (Row)	x (cm)	y (cm)	z (cm)	h _x	h _y	h _z
1	1	1	6.730	-7.712	4.378	0.00605	-0.00693	0.00393
2	1	2	7.395	-7.078	4.378	0.00664	-0.00636	0.00393
3	1	3	8.000	-6.386	4.378	0.00719	-0.00574	0.00393
4	1	4	8.540	-5.642	4.378	0.00767	-0.00507	0.00393
5	1	5	9.012	-4.854	4.378	0.00809	-0.00436	0.00393
6	1	6	9.411	-4.026	4.378	0.00845	-0.00362	0.00393
7	1	7	9.734	-3.165	4.378	0.00874	-0.00284	0.00393
8	1	8	9.979	-2.279	4.378	0.00896	-0.00205	0.00393
9	1	9	10.143	-1.375	4.378	0.00911	-0.00124	0.00393
10	1	10	10.226	-0.460	4.378	0.00918	-0.00041	0.00393
11	1	11	10.226	0.460	4.378	0.00918	0.00041	0.00393
12	1	12	10.143	1.375	4.378	0.00911	0.00124	0.00393
13	1	13	9.979	2.279	4.378	0.00896	0.00205	0.00393
14	1	14	9.734	3.165	4.378	0.00874	0.00284	0.00393
15	1	15	9.411	4.026	4.378	0.00845	0.00362	0.00393
16	1	16	9.012	4.854	4.378	0.00809	0.00436	0.00393
17	1	17	8.540	5.642	4.378	0.00767	0.00507	0.00393
18	1	18	8.000	6.386	4.378	0.00719	0.00574	0.00393
19	1	19	7.395	7.078	4.378	0.00664	0.00636	0.00393
20	1	20	6.730	7.712	4.378	0.00605	0.00693	0.00393
21	2	1	6.961	-7.977	3.443	0.00625	-0.00717	0.00309
22	2	2	7.649	-7.321	3.443	0.00687	-0.00658	0.00309
23	2	3	8.274	-6.605	3.443	0.00743	-0.00593	0.00309
24	2	4	8.834	-5.836	3.443	0.00793	-0.00524	0.00309
25	2	5	9.321	-5.020	3.443	0.00837	-0.00451	0.00309
26	2	6	9.734	-4.164	3.443	0.00874	-0.00374	0.00309
27	2	7	10.068	-3.274	3.443	0.00904	-0.00294	0.00309
28	2	8	10.322	-2.358	3.443	0.00927	-0.00212	0.00309
29	2	9	10.491	-1.422	3.443	0.00942	-0.00128	0.00309
30	2	10	10.577	-0.475	3.443	0.00950	-0.00043	0.00309
31	2	11	10.577	0.475	3.443	0.00950	0.00043	0.00309
32	2	12	10.491	1.422	3.443	0.00942	0.00128	0.00309
33	2	13	10.322	2.358	3.443	0.00927	0.00212	0.00309
34	2	14	10.068	3.274	3.443	0.00904	0.00294	0.00309
35	2	15	9.734	4.164	3.443	0.00874	0.00374	0.00309
36	2	16	9.321	5.020	3.443	0.00837	0.00451	0.00309
37	2	17	8.834	5.836	3.443	0.00793	0.00524	0.00309
38	2	18	8.274	6.605	3.443	0.00743	0.00593	0.00309
39	2	19	7.649	7.321	3.443	0.00687	0.00658	0.00309

40	2	20	6.961	7.977	3.443	0.00625	0.00717	0.00309
41	3	1	7.136	-8.178	2.479	0.00641	-0.00735	0.00223
42	3	2	7.841	-7.505	2.479	0.00704	-0.00674	0.00223
43	3	3	8.482	-6.771	2.479	0.00762	-0.00608	0.00223
44	3	4	9.056	-5.983	2.479	0.00813	-0.00537	0.00223
45	3	5	9.556	-5.146	2.479	0.00858	-0.00462	0.00223
46	3	6	9.979	-4.269	2.479	0.00896	-0.00383	0.00223
47	3	7	10.322	-3.356	2.479	0.00927	-0.00301	0.00223
48	3	8	10.581	-2.417	2.479	0.00950	-0.00217	0.00223
49	3	9	10.755	-1.458	2.479	0.00966	-0.00131	0.00223
50	3	10	10.843	-0.487	2.479	0.00974	-0.00044	0.00223
51	3	11	10.843	0.487	2.479	0.00974	0.00044	0.00223
52	3	12	10.755	1.458	2.479	0.00966	0.00131	0.00223
53	3	13	10.581	2.417	2.479	0.00950	0.00217	0.00223
54	3	14	10.322	3.356	2.479	0.00927	0.00301	0.00223
55	3	15	9.979	4.269	2.479	0.00896	0.00383	0.00223
56	3	16	9.556	5.146	2.479	0.00858	0.00462	0.00223
57	3	17	9.056	5.983	2.479	0.00813	0.00537	0.00223
58	3	18	8.482	6.771	2.479	0.00762	0.00608	0.00223
59	3	19	7.841	7.505	2.479	0.00704	0.00674	0.00223
60	3	20	7.136	8.178	2.479	0.00641	0.00735	0.00223
61	4	1	7.253	-8.312	1.495	0.00652	-0.00747	0.00134
62	4	2	7.970	-7.628	1.495	0.00716	-0.00685	0.00134
63	4	3	8.622	-6.882	1.495	0.00774	-0.00618	0.00134
64	4	4	9.205	-6.081	1.495	0.00827	-0.00546	0.00134
65	4	5	9.713	-5.231	1.495	0.00872	-0.00470	0.00134
66	4	6	10.143	-4.339	1.495	0.00911	-0.00390	0.00134
67	4	7	10.491	-3.411	1.495	0.00942	-0.00306	0.00134
68	4	8	10.755	-2.457	1.495	0.00966	-0.00221	0.00134
69	4	9	10.932	-1.482	1.495	0.00982	-0.00133	0.00134
70	4	10	11.021	-0.495	1.495	0.00990	-0.00044	0.00134
71	4	11	11.021	0.495	1.495	0.00990	0.00044	0.00134
72	4	12	10.932	1.482	1.495	0.00982	0.00133	0.00134
73	4	13	10.755	2.457	1.495	0.00966	0.00221	0.00134
74	4	14	10.491	3.411	1.495	0.00942	0.00306	0.00134
75	4	15	10.143	4.339	1.495	0.00911	0.00390	0.00134
76	4	16	9.713	5.231	1.495	0.00872	0.00470	0.00134
77	4	17	9.205	6.081	1.495	0.00827	0.00546	0.00134
78	4	18	8.622	6.882	1.495	0.00774	0.00618	0.00134
79	4	19	7.970	7.628	1.495	0.00716	0.00685	0.00134
80	4	20	7.253	8.312	1.495	0.00652	0.00747	0.00134
81	5	1	7.312	-8.380	0.500	0.00657	-0.00753	0.00045
82	5	2	8.035	-7.690	0.500	0.00722	-0.00691	0.00045

83	5	3	8.692	-6.938	0.500	0.00781	-0.00623	0.00045
84	5	4	9.279	-6.131	0.500	0.00834	-0.00551	0.00045
85	5	5	9.792	-5.274	0.500	0.00880	-0.00474	0.00045
86	5	6	10.226	-4.374	0.500	0.00918	-0.00393	0.00045
87	5	7	10.577	-3.439	0.500	0.00950	-0.00309	0.00045
88	5	8	10.843	-2.477	0.500	0.00974	-0.00222	0.00045
89	5	9	11.021	-1.494	0.500	0.00990	-0.00134	0.00045
90	5	10	11.111	-0.499	0.500	0.00998	-0.00045	0.00045
91	5	11	11.111	0.499	0.500	0.00998	0.00045	0.00045
92	5	12	11.021	1.494	0.500	0.00990	0.00134	0.00045
93	5	13	10.843	2.477	0.500	0.00974	0.00222	0.00045
94	5	14	10.577	3.439	0.500	0.00950	0.00309	0.00045
95	5	15	10.226	4.374	0.500	0.00918	0.00393	0.00045
96	5	16	9.792	5.274	0.500	0.00880	0.00474	0.00045
97	5	17	9.279	6.131	0.500	0.00834	0.00551	0.00045
98	5	18	8.692	6.938	0.500	0.00781	0.00623	0.00045
99	5	19	8.035	7.690	0.500	0.00722	0.00691	0.00045
100	5	20	7.312	8.380	0.500	0.00657	0.00753	0.00045
101	6	1	7.312	-8.380	-0.500	0.00657	-0.00753	-0.00045
102	6	2	8.035	-7.690	-0.500	0.00722	-0.00691	-0.00045
103	6	3	8.692	-6.938	-0.500	0.00781	-0.00623	-0.00045
104	6	4	9.279	-6.131	-0.500	0.00834	-0.00551	-0.00045
105	6	5	9.792	-5.274	-0.500	0.00880	-0.00474	-0.00045
106	6	6	10.226	-4.374	-0.500	0.00918	-0.00393	-0.00045
107	6	7	10.577	-3.439	-0.500	0.00950	-0.00309	-0.00045
108	6	8	10.843	-2.477	-0.500	0.00974	-0.00222	-0.00045
109	6	9	11.021	-1.494	-0.500	0.00990	-0.00134	-0.00045
110	6	10	11.111	-0.499	-0.500	0.00998	-0.00045	-0.00045
111	6	11	11.111	0.499	-0.500	0.00998	0.00045	-0.00045
112	6	12	11.021	1.494	-0.500	0.00990	0.00134	-0.00045
113	6	13	10.843	2.477	-0.500	0.00974	0.00222	-0.00045
114	6	14	10.577	3.439	-0.500	0.00950	0.00309	-0.00045
115	6	15	10.226	4.374	-0.500	0.00918	0.00393	-0.00045
116	6	16	9.792	5.274	-0.500	0.00880	0.00474	-0.00045
117	6	17	9.279	6.131	-0.500	0.00834	0.00551	-0.00045
118	6	18	8.692	6.938	-0.500	0.00781	0.00623	-0.00045
119	6	19	8.035	7.690	-0.500	0.00722	0.00691	-0.00045
120	6	20	7.312	8.380	-0.500	0.00657	0.00753	-0.00045
121	7	1	7.253	-8.312	-1.495	0.00652	-0.00747	-0.00134
122	7	2	7.970	-7.628	-1.495	0.00716	-0.00685	-0.00134
123	7	3	8.622	-6.882	-1.495	0.00774	-0.00618	-0.00134
124	7	4	9.205	-6.081	-1.495	0.00827	-0.00546	-0.00134
125	7	5	9.713	-5.231	-1.495	0.00872	-0.00470	-0.00134

126	7	6	10.143	-4.339	-1.495	0.00911	-0.00390	-0.00134
127	7	7	10.491	-3.411	-1.495	0.00942	-0.00306	-0.00134
128	7	8	10.755	-2.457	-1.495	0.00966	-0.00221	-0.00134
129	7	9	10.932	-1.482	-1.495	0.00982	-0.00133	-0.00134
130	7	10	11.021	-0.495	-1.495	0.00990	-0.00044	-0.00134
131	7	11	11.021	0.495	-1.495	0.00990	0.00044	-0.00134
132	7	12	10.932	1.482	-1.495	0.00982	0.00133	-0.00134
133	7	13	10.755	2.457	-1.495	0.00966	0.00221	-0.00134
134	7	14	10.491	3.411	-1.495	0.00942	0.00306	-0.00134
135	7	15	10.143	4.339	-1.495	0.00911	0.00390	-0.00134
136	7	16	9.713	5.231	-1.495	0.00872	0.00470	-0.00134
137	7	17	9.205	6.081	-1.495	0.00827	0.00546	-0.00134
138	7	18	8.622	6.882	-1.495	0.00774	0.00618	-0.00134
139	7	19	7.970	7.628	-1.495	0.00716	0.00685	-0.00134
140	7	20	7.253	8.312	-1.495	0.00652	0.00747	-0.00134
141	8	1	7.136	-8.178	-2.479	0.00641	-0.00735	-0.00223
142	8	2	7.841	-7.505	-2.479	0.00704	-0.00674	-0.00223
143	8	3	8.482	-6.771	-2.479	0.00762	-0.00608	-0.00223
144	8	4	9.056	-5.983	-2.479	0.00813	-0.00537	-0.00223
145	8	5	9.556	-5.146	-2.479	0.00858	-0.00462	-0.00223
146	8	6	9.979	-4.269	-2.479	0.00896	-0.00383	-0.00223
147	8	7	10.322	-3.356	-2.479	0.00927	-0.00301	-0.00223
148	8	8	10.581	-2.417	-2.479	0.00950	-0.00217	-0.00223
149	8	9	10.755	-1.458	-2.479	0.00966	-0.00131	-0.00223
150	8	10	10.843	-0.487	-2.479	0.00974	-0.00044	-0.00223
151	8	11	10.843	0.487	-2.479	0.00974	0.00044	-0.00223
152	8	12	10.755	1.458	-2.479	0.00966	0.00131	-0.00223
153	8	13	10.581	2.417	-2.479	0.00950	0.00217	-0.00223
154	8	14	10.322	3.356	-2.479	0.00927	0.00301	-0.00223
155	8	15	9.979	4.269	-2.479	0.00896	0.00383	-0.00223
156	8	16	9.556	5.146	-2.479	0.00858	0.00462	-0.00223
157	8	17	9.056	5.983	-2.479	0.00813	0.00537	-0.00223
158	8	18	8.482	6.771	-2.479	0.00762	0.00608	-0.00223
159	8	19	7.841	7.505	-2.479	0.00704	0.00674	-0.00223
160	8	20	7.136	8.178	-2.479	0.00641	0.00735	-0.00223
161	9	1	6.961	-7.977	-3.443	0.00625	-0.00717	-0.00309
162	9	2	7.649	-7.321	-3.443	0.00687	-0.00658	-0.00309
163	9	3	8.274	-6.605	-3.443	0.00743	-0.00593	-0.00309
164	9	4	8.834	-5.836	-3.443	0.00793	-0.00524	-0.00309
165	9	5	9.321	-5.020	-3.443	0.00837	-0.00451	-0.00309
166	9	6	9.734	-4.164	-3.443	0.00874	-0.00374	-0.00309
167	9	7	10.068	-3.274	-3.443	0.00904	-0.00294	-0.00309
168	9	8	10.322	-2.358	-3.443	0.00927	-0.00212	-0.00309

169	9	9	10.491	-1.422	-3.443	0.00942	-0.00128	-0.00309
170	9	10	10.577	-0.475	-3.443	0.00950	-0.00043	-0.00309
171	9	11	10.577	0.475	-3.443	0.00950	0.00043	-0.00309
172	9	12	10.491	1.422	-3.443	0.00942	0.00128	-0.00309
173	9	13	10.322	2.358	-3.443	0.00927	0.00212	-0.00309
174	9	14	10.068	3.274	-3.443	0.00904	0.00294	-0.00309
175	9	15	9.734	4.164	-3.443	0.00874	0.00374	-0.00309
176	9	16	9.321	5.020	-3.443	0.00837	0.00451	-0.00309
177	9	17	8.834	5.836	-3.443	0.00793	0.00524	-0.00309
178	9	18	8.274	6.605	-3.443	0.00743	0.00593	-0.00309
179	9	19	7.649	7.321	-3.443	0.00687	0.00658	-0.00309
180	9	20	6.961	7.977	-3.443	0.00625	0.00717	-0.00309
181	10	1	6.730	-7.712	-4.378	0.00605	-0.00693	-0.00393
182	10	2	7.395	-7.078	-4.378	0.00664	-0.00636	-0.00393
183	10	3	8.000	-6.386	-4.378	0.00719	-0.00574	-0.00393
184	10	4	8.540	-5.642	-4.378	0.00767	-0.00507	-0.00393
185	10	5	9.012	-4.854	-4.378	0.00809	-0.00436	-0.00393
186	10	6	9.411	-4.026	-4.378	0.00845	-0.00362	-0.00393
187	10	7	9.734	-3.165	-4.378	0.00874	-0.00284	-0.00393
188	10	8	9.979	-2.279	-4.378	0.00896	-0.00205	-0.00393
189	10	9	10.143	-1.375	-4.378	0.00911	-0.00124	-0.00393
190	10	10	10.226	-0.460	-4.378	0.00918	-0.00041	-0.00393
191	10	11	10.226	0.460	-4.378	0.00918	0.00041	-0.00393
192	10	12	10.143	1.375	-4.378	0.00911	0.00124	-0.00393
193	10	13	9.979	2.279	-4.378	0.00896	0.00205	-0.00393
194	10	14	9.734	3.165	-4.378	0.00874	0.00284	-0.00393
195	10	15	9.411	4.026	-4.378	0.00845	0.00362	-0.00393
196	10	16	9.012	4.854	-4.378	0.00809	0.00436	-0.00393
197	10	17	8.540	5.642	-4.378	0.00767	0.00507	-0.00393
198	10	18	8.000	6.386	-4.378	0.00719	0.00574	-0.00393
199	10	19	7.395	7.078	-4.378	0.00664	0.00636	-0.00393
200	10	20	6.730	7.712	-4.378	0.00605	0.00693	-0.00393

Beta Particle Probability Distribution

Table E-9 below shows the ^{60}Co beta-particle energy in MeV, the probability distribution in particles MeV^{-1} nuclear transition $^{-1}$, and the probability in particles nuclear transition $^{-1}$. The probabilities are summed for the energy bin upper boundaries: 0.00, 0.02, 0.04, 0.06, 0.08, 0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24, 0.26, 0.28, 0.30, 0.32, and 1.49. The density probabilities

for ^{60}Co beta particles were found using the MIRDsoft database, a free database supported by the SNMMI MIRD Committee using values based on ICRP Report 107 (SNMMI MIRD Committee, n.d.). From the probability density function, the integrated probability of each energy line was calculated using the trapezoidal rule.

$$\text{Area} = \frac{\text{Probability}_1 + \text{Probability}_2}{2} \times (\text{Energy}_2 - \text{Energy}_1)$$

A sample calculation is shown for the first two energies listed in Table E-9 below, 0 MeV

and 0.0001 MeV, and the respective probability densities, $6.626 \frac{\text{\# of particles}}{\text{MeV transition}}$ and

$6.623 \frac{\text{\# of particles}}{\text{MeV transition}}$.

$$\text{Area} = \frac{6.626 \frac{\text{\# of particles}}{\text{MeV transition}} + 6.623 \frac{\text{\# of particles}}{\text{MeV transition}}}{2} \cdot (0.0001 \text{ MeV} - 0 \text{ MeV}) =$$

$$0.0006625 \frac{\text{particles}}{\text{nuclear transition}}$$

Table E-9, ^{60}Co Beta Particle Energy Probabilities

Energy [MeV]	Probability density [# / MeV / nt]	Probability (# / nt)	Bin Summation
0	6.626	0	-
0.0001	6.623	0.000662	-
0.00011	6.623	6.62E-05	-
0.00012	6.622	6.62E-05	-
0.00013	6.622	6.62E-05	-
0.00014	6.622	6.62E-05	-
0.00015	6.621	6.62E-05	-
0.00016	6.621	6.62E-05	-
0.00018	6.621	0.000132	-
0.0002	6.62	0.000132	-
0.00022	6.619	0.000132	-
0.00024	6.619	0.000132	-
0.00026	6.618	0.000132	-
0.00028	6.618	0.000132	-
0.0003	6.617	0.000132	-
0.00032	6.616	0.000132	-
0.00036	6.615	0.000265	-

0.0004	6.614	0.000265	-
0.00045	6.613	0.000331	-
0.0005	6.611	0.000331	-
0.00055	6.61	0.000331	-
0.0006	6.608	0.00033	-
0.00065	6.607	0.00033	-
0.0007	6.606	0.00033	-
0.00075	6.604	0.00033	-
0.0008	6.603	0.00033	-
0.00085	6.601	0.00033	-
0.0009	6.6	0.00033	-
0.001	6.597	0.00066	-
0.0011	6.594	0.00066	-
0.0012	6.591	0.000659	-
0.0013	6.588	0.000659	-
0.0014	6.586	0.000659	-
0.0015	6.583	0.000658	-
0.0016	6.58	0.000658	-
0.0018	6.574	0.001315	-
0.002	6.568	0.001314	-
0.0022	6.563	0.001313	-
0.0024	6.557	0.001312	-
0.0026	6.551	0.001311	-
0.0028	6.545	0.00131	-
0.003	6.54	0.001309	-
0.0032	6.534	0.001307	-
0.0036	6.523	0.002611	-
0.004	6.516	0.002608	-
0.0045	6.507	0.003256	-
0.005	6.497	0.003251	-
0.0055	6.488	0.003246	-
0.006	6.478	0.003242	-
0.0065	6.469	0.003237	-
0.007	6.459	0.003232	-
0.0075	6.45	0.003227	-
0.008	6.44	0.003223	-
0.0085	6.431	0.003218	-
0.009	-6.422	0.003213	-
0.01	6.403	0.006413	-
0.011	6.385	0.006394	-
0.012	6.367	0.006376	-
0.013	6.349	0.006358	-
0.014	6.332	0.006341	-

0.015	6.315	0.006323	-
0.016	6.298	0.006307	-
0.018	6.265	0.012563	-
0.02	6.234	0.012499	0.12819
0.022	6.203	0.012437	-
0.024	6.172	0.012375	-
0.026	6.142	0.012314	-
0.028	6.113	0.012255	-
0.03	6.083	0.012196	-
0.032	6.053	0.012136	-
0.036	5.993	0.024092	-
0.04	5.932	0.02385	0.12166
0.045	5.853	0.029463	-
0.05	5.771	0.02906	-
0.055	5.685	0.02864	-
0.06	5.596	0.028203	0.11537
0.065	5.502	0.027745	-
0.07	5.405	0.027268	-
0.075	5.304	0.026772	-
0.08	5.198	0.026255	0.10804
0.085	5.089	0.025718	-
0.09	4.977	0.025165	-
0.1	4.742	0.048595	0.09948
0.11	4.494	0.04618	-
0.12	4.235	0.043645	0.08983
0.13	3.967	0.04101	-
0.14	3.692	0.038295	0.07931
0.15	3.411	0.035515	-
0.16	3.127	0.03269	0.06821
0.18	2.557	0.05684	0.05684
0.2	1.998	0.04555	0.04555
0.22	1.469	0.03467	0.03467
0.24	0.9907	0.024597	0.02460
0.26	0.5822	0.015729	0.01573
0.28	0.2658	0.00848	0.00848
0.3	0.06436	0.003302	0.00330
0.32	0.001027	0.000654	0.00065
0.36	0.00105	4.15E-05	-
0.4	0.00107	4.24E-05	-
0.45	0.001089	5.4E-05	-
0.5	0.001102	5.48E-05	-
0.55	0.001108	5.53E-05	-
0.6	0.001108	5.54E-05	-

0.65	0.001102	5.53E-05	-
0.7	0.001089	5.48E-05	-
0.75	0.00107	5.4E-05	-
0.8	0.001044	5.29E-05	-
0.85	0.00101	5.13E-05	-
0.9	0.0009695	4.95E-05	-
1	0.0008627	9.16E-05	-
1.1	0.0007174	7.9E-05	-
1.2	0.0005296	6.23E-05	-
1.3	0.0003083	4.19E-05	-
1.4	9.57E-05	2.02E-05	-
1.49139	0	4.37E-06	0.00092

Planar Source Tallies and Averages

The summation tally at the whole-body dosimetric depth for point detectors from a planar source, +F2006, tracked all energy deposited in the two hundred point detector cells, added them together per particle history, and performed statistical analysis over all histories to result in $1.15121 \times 10^{-4} \text{ MeV g}^{-1}$. Since these values were all acquired during one MCNP simulation, they are not truly independent and the propagation of errors calculation to sum in quadrature is not applicable. The MCNP simulation reported a true relative error of $0.0006 \text{ MeV g}^{-1}$, which includes covariance as the detectors are highly dependent on fluctuations per particle and spatial correlations.

The summation tally at the basal layer of the skin dosimetric depth for point detectors from a planar source, +F2006, resulted in $2.36093 \times 10^{-4} \text{ MeV g}^{-1}$. The MCNP simulation reported a true relative error of $0.0039 \text{ MeV g}^{-1}$.

The summation tally at the basal layer of the skin dosimetric depth for disc detectors from a planar source, +F2006, tracked all energy deposited in the 200 disc detector cells, added them together per particle history, and performed statistical analysis over all histories to result in $2.24622 \times 10^{-4} \text{ MeV g}^{-1}$. The MCNP simulation reported a true relative error of $0.0015 \text{ MeV g}^{-1}$.

MCNP Tally to Dose Conversions

The following equations show the MCNP tally to dose conversions used from each MCNP simulation result.

Table E-10, MCNP Result Tallies

	Tally (starting particle ⁻¹)	Unit	Relative Error
Whole Body Point Source F5	4.31123×10^{-2}	particles cm ⁻²	0.0001
Whole Body Point Source +F6	1.48229×10^{-3}	MeV g ⁻¹	0.0610
Whole Body Planar Source +F6	1.15121×10^{-4}	MeV g ⁻¹	0.0006
Basal Layer Point Source F5	5.13092×10^{-1}	particles cm ⁻²	$< 5 \times 10^{-5}$
Basal Layer Point Source +F6	1.04061×10^{-2}	MeV g ⁻¹	0.0250
Basal Layer Planar Source +F6 (Point Detectors)	2.36093×10^{-4}	MeV g ⁻¹	0.0039
Basal Layer Planar Source +F6 (Disc Detectors)	2.24622×10^{-4}	MeV g ⁻¹	0.0015
MIRD Whole Body Point Source F6	5.01201×10^{-5}	MeV g ⁻¹	0.0002

The whole-body F5 tally and uncertainty from a point source is converted to whole-body radiation dose below.

Given:

$$E = \text{energy } \gamma^{-1} \text{ in MeV } \gamma^{-1} = 1.25 \frac{\text{MeV}}{\gamma}$$

$$\frac{\mu_{en}}{\rho} = \frac{0.02938 \text{ cm}^2}{g}; \text{ the mass attenuation coefficient for soft tissue at 1.25 MeV}$$

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} \cdot \frac{2 \gamma}{\text{decay}} = 7.4 \times 10^5 \frac{\gamma}{s}$$

Tally Conversion:

$$\frac{4.31123 \times 10^{-2} \frac{\text{particles}}{\text{cm}^2}}{\text{starting particle}} \cdot \frac{1.25 \text{ MeV}}{\gamma} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{0.02938 \text{ cm}^2}{g} \cdot \frac{1000 \text{ g}}{kg} \cdot \frac{7.4 \times 10^5 \gamma}{s} \cdot \frac{3600 \text{ s}}{h} \cdot \frac{24 \text{ h}}{d} \cdot \frac{365.25 \text{ d}}{y} =$$

$$\frac{\frac{\text{J}}{kg} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} =$$

$$5920 \frac{\text{mGy}}{y} \text{ or } 676 \frac{\mu\text{Gy}}{h}$$

The relative error given from the MCNP simulation of 0.0001 represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output.

$$0.0001 \cdot 2 \cdot \frac{4.31123 \times 10^{-2} \text{ particles}}{\text{cm}} = \frac{8.62246 \times 10^{-6} \text{ particles}}{\text{cm}}$$

Uncertainty Tally Conversion:

$$\frac{\frac{8.62246 \times 10^{-6} \text{ particles}}{\text{cm}}}{\text{starting particle}} \cdot \frac{1.25 \text{ MeV}}{\gamma} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{0.02938 \text{ cm}^2}{\text{g}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \gamma}{\text{s}} \cdot \frac{3600 \text{ s}}{\text{h}} \cdot \frac{24 \text{ h}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}} = =$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} = 1 \frac{\text{mGy}}{\text{yr}} \text{ or } 1 \frac{\mu\text{Gy}}{\text{h}}$$

The basal layer of the skin F5 tally and uncertainty from a point source is converted to basal layer of the skin radiation dose below.

Given:

$$E = \text{energy } \gamma^{-1} \text{ in MeV } \gamma^{-1} = 1.25 \frac{\text{MeV}}{\gamma}$$

$$\frac{\mu_{en}}{\rho} = \frac{0.02938 \text{ cm}^2}{\text{g}}; \text{ the mass attenuation coefficient for soft tissue at 1.25 MeV}$$

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} \cdot \frac{2 \gamma}{\text{decay}} = 7.4 \times 10^5 \frac{\gamma}{\text{s}}$$

Tally Conversion:

$$\frac{\frac{5.13092 \times 10^{-1} \text{ particles}}{\text{cm}^2}}{\text{starting particle}} \cdot \frac{1.25 \text{ MeV}}{\gamma} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{0.02938 \text{ cm}^2}{\text{g}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \gamma}{\text{s}} \cdot \frac{86400 \text{ s}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}} = =$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} = 70500 \frac{\text{mGy}}{\text{y}} \text{ or } 8040 \frac{\mu\text{Gy}}{\text{h}}$$

The relative error given from the MCNP simulation of 0.0000 is not truly zero, but indicates that the error is smaller than can be reported. It is assumed that the error is less than 5×10^{-5} and will be assigned the most conservative value of 4×10^{-5} for calculation purposes. The value of 4×10^{-5} represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output.

$$4 \times 10^{-5} \cdot 2 \cdot \frac{5.13092 \times 10^{-1} \text{ particles}}{\text{cm}} = \frac{4.10474 \times 10^{-5} \text{ particles}}{\text{cm}}$$

Uncertainty Tally Conversion:

$$\frac{\frac{4.10474 \times 10^{-5} \text{ particles}}{\text{cm}^2}}{\text{starting particle}} \cdot \frac{1.25 \text{ MeV}}{\gamma} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{0.02938 \text{ cm}^2}{\text{g}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \gamma}{\text{s}} \cdot \frac{86400 \text{ s}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}} =$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}} =$$

$$6 \frac{\text{mGy}}{\text{y}} \text{ or } 1 \frac{\mu\text{Gy}}{\text{h}}$$

The whole body +F6 tally and uncertainty from a point source is converted to whole-body radiation dose below.

Given:

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{\text{s}} \cdot \frac{2 \gamma}{\text{decay}} = 7.4 \times 10^5 \frac{\gamma}{\text{s}}$$

Tally Conversion:

$$\frac{\frac{1.48229 \times 10^{-3} \text{ MeV}}{\text{g}}}{\text{starting particle}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \gamma}{\text{s}} \cdot \frac{86400 \text{ s}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}} = 5550 \frac{\text{mGy}}{\text{y}} \text{ or } 633 \frac{\mu\text{Gy}}{\text{h}}$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}$$

The relative error given from the MCNP simulation of 0.061 represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to

dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output.

$$0.061 \cdot 2 \cdot \frac{1.48229 \times 10^{-3} \text{ MeV}}{g} = \frac{1.80839 \times 10^{-4} \text{ MeV}}{g}$$

Uncertainty Tally Conversion:

$$\frac{\frac{1.80839 \times 10^{-4} \text{ MeV}}{g}}{\frac{\text{starting particle}}{\text{MeV}}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 677 \frac{\text{mGy}}{y} \text{ or } 77 \frac{\mu\text{Gy}}{h}$$

$$\frac{\frac{J}{kg} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}{\frac{J}{kg} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}$$

The basal layer of the skin +F6 tally and uncertainty from a point source is converted to basal layer of the skin radiation dose below.

Given:

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{s} \cdot \frac{2 \gamma}{\text{decay}} = 7.4 \times 10^5 \frac{\gamma}{s}$$

Tally Conversion:

$$\frac{\frac{1.04061 \times 10^{-2} \text{ MeV}}{g}}{\frac{\text{starting particle}}{\text{MeV}}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 38900 \frac{\text{mGy}}{y} \text{ or } 4440 \frac{\mu\text{Gy}}{h}$$

$$\frac{\frac{J}{kg} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}{\frac{J}{kg} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}$$

The relative error given from the MCNP simulation of 0.025 represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output

$$0.025 \cdot 2 \cdot \frac{1.04061 \times 10^{-2} \text{ MeV}}{g} = \frac{5.20305 \times 10^{-4} \text{ MeV}}{g}$$

Uncertainty Tally Conversion:

$$\frac{\frac{5.20305 \times 10^{-4} \text{ MeV}}{g}}{\frac{\text{starting particle}}{\text{MeV}}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \text{ y}}{\text{s}} \cdot \frac{86400 \text{ s}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}} = 1950 \frac{\text{mGy}}{\text{y}} \text{ or } 222 \frac{\mu\text{Gy}}{\text{h}}$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy} \cdot \text{mGy}}$$

The whole body +F6 tally and uncertainty from a planar source is converted to whole-body radiation dose below.

Given:

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} \cdot \frac{2 \text{ y}}{\text{decay}} = 7.4 \times 10^5 \frac{\text{y}}{\text{s}}$$

Average Tally Conversion:

$$\frac{\frac{1.15121 \times 10^{-4} \text{ MeV}}{g}}{\frac{\text{starting particle}}{\text{MeV}}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \text{ y}}{\text{s}} \cdot \frac{86400 \text{ s}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}} = 431 \frac{\text{mGy}}{\text{y}} \text{ or } 49.1 \frac{\mu\text{Gy}}{\text{h}}$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy} \cdot \text{mGy}}$$

The relative error given from the MCNP simulation of 0.0006 represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output.

$$0.0006 \cdot 2 \cdot \frac{1.15121 \times 10^{-4} \text{ MeV}}{g} = \frac{1.38145 \times 10^{-7} \text{ MeV}}{g}$$

Uncertainty Tally Conversion:

$$\frac{\frac{1.38145 \times 10^{-7} \text{ MeV}}{g}}{\frac{\text{starting particle}}{\text{MeV}}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \text{ y}}{\text{s}} \cdot \frac{86400 \text{ s}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}} = 1 \frac{\text{mGy}}{\text{y}} \text{ or } 0.1 \frac{\mu\text{Gy}}{\text{h}}$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy} \cdot \text{mGy}}$$

The basal layer of the skin +F6 tally and uncertainty from a planar source with point detectors is converted to basal layer of the skin radiation dose below.

Given:

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} \cdot \frac{2 \gamma}{\text{decay}} = 7.4 \times 10^5 \frac{\gamma}{s}$$

Average Tally Conversion:

$$\frac{\frac{2.36093 \times 10^{-4} \text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{kg} \cdot \frac{7.4 \times 10^5 \gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y}}{\frac{\frac{J}{kg} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}} = 883 \frac{\text{mGy}}{y} \text{ or } 101 \frac{\mu\text{Gy}}{h}$$

The relative error given from the MCNP simulation of 0.0039 represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output.

$$0.0039 \cdot 2 \cdot \frac{2.36093 \times 10^{-4} \text{ MeV}}{g} = \frac{1.84153 \times 10^{-6} \text{ MeV}}{g}$$

Uncertainty Tally Conversion:

$$\frac{\frac{1.84153 \times 10^{-6} \text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{kg} \cdot \frac{7.4 \times 10^5 \gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y}}{\frac{\frac{J}{kg} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}} = 7 \frac{\text{mGy}}{y} \text{ or } 1 \frac{\mu\text{Gy}}{h}$$

The basal layer of the skin +F6 tally and uncertainty from a planar source with disc detectors is converted to basal layer of the skin radiation dose below.

Given:

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{1 \text{ Bq}} \cdot \frac{2 \gamma}{\text{decay}} = 7.4 \times 10^5 \frac{\gamma}{s}$$

Average Tally Conversion:

$$\frac{\frac{2.24622 \times 10^{-4} \text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \text{ y}}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y}}{\frac{\frac{J}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy} \cdot \text{mGy}}} = 840 \frac{\text{mGy}}{y} \text{ or } 95.8 \frac{\mu\text{Gy}}{h}$$

The relative error given from the MCNP simulation of 0.0015 represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output.

$$0.0015 \cdot 2 \cdot \frac{2.24622 \times 10^{-4} \text{ MeV}}{g} = \frac{6.73866 \times 10^{-7} \text{ MeV}}{g}$$

Uncertainty Tally Conversion:

$$\frac{\frac{6.73866 \times 10^{-7} \text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \text{ y}}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y}}{\frac{\frac{J}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy} \cdot \text{mGy}}} = 3 \frac{\text{mGy}}{y} \text{ or } 0.3 \frac{\mu\text{Gy}}{h}$$

The whole body F6 tally and uncertainty from a point source for the MIRD method is converted to whole-body radiation dose below.

Given:

$$A = \text{source activity} = 0.37 \text{ MBq} \cdot \frac{10^6 \text{ Bq}}{1 \text{ MBq}} \cdot \frac{1 \text{ decay}}{s} \cdot \frac{2 \text{ y}}{\text{decay}} = 7.4 \times 10^5 \frac{\text{y}}{s}$$

Tally Conversion:

$$\frac{\frac{5.01201 \times 10^{-5} \text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \text{ y}}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y}}{\frac{\frac{J}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy} \cdot \text{mGy}}} = 188 \frac{\text{mGy}}{y} \text{ or } 21.4 \frac{\mu\text{Gy}}{h}$$

The relative error given from the MCNP simulation of 0.0002 represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output.

$$0.0002 \cdot 2 \cdot \frac{5.01201 \times 10^{-5} \text{ MeV}}{g} = \frac{2.00480 \times 10^{-8} \text{ MeV}}{g}$$

Uncertainty Tally Conversion:

$$\frac{\frac{2.00480 \times 10^{-8} \text{ MeV}}{g}}{\frac{\text{starting particle}}{\text{starting particle}}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{7.4 \times 10^5 \gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 1 \frac{\text{mGy}}{y} \text{ or } 0.1 \frac{\mu\text{Gy}}{h}$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}$$

Calculated Potential Whole-Body Dose from Different Radioactivity Concentrations

The dose coefficient for the whole-body radiation dose to the pangolin from a planar source of $1.84424 \times 10^{-11} \text{ mGy starting particle}^{-1}$ was used to calculate the potential whole-body dose to the pangolin from different radioactivity concentrations.

$$\frac{\frac{1.15121 \times 10^{-4} \text{ MeV}}{g}}{\frac{\text{starting particle}}{\text{starting particle}}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} = \frac{1.84424 \times 10^{-11} \text{ mGy}}{\text{starting particle}}$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}$$

The radioactivity required to meet the dose rate goal of 350 mGy y^{-1} to the whole body from a planar source of ^{60}Co spread over 200 cm^2 is calculated below.

Given:

Dose rate goal is 350 mGy y^{-1}

Dose coefficient is $1.84424 \times 10^{-11} \text{ mGy starting particle}^{-1}$

^{60}Co produces two gamma particles per decay

$$\frac{350 \frac{\text{mGy}}{y} \cdot \frac{y}{365.25 \text{ d}} \cdot \frac{1 \text{ d}}{86400 \text{ s}}}{\frac{1.84424 \times 10^{-11} \text{ mGy}}{\text{starting particle}}} = \frac{6.02476 \times 10^5 \text{ starting particles}}{s} \cdot \frac{\text{decay}}{2 \gamma} \cdot \frac{1 \text{ Bq}}{\frac{1 \text{ decay}}{s}} = 3.01 \times$$

$10^5 \text{ Bq or } 0.301 \text{ MBq}$

$$\frac{1.84424 \times 10^{-11} \text{ mGy}}{\text{starting particle}} \cdot \frac{3.01 \times 10^5 \text{ decays}}{s} \cdot \frac{2 \gamma}{\text{decay}} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 350 \frac{\text{mGy}}{y} \text{ or } 40.0 \frac{\mu\text{Gy}}{h}$$

The relative error given from the MCNP simulation of 0.0006 represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to

dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output.

$$0.0006 \cdot 2 \cdot \frac{1.15121 \times 10^{-4} \text{ MeV}}{g} = \frac{1.38145 \times 10^{-7} \text{ MeV}}{g}$$

Uncertainty Tally Conversion:

$$\frac{\frac{1.38145 \times 10^{-7} \text{ MeV}}{g}}{\text{starting particle}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{3.01 \times 10^5 \text{ decays}}{s} \cdot \frac{2 \gamma}{\text{decay}} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 1 \frac{\text{mGy}}{y} \text{ or } 0.1 \frac{\mu\text{Gy}}{h}$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}{\text{Gy}}$$

The potential whole-body radiation dose from a 0.2 MBq planar source of ^{60}Co spread over 200 cm² is calculated below.

Given:

Dose coefficient is $1.84424 \times 10^{-11} \text{ mGy starting particle}^{-1}$

$$0.2 \text{ MBq} = 2 \times 10^5 \frac{\text{decays}}{s} \cdot \frac{2 \gamma}{\text{decay}} = 4 \times 10^5 \frac{\gamma}{s}$$

$$\frac{1.84424 \times 10^{-11} \text{ mGy}}{\text{starting particle}} \cdot 4 \times 10^5 \frac{\gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 233 \frac{\text{mGy}}{y} \text{ or } 26.6 \frac{\mu\text{Gy}}{h}$$

Uncertainty Tally Conversion:

$$\frac{\frac{1.38145 \times 10^{-7} \text{ MeV}}{g}}{\text{starting particle}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot 4 \times 10^5 \frac{\gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 1 \frac{\text{mGy}}{y} \text{ or } 0.1 \frac{\mu\text{Gy}}{h}$$

$$\frac{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}}{\text{Gy}}$$

The potential whole-body radiation dose from a 0.154 MBq planar source of ^{60}Co spread over 200 cm² is calculated below. The radioactivity concentration of 0.154 MBq is the concentration at which the basal layer of the skin radiation dose rates will be within radiation dose rate goals.

Given:

Dose coefficient is $1.84424 \times 10^{-11} \text{ mGy starting particle}^{-1}$

$$0.1544 \text{ MBq} = \frac{1.544 \times 10^5 \text{ decays}}{s} \cdot \frac{2 \gamma}{\text{decay}} = 3.088 \times 10^5 \frac{\gamma}{s}$$

$$\frac{1.84424 \times 10^{-11} \text{ mGy}}{\text{starting particle}} \cdot 3.088 \times 10^5 \frac{\gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 180 \frac{\text{mGy}}{y} \text{ or } 20.5 \frac{\mu\text{Gy}}{h}$$

Uncertainty Tally Conversion:

$$\frac{\frac{1.38145 \times 10^{-7} \text{ MeV}}{g}}{\text{starting particle}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{3.088 \times 10^5 \frac{\gamma}{s}}{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 1 \frac{\text{mGy}}{y} \text{ or } 0.1 \frac{\mu\text{Gy}}{h}$$

The potential whole-body radiation dose from a 0.1 MBq planar source of ^{60}Co spread over 200 cm² is calculated below.

Given:

Dose coefficient is $1.84424 \times 10^{-11} \text{ mGy starting particle}^{-1}$

$$0.1 \text{ MBq} = \frac{1 \times 10^5 \text{ decays}}{s} \cdot \frac{2 \gamma}{\text{decay}} = 2 \times 10^5 \frac{\gamma}{s}$$

$$\frac{1.84424 \times 10^{-11} \text{ mGy}}{\text{starting particle}} \cdot 2 \times 10^5 \frac{\gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 116 \frac{\text{mGy}}{y} \text{ or } 13.2 \frac{\mu\text{Gy}}{h}$$

Uncertainty Tally Conversion:

$$\frac{\frac{1.38145 \times 10^{-7} \text{ MeV}}{g}}{\text{starting particle}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{2 \times 10^5 \frac{\gamma}{s}}{\frac{\text{J}}{\text{kg}} \cdot \frac{10^{-3} \text{ Gy}}{\text{mGy}}} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 1 \frac{\text{mGy}}{y} \text{ or } 0.1 \frac{\mu\text{Gy}}{h}$$

The potential whole-body radiation dose from a 0.037 MBq planar source of ^{60}Co spread over 200 cm² is calculated below.

Given:

Dose coefficient is $1.844 \times 10^{-14} \text{ mGy starting particle}^{-1}$

$$0.037 \text{ MBq} = \frac{3.7 \times 10^4 \text{ decays}}{s} \cdot \frac{2 \gamma}{\text{decay}} = 7.4 \times 10^4 \frac{\gamma}{s}$$

$$\frac{1.84424 \times 10^{-11} \text{ mGy}}{\text{starting particle}} \cdot \frac{7.4 \times 10^4 \gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 43.1 \frac{\text{mGy}}{y} \text{ or } 4.91 \frac{\mu\text{Gy}}{h}$$

Uncertainty Tally Conversion:

$$\frac{\frac{1.38145 \times 10^{-7} \text{ MeV}}{\text{g}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot 7.4 \times 10^4 \frac{\gamma}{\text{s}} \cdot \frac{86400 \text{ s}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}}}{\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} \cdot \frac{\text{mGy}}{\text{mGy}}} = 0.1 \frac{\text{mGy}}{\text{y}} \text{ or } 0.01 \frac{\mu\text{Gy}}{\text{h}}$$

The potential whole-body radiation dose from a 0.01 MBq planar source of ^{60}Co spread over 200 cm² is calculated below.

Given:

Dose coefficient is $1.84424 \times 10^{-11} \text{ mGy starting particle}^{-1}$

$$0.01 \text{ MBq} = 1 \times 10^4 \frac{\text{decays}}{\text{s}} \cdot \frac{2 \gamma}{\text{decay}} = 2 \times 10^4 \frac{\gamma}{\text{s}}$$

$$\frac{1.84424 \times 10^{-11} \text{ mGy}}{\text{starting particle}} \cdot 2 \times 10^4 \frac{\gamma}{\text{s}} \cdot \frac{86400 \text{ s}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}} = 11.6 \frac{\text{mGy}}{\text{y}} \text{ or } 1.33 \frac{\mu\text{Gy}}{\text{h}}$$

Uncertainty Tally Conversion:

$$\frac{\frac{1.38145 \times 10^{-7} \text{ MeV}}{\text{g}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot 2 \times 10^4 \frac{\gamma}{\text{s}} \cdot \frac{86400 \text{ s}}{\text{d}} \cdot \frac{365.25 \text{ d}}{\text{y}}}{\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} \cdot \frac{\text{mGy}}{\text{mGy}}} = 0.1 \frac{\text{mGy}}{\text{y}} \text{ or } 0.01 \frac{\mu\text{Gy}}{\text{h}}$$

Calculated Basal Layer of the Skin Dose from Different Radioactivity Concentrations

The dose coefficient for the basal layer of the skin radiation dose to the pangolin from a planar source of $3.59844 \times 10^{-11} \text{ mGy starting particle}^{-1}$ was used to calculate the potential basal layer of the skin dose to the pangolin from different radioactivity concentrations.

$$\frac{\frac{2.24622 \times 10^{-4} \text{ MeV}}{\text{g}} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{\text{kg}}}{\frac{\frac{\text{J}}{\text{kg}} \cdot 10^{-3} \text{ Gy}}{\text{Gy}} \cdot \frac{\text{mGy}}{\text{mGy}}} = \frac{3.59844 \times 10^{-11} \text{ mGy}}{\text{starting particle}}$$

The radioactivity required to meet the dose rate goal of 350 mGy y⁻¹ to the basal layer of the skin from a planar source of ^{60}Co spread over 200 cm² is calculated below.

Given:

Dose rate goal is 350 mGy y⁻¹

Dose coefficient is $3.59844 \times 10^{-11} \text{ mGy starting particle}^{-1}$

⁶⁰Co produces two gamma particles per decay

$$\frac{350 \frac{mGy}{y} \cdot \frac{y}{365.25 d} \cdot \frac{1 d}{86400 s}}{\frac{3.59844 \times 10^{-11} mGy}{starting particle}} = \frac{3.08776 \times 10^5 starting particles}{s} \cdot \frac{decay}{2 \gamma} \cdot \frac{1 Bq}{\frac{1 decay}{s}} = 1.54 \times$$

$10^5 Bq$ or $0.154 MBq$

$$\frac{3.59844 \times 10^{-11} mGy}{starting particle} \cdot \frac{1.544 \times 10^5 decays}{s} \cdot \frac{2 \gamma}{decay} \cdot \frac{86400 s}{d} \cdot \frac{365.25 d}{y} = 350 \frac{mGy}{y} \text{ or } 40.0 \frac{\mu Gy}{h}$$

The relative error given from the MCNP simulation of 0.0015 represents one standard deviation from the mean. To find the absolute error in two standard deviations for conversion to dose, the relative error is multiplied by two and then multiplied by the tally. The absolute error in two standard deviations is then converted to dose and provides the uncertainty in the tally output.

$$0.0015 \cdot 2 \cdot \frac{2.24622 \times 10^{-4} MeV}{g} = \frac{6.73866 \times 10^{-7} MeV}{g}$$

Uncertainty Tally Conversion:

$$\frac{\frac{6.73866 \times 10^{-7} MeV}{g}}{\frac{starting particle}{}} \cdot \frac{1.602 \times 10^{-13} J}{MeV} \cdot \frac{1000 g}{kg} \cdot \frac{1.544 \times 10^5 decays}{s} \cdot \frac{2 \gamma}{decay} \cdot \frac{86400 s}{d} \cdot \frac{365.25 d}{y} = 1 \frac{mGy}{y} \text{ or } 0.1 \frac{\mu Gy}{h}$$

$$\frac{\frac{J}{kg} \cdot \frac{10^{-3} Gy}{mGy}}{Gy}$$

The potential basal layer of skin radiation dose from a 0.301 MBq planar source of ⁶⁰Co spread over 200 cm² is calculated below. The radioactivity concentration of 0.301 MBq is the concentration at which the whole-body radiation dose rates will be within radiation dose rate goals.

Given:

Dose coefficient is $3.59844 \times 10^{-11} mGy \text{ starting particle}^{-1}$

$$0.301 MBq = \frac{3.01 \times 10^5 decays}{s} \cdot \frac{2 \gamma}{decay} = 6.02 \times 10^5 \frac{\gamma}{s}$$

$$\frac{3.59844 \times 10^{-11} mGy}{starting particle} \cdot 6.02 \times 10^5 \frac{\gamma}{s} \cdot \frac{86400 s}{d} \cdot \frac{365.25 d}{y} = 684 \frac{mGy}{y} \text{ or } 78.0 \frac{\mu Gy}{h}$$

Uncertainty Tally Conversion:

$$\frac{\frac{6.73866 \times 10^{-7} \text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{kg} \cdot \frac{6.02 \times 10^5 \gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y}}{\frac{\frac{J}{kg} \cdot 10^{-3} \text{ Gy}}{\text{Gy} \cdot \text{mGy}}} = 2 \frac{\text{mGy}}{y} \text{ or } 0.2 \frac{\mu\text{Gy}}{h}$$

The potential basal layer of the skin radiation dose from a 0.2 MBq planar source of ^{60}Co spread over 200 cm² is calculated below.

Given:

Dose coefficient is $3.59844 \times 10^{-11} \text{ mGy starting particle}^{-1}$

$$0.2 \text{ MBq} = \frac{2 \times 10^5 \text{ decays}}{s} \cdot \frac{2 \gamma}{\text{decay}} = 4 \times 10^5 \frac{\gamma}{s}$$

$$\frac{3.59844 \times 10^{-11} \text{ mGy}}{\text{starting particle}} \cdot 4 \times 10^5 \frac{\gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 454 \frac{\text{mGy}}{y} \text{ or } 51.8 \frac{\mu\text{Gy}}{h}$$

Uncertainty Tally Conversion:

$$\frac{\frac{6.73866 \times 10^{-7} \text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{kg} \cdot 4 \times 10^5 \frac{\gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y}}{\frac{\frac{J}{kg} \cdot 10^{-3} \text{ Gy}}{\text{Gy} \cdot \text{mGy}}} = 2 \frac{\text{mGy}}{y} \text{ or } 0.3 \frac{\mu\text{Gy}}{h}$$

The potential basal layer of the skin radiation dose from a 0.1 MBq planar source of ^{60}Co spread over 200 cm² is calculated below.

Given:

Dose coefficient is $3.59844 \times 10^{-11} \text{ mGy starting particle}^{-1}$

$$0.1 \text{ MBq} = \frac{1 \times 10^5 \text{ decays}}{s} \cdot \frac{2 \gamma}{\text{decay}} = 2 \times 10^5 \frac{\gamma}{s}$$

$$\frac{3.59844 \times 10^{-11} \text{ mGy}}{\text{starting particle}} \cdot 2 \times 10^5 \frac{\gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y} = 227 \frac{\text{mGy}}{y} \text{ or } 25.9 \frac{\mu\text{Gy}}{h}$$

Uncertainty Tally Conversion:

$$\frac{\frac{6.73866 \times 10^{-7} \text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13} \text{ J}}{\text{MeV}} \cdot \frac{1000 \text{ g}}{kg} \cdot 2 \times 10^5 \frac{\gamma}{s} \cdot \frac{86400 \text{ s}}{d} \cdot \frac{365.25 \text{ d}}{y}}{\frac{\frac{J}{kg} \cdot 10^{-3} \text{ Gy}}{\text{Gy} \cdot \text{mGy}}} = 1 \frac{\text{mGy}}{y} \text{ or } 0.1 \frac{\mu\text{Gy}}{h}$$

The potential basal layer of the skin radiation dose from a 0.037 MBq planar source of ^{60}Co spread over 200 cm^2 is calculated below.

Given:

Dose coefficient is $3.59844 \times 10^{-11}\text{ mGy starting particle}^{-1}$

$$0.037\text{ MBq} = \frac{3.7 \times 10^4\text{ decays}}{s} \cdot \frac{2\gamma}{\text{decay}} = 7.4 \times 10^4 \frac{\gamma}{s}$$

$$\frac{3.59844 \times 10^{-11}\text{ mGy}}{\text{starting particle}} \cdot 7.4 \times 10^4 \frac{\gamma}{s} \cdot \frac{86400\text{ s}}{d} \cdot \frac{365.25\text{ d}}{y} = 84.0 \frac{\text{mGy}}{y} \text{ or } 9.59 \frac{\mu\text{Gy}}{h}$$

Uncertainty Tally Conversion:

$$\frac{\frac{6.73866 \times 10^{-7}\text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13}\text{ J}}{\text{MeV}} \cdot \frac{1000\text{ g}}{kg} \cdot 7.4 \times 10^4 \frac{\gamma}{s} \cdot \frac{86400\text{ s}}{d} \cdot \frac{365.25\text{ d}}{y}}{\frac{\frac{J}{kg} \cdot 10^{-3}\text{ Gy}}{\text{Gy}} \cdot \frac{10^{-3}\text{ mGy}}{\text{mGy}}} = 0.3 \frac{\text{mGy}}{y} \text{ or } 0.03 \frac{\mu\text{Gy}}{h}$$

The potential basal layer of the skin radiation dose from a 0.01 MBq planar source of ^{60}Co spread over 200 cm^2 is calculated below.

Given:

Dose coefficient is $3.59844 \times 10^{-11}\text{ mGy starting particle}^{-1}$

$$0.01\text{ MBq} = \frac{1 \times 10^4\text{ decays}}{s} \cdot \frac{2\gamma}{\text{decay}} = 2 \times 10^4 \frac{\gamma}{s}$$

$$\frac{3.59844 \times 10^{-11}\text{ mGy}}{\text{starting particle}} \cdot 2 \times 10^4 \frac{\gamma}{s} \cdot \frac{86400\text{ s}}{d} \cdot \frac{365.25\text{ d}}{y} = 22.7 \frac{\text{mGy}}{y} \text{ or } 2.60 \frac{\mu\text{Gy}}{h}$$

Uncertainty Tally Conversion:

$$\frac{\frac{6.73866 \times 10^{-7}\text{ MeV}}{g} \cdot \frac{1.602 \times 10^{-13}\text{ J}}{\text{MeV}} \cdot \frac{1000\text{ g}}{kg} \cdot 2 \times 10^4 \frac{\gamma}{s} \cdot \frac{86400\text{ s}}{d} \cdot \frac{365.25\text{ d}}{y}}{\frac{\frac{J}{kg} \cdot 10^{-3}\text{ Gy}}{\text{Gy}} \cdot \frac{10^{-3}\text{ mGy}}{\text{mGy}}} = 0.1 \frac{\text{mGy}}{y} \text{ or } 0.01 \frac{\mu\text{Gy}}{h}$$