AN ABSTRACT OF THE THESIS OF

Michelle LeAnne Comolli for the degree of Master of Science in Radiation Health Physics presented on October 4, 2013.
Title: Comparison of Dosimetric Modeling of the International Commission on Radiological Protection Trout Reference Animal.

Abstract approved:

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Kathryn A. Higley

Radiation protection has historically been from a human protection approach, therefore many studies have neglected the potential dose contribution from the gastrointestinal tract (GIT) in animal studies. The International Commission on Radiological Protection (ICRP) utilized simplified geometric shapes with Dose Conversion Factors (DCF) based on homogenized models for the trout reference animal, one of twelve reference animals and plants (RAPs). Utilizing data collected from Pacific Proving Ground site studies from the 1960's-1970's, dose rates estimations were done, with and without the contribution of the GIT, using activity concentrations of ^{239,240}Pu, ^{90}Sr, and ^{137}Cs in tissues of fish from varying trophic levels. The comparison of voxelized models with ICRP 108 DCFs and homogenized whole body dose method were also compared. Dose rate estimations excluding the GIT resulted in an underestimate of dose rate by more than a magnitude in some cases. Individual organ dose rates calculated using the voxel models to whole body dose rates calculated using the homogeneous model dose rates differed by a magnitude of -1 to 4.

Comparison of Dosimetric Modeling of the International Commission on Radiological Protection Trout Reference Animal.

by
Michelle LeAnne Comolli

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Michelle LeAnne Comolli, Author

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Chapter 1 - Introduction

Environmental radiation protection has historically focused humans. The assumption has been that while individual species may not always be protected, standards set for environmental control adequate for human protection "will ensure that other species are not put at risk" (ICRP 1991). This ideology is further illustrated in the methods and objectives of many of the non-human biota studies, particularly the practice of examining biota that are consumed by humans and the discarding of non-edible tissues, such as the gastrointestinal tract (GIT) of these organisms.

The field of radioecology has started to shift towards the protection of non-human biota without regard to their direct dose impact on humans. Evidence has begun to surface that emphasize the use of humans as the standard for radiological protection for all biota is inappropriate (Jones et al. 2003). There are several environmental releases of radionuclides that can be used to challenge previous conceptions regarding their ecological effects.

Between 1946 and 1958, the United States conducted nuclear weapons testing in the Marshall Islands, culminating in 66 separate releases. On March 1, 1954, the Castle Bravo hydrogen bomb was tested, with a yield of approximately 15 megatons which was approximately 2.5 times greater than initially expected (Cronkite et al. 1997). In addition to the large yield, the wind shifted causing a plume, covering several of the islands with fallout as well as dispersal via ocean currents in various directions. Near immediate effects were seen in fisherman that were exposed to the fallout (Cronkite et al. 1997).

The Marshal Islands have been the location of several radiological studies due to the weapons testing performed in the area.

In 1957, the Mayak Nuclear Facility located in the Chelyabinsk Region of Russia experienced an explosion of a storage tank, releasing high levels of ^{90}Sr, ^{137}Cs, and ^{239}Pu in to the environment. Aside from this single incident, which is considered to be one of the worst nuclear accidents in history, there were regular environmental releases via aerosol, underground storage tank leakage, and waterway contamination of Techa River (Ilyinskikh et al. 1999). Additionally, Mayak began dumping high-level waste into Lake Karachay. A drought in 1967 caused the lake water levels to drop so low that radioactive sediment was transported up to 70 km away. In 2010, concentrations in Lake Karachay measured 6.5×10^6 Bq/L of ^{90}Sr, 1.6×10^7 Bq/L ^{137}Cs, and 3.0×10^3 Bq/L total alpha activity (Atamanyuk 2012).

From 1943 to 1989, the Hanford Site, located in southern Washington along the Columbia River, produced Pu for the Department of Energy's weapons program. This production resulted in atmospheric releases (Gephart 2010). There are an estimated 177 underground storage tanks, 7 of which are leaking with varying reports on the ability of the radioactive material to reach the Columbia River located approximately 5 miles from the site (Washington Department of Ecology 2013). Contaminated rabbit droppings have been found on site. While only one of the 18 rabbits surveyed have been found to be contaminated, the potential exists for contamination to move into the food chain via natural wildlife (U.S. Department of Energy 2009).

The Windscale nuclear reactor facility and plutonium-production plant, located in northwestern England, experienced a significant atmospheric radiological release after a fire erupted in one of the two gas-cooled nuclear reactor cores in October, 1957. Uranium cartridges ruptured due to overheating and began to oxidize. The resulting fire took 16 hours to extinguish, releasing an estimated 6×10^{14} -7.5×10^{14} Bq ^{131}I, 2×10^{13}-4.5×10^{13} Bq ^{137}Cs, as well as varying amounts of ^{89,90}Sr and ^{210}210. Due to this event, dumping of milk within a 500 km^2 area was mandated for several weeks (Higley 2011).

In January, 1968, a B-52 carrying four nuclear weapons crashed approximately 7.5 miles from Thule AB, Greenland. All four of the nuclear weapons detonated, resulting in extensive Pu contamination. Random surveys found alpha radiation levels to be in excess of 2,000,000 CPM on the debris scattered throughout the crash site. The contaminated area was later determined to be 3 miles long and 1 mile wide. Weather conditions and poor visibility hindered immediate detection and clean-up efforts (Defense Atomic Support Agency Nuclear Emergency Team 1968).

The Unit 2 reactor of Three Mile Island, located near Middletown, Pennsylvania, experienced a partial meltdown on March 28, 1979, after a feedwater pump failed to supply the steam generators with water for reactor core heat removal. This event triggered an automatic shutdown of the reactor and turbine-generator. A pressure relief valve was opened to relieve increasing pressure within the primary system, which subsequently remained stuck in the open position, despite pressure returning to normal levels. Instrumentation indicated that the valve was closed leading to the release of

cooling water through the open valve. Continuing to receive inadequate and contradictory information from the instrumentation, staff had no indication that the core was becoming exposed due to loss-of-coolant. Compounding the situation with further incorrect actions, the core began to overheat resulting in the zirconium cladding to rupture and the fuel pellets began to melt. Once aware of the problem, coolant was restored to the core to regain control of the reactor. While this was one of the most serious accident scenarios for a nuclear power plant, containment remained intact. Although there was a release of radioactive gases into the atmosphere, it was ultimately determined that exposure to the population did not go above background levels (NRC 2013).

The Chernobyl nuclear plant located near Kiev experienced the most deadly nuclear power accident in history on April 26, 1986. To conduct a test to determine the spin-down time of the turbines following loss of the main electrical power supply, staff disabled automatic shutdown mechanisms. Control rods were removed from the reactor to begin the test. The condition of the reactor became extremely unstable by the time the operator began the shut down process. An excessive amount of control rods had been removed for the test and the negative void coefficient design of the control rods resulted in a dramatic surge of power to the reactor once they were inserted. The reaction resulted in a rapid pressure build-up causing fuel channels to rupture, preventing the half-inserted control rods from continuing their insertion into the core. The emergency cooling circuit ruptured, leading to a steam explosion immediately followed by a second explosion.

Fission fragments and hot graphite were ejected into the air. It was estimated that approximately 5% of the 192 tons of fuel was released as well as all of the xenon gas, and roughly half of the ^{131}I and ^{137}Cs (an estimate 5200 PBq of activity). Two workers died in the explosion, followed by the death of an additional 28 people, including 6 firemen, in the weeks following of acute radiation poisoning. Radiation doses were estimated to be as high as 20,000 mSv on day one of the accident (World Nuclear Association 2013).

The most recent accident occurred March 11, 2011 after a magnitude 9.0 earthquake occurred off the coast of Japan was followed by two of the largest Tsunamis in Japan's history. TEPCO's Fukushima Daiichi nuclear power plant, located on the eastern coast of Japan, experienced an automatic shutdown following the earthquake, as designed. Approximately 50 minutes later, Japan was hit by a tsunami with an estimated height of 14 meters, exceeding the 10 meter sea wall. The sudden insurgence of water damaged electrical systems and flooded the back-up generators. As designed, battery powered automatic systems kept water circulating in the reactors for the next 72 hours. Due to the nationwide devastation caused by the earthquake and tsunami, power was not restored to these reactors until late March, resulting in a drop in water levels inside the core. Interaction between the steam and the zirconium fuel cladding created significant amounts of hydrogen gas which was released in an attempt to reduce core pressure. This resulted in three hydrogen explosions between March 12 and March 15. Additionally, leaks from the cooling pools, resulted in a release of ^{131}I and ^{137}Cs. An evacuation was eventually ordered for the area within a 20 km radius of the plant (“Report of the

Japanese Government to the IAEA Ministerial Conference on Nuclear Safety", 2011). The French Institute for Radiological Protection and Nuclear Safety reported that nearly a year following the accident, an estimated total release of 6,550 PBq of ^{133}Xe, 408 PBq of ^{131}I, 145 PBq of ^{132}Te, and 58 PBq of ^{137}Cs, with the majority of release occurring in the days immediately following the accident (IRSN, 2012).

There have been several radiological releases into the environment from these accidents. Until recently, radiation protection has focused solely on the effects to humans. A considerable amount of available data on non-human biota has been extrapolated from measured effects of a different population of a higher organizational level and reducing the studied populations to a simplified model, compounding uncertainties in measurement (Brèchignac 2003). This research investigates historical methods of dose estimation in animals with the goal of determining an appropriate approach to internal dosimetry in non-human biota.

Chapter 2 - Literature Review

2.01 Evolution of Dose Calculation Methods

The International Commission on Radiological Protection (ICRP) was formed in 1928 by the International Congress of Radiology. The ICRP, an independent organization taking the role as the primary authority on radiological protection, initially focused solely on the radiological protection of humans. In 1977, the Commission's stance on radiological protection of non-human biota was that "...the level of safety required for the protection of all human individuals is thought likely to be adequate to protect other species", stating that the Commission "...believes that if man is adequately protected, then other living things are also likely to be sufficiently protected" (ICRP 1977).

The ICRP Publication 60 expanded their recommendations, stating the belief that "...the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species" (1991). At that time the Commission continued with the belief that the transfer of radionuclides through the environment, as it pertains to the radiological protection of man was of sufficient concern.

In 2007, the Commission acknowledged the importance of protecting the environment in the ICRP Publication 103. Recommendations were made to develop a

comprehensive and systematic approach to develop a numerical framework containing key points of reference. The Commission announced their efforts to develop a set of Reference Animals and Plants (RAPs), including typical organisms representative of major environments, to aid in the understanding of the relationships between exposure and dose, dose and effect, and the possible consequences of such effects.

2.01.01 Reference Animals and Plants (RAPs)

The ICRP Publication 108 outlines the Commission's recommendations for environmental protection and the general goals of preventing and reducing harmful radiological effects in the environment to a level that would have "negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities, and ecosystems." The Commission introduced the concept of reference animals and plants (RAPs) as well as defining a small set, including their relevant databases, similar to Reference Man. The report addresses pathways of exposure, available dosimetric data at various life cycle stages, and tabulates derived dose conversion factors for 75 radionuclides for the calculation of dose from a source that is internal or external to the organism. The report was designed to provide a basis for the fundamental understanding of the relationships between exposure and dose, and related categories of effect, which can be used to develop applications with specific approached to assess and manage risks to non-human species on a situational basis (ICRP 2008).

The system used to define RAPs for the assessment of radiological effects in non-human biota is similar to the approach developed by Pentreath. This was accomplished using limited types of animals and plants to create reference points relating exposure to dose, and dose to varying categories of effect, as they pertain to the normal biology of the selected types of plants in animals. The framework for the selection of the animals and plants to be used as reference was tasked to the ICRP Committee 5 (ICRP 2008).

The criteria chosen to select the reference organisms were heavily weighted by the amount of data available and the potential use of the reference organism, as well as the practicality of experimentally obtaining data about the radiological effects on the organism. The latter limited the use of certain animals, such as aquatic mammals, despite the fact that they are the subject of many environmental conservation projects (Pentreath 2012). Committee 5 asserted that a mindful regard to the variety of operational and regulatory requirements and construction of a framework flexible enough to accommodate additional knowledge and future needs was necessary. The framework must also encompass the general components of various ecosystems and chose reference organisms which represented important components of their ecosystem. Additionally, it was necessary to address the different exposure situations that may be experienced at different points in the lifecycle. The selection, therefore, needed to include a range of life histories to represent varying methods and stages of reproduction, life span, and cellular makeup (ICRP 2008).

Eight criteria were set for the selection of a small, yet practical, set of RAPs. (1) A reasonable amount of radiobiological data, including probable radiological effects, on the organism was already available. (2) The organism was amenable to future research for the purposes of obtaining missing or incomplete data. (3) The organism was considered to be representative of the typical fauna or flora the ecosystem of interest as well as having wide geographic variation. (4) The organism was likely to be exposed to radiation from the range of radionuclides from a given situation due to bioaccumulation, nature of their surroundings, as well as their natural characteristics such as: overall life span, life cycle, and general biology. (5) The organism's life cycle was likely to be relevant for the evaluation of dose rate, total dose, the formulation of varying dose effect responses. (6) The organism's exposure to radiation was capable of being modeled using geometries that are relatively simple. (7) The chance of identifying any effects at the individual organism level and the ability to relate the effects to exposure to radiation is reasonable, with the exception of bacteria and unicellular organisms due to high radiological resistance. (8) The organism had some form of public or political distinction, such that decision makers and the general public would likely be able to recognize the organism in common language (Pentreath 2012).

The set of RAPs include 12 categories, each with a single corresponding reference animal or plan, is outlined in ICRP Publication 108.

(1) The reference deer represents the category "larger terrestrial mammal". Deer, belonging to the family Cervidae, contain over 45 species throughout North

and South America, Europe, and Asia and are the primary large mammal in vast areas of land. Their average life span is 15 years and a reproduction lifespan averaging 10 years with the production of one offspring per year.

(2) The reference rat, a rodent in the family Muridae, represents the category "small terrestrial mammal". Second only to humans, rodents have been the source of a significant amount of radiation effect. Rats have a worldwide presence and characteristically live in colonies. They have an average life span of 2 years and begin breeding at the age of 100 days with a gestation cycle of 24 days. A female will have approximately seven litters in her life span with an average litter size of seven offspring.

(3) The reference duck, of the family Anatidae, is the selection for the "aquatic bird" category. They are considered to be typical of wetland area animals and their potential radiological exposure may increase from external sources such as radionuclides in soil, estuarine, or seawater, as well as internally from ingesting small aquatic animals and aquatic and terrestrial plant matter.

(4) The category "amphibian" is represented by the reference frog, of the family Ranidae and is typical of wetland areas. Their life cycle includes the aquatic egg stage, tadpole stage, followed by the terrestrial adult frog stage. Their combination of freshwater and terrestrial environments presents extensive potential for exposure situations. Frogs have an average life span of 10 years, reaching sexual maturity at age 3 years. Reproduction occurs in water (approximately 3000 eggs laid

each spring per female), with the tadpole hatching from fertilized eggs after 10 days, where it lives for the next 100 days until it metamorphosis into the frog stage and then spending the remaining life span, with the exception of breeding, out of water, including a 16 week winter hibernation period in the mud.

(5) "Freshwater fish" is represented by the reference trout, of the family Salmonidae. Salmonids contain marine and freshwater fish with some species being anadromous, such as salmon. To avoid the complications associated with migratory pattern (moving between marine and fresh water environments) the trout was chosen as the reference animal of this category as opposed to salmon. Trout and salmon are considered to be biological indicators of water quality, and as such, are a common subject for environmental legislation as well as laboratory studies. Because of this, there is substantial data on their metabolism and accumulation of environmental contaminants, including radionuclides, as well as radiological effects. The reference trout "have the characteristics of a trout that lives its life in soft water." They have a lifespan of 6 years and reach sexual maturity at age 4 years. They reproduce annually (twice in their lifetime), releasing 1500 eggs each fall.

(6) The "marine fish" category is represented by the reference flatfish, belonging to the Pleuronectidae family. Typical examples of pleuronectids are flounder, plaice, and halibut. The can be found in marine and brackish water and have also been the subject of many laboratory experiments, resulting in considerable data regarding radiological effects and accumulation of radionuclides. The reference

flatfish has typical characteristics of fish in that family. They have a lifespan of 10 years, reaching sexual maturity at age 4 years. The females release 300,000 eggs, on average, each year. The eggs hatch on day 15 and the fish is in its adult form at age 50 days.

(7) The reference bee represents the "terrestrial insect" category. There are considered to be "more species of insects on this planet than of all the other forms of life put together." As the most studied and easily reared insect, there is a lot known about the characteristic lifecycle of the bee. The reference bee is in the family Apidea. Eggs hatch on day 4 and the resulting larvae becomes a pupa 2 days later, reaching adulthood on day 20. A worker bee has a life span of 100 days and some will lay unfertilized eggs. Some of the unfertilized eggs will hatch as male bees. Young queens and male bees leave the nest in late summer to mate. The males then die and the queens hibernate. The following autumn, the queen sets up her colony, where she lives for 3 years. She will lay 600,000 eggs in her lifetime (200,000 each year). The queen can decide to lay fertilized eggs, which hatch as female (worker or queen bees), or unfertilized eggs, which will hatch as male worker bees.

(8) The reference crab represent the "marine crustacean" category and is in the Cancridae family. Crabs are mainly brackish or fresh water animals with some that are essentially terrestrial. Since there are many species that are commercially farmed, there have been many studies conducted on them, providing radiobiological and radiochemical analysis data. The reference crab has a life span of 15 years and

is considered to be reasonably large, residing in temperate water. Males mature at age 5 years and females mature at age 10 years. Females produce an average of 2 million fertilized eggs in late fall. After the eggs have been housed in a clutch beneath her body for 6 months, the larvae are released where they spend the next 60 days in a water column before settling to the bottom to continue maturing. Crabs shed their hard exoskeleton as they grow. It is assumed that once the reference crab reaches adulthood, they will moult once per year.

(9) The "terrestrial annelid" is represented by the reference earthworm of the Lumbricidae family. They are common throughout the world with the exception of deserts, areas of constant snow and ice, and areas that are completely void of soil and vegetation, and are naturally occurring in Europe, Asia (western), and North America. They have been the subject of extensive studies regarding inorganic and organic toxins such as insecticides, fungicides, herbicides, and heavy metals. The reference earthworm has a life span of 4 years, hatch after 4 weeks, and produce five cocoons per week after reaching sexual maturity at age 10 weeks.

(10) The reference pine tree of the family Pinacea represents the "large terrestrial plant" category. They are naturally occurring throughout the Northern hemisphere and from just south of the equator to the Arctic Circle. They have been introduced to many areas within the Southern hemisphere and survive in a wide variety of environments. They are easily cultivated and have been well studied with regards to their physiology and general biology. Additionally, there is a significant

amount of data regarding their exposure to radiation and its effects. The reference tree grows in a temperate region. It has a life span of 200 years and reach sexual maturity at age 10 years. They produce ovoid cones that reach maturity in 18 months. The growth rate of young trees is 1 meter per year.

(11) Reference wild grass of the family Poaceae (formerly known as the Gramineae) represents the "small terrestrial plant" category. Grass, of some form, is the dominating plant in much of the terrestrial environment. Grass is present worldwide and occurs in a variety of forms. Due to their wide use as a food crop, they are well studied. There is considerable data regarding their accumulation of various chemicals. The reference wild grass is characteristic of "barley-type" wild grass. It is a perennial with a flowering spikelet on the stalk above the ground.

(12) The "seaweed" category is represented by the reference brown seaweed. It occurs in coastal water worldwide and is the primary macroscopic plant in the marine environment. Due to extensive use in examining the adsorption or absorption of chemicals in marine and brackish water, particularly metal, there have been considerable studies done on their chemical composition. They have also been used extensively as radionuclide dispersion indicators in aquatic environments. There is continuing debate as to the classification of seaweeds. The reference brown seaweed is assumed to possess the characteristics of a Cyclosporean brown intertidal seaweed. It therefore spends 75% of the time covered with sea water and then dries

out and spends the remaining 25% of the time covered with a coating of silt. It is a diploid sporophyte and has a life span of 5 years, reproducing annually.

2.01.02 Homogenized Modeling

The method presented in ICRP 108 assumes a homogeneous model for both reference fish and utilize the concept of a uniform isotropic organism within an infinite homogeneous medium, whose body density is equal to that of the medium. The activity of the nuclide of interest is assumed to be distributed uniformly throughout its body. DCFs, defined as absorbed dose rate per specific activity, are expressed in units of $\left[\frac{\mu Gy\ d^{-1}}{Bq\ kg^{-1}}\right]$ (ICRP 2008).

ICRP 108 uses simplified geometrical models for the purposes of determining absorbed fractions in situations when the activity (gamma radiation) is concentrated in an organ. Due to the longer range of gammas, a significant amount of the particle's energy may be deposited away from the original source. Larger organisms, such as the reference deer, is modeled as a large ellipsoid, with a smaller ellipsoid as the liver, and a yet smaller ellipsoid as the testes, each with their own specific densities. With smaller organisms, such as the reference fish which is an even more simplified model, it is assumed to have organs which are homogeneous with the remainder of the body, and the entire fish body is modeled as an ellipsoidal geometry to reflect the boundary between body and medium (ICRP 2008). An example of the model used for absorbed fraction simulations in reference fish is illustrated in Figure 1.

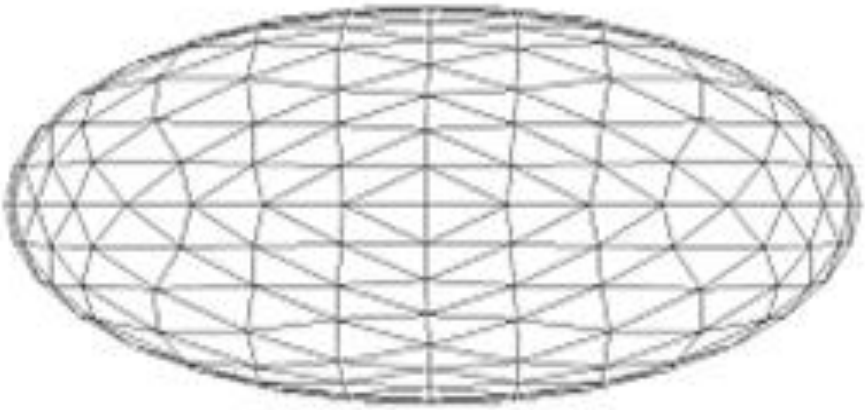

Figure 1: Simplified Fish Model

2.01.03 Pacific Proving Grounds Research Used in this Study

Radiological Resurvey of Animals, Soils and Groundwater at Bikini Atoll, 1969

In a paper published in 1969, Held reports on a joint sampling program conducted with the Atomic Energy Commission's Health and Safety Laboratory, Division of Biology and Medicine, U.S. Naval Radiological Defense Laboratory, Trust Territory, and the University of Washington. The objective was to determine the habitability of Bikini for the reoccupation of the residents by evaluating collected data for potential radiological hazards to people. Samples included animal food products, as wells as soil, crater sediments, and ground water for estimating future radiological distribution in biota.

The samples were dried, ground, and compressed into uniformly distributed mass and density segments. All samples underwent gamma spectrometry using NaI detectors

(thallium-drifted) with a 256-channel analyzer for a minimum count time of 100 minutes, with some samples counted for 1000 minutes with either a 3 x 3-inch detector or two 5 x 5-inch detector systems as a summing spectrometer. Resolution was determined by Schonfeld's method of least squares and all values were corrected for decay to the date of sample collection. Strontium-90 was measured using the equilibrium concentration with its daughter, ^{90}Y, using solvent extraction and precipitation. Alpha spectrometry was used to analyze Pu which was extracted by a combination of solvent extraction and anion exchange and using ^{236}Pu to determine chemical yield.

The results of the study concentrated on food sources of the potential island residents, with the exception of plant life. While levels were detectable, it was determined that animals in the daily diet were safe to consume with the only restriction being coconut crabs, which contained high concentrations of ^{90}Sr. Additional recommendations included the removal of debris and covering the inhabited areas with coral gravel to act as shielding from concentrations in the soil. The overall conclusion of the study was that islands were safe to reoccupy (Held 1969).

Radiological Survey of Plants, Animals and Soil at Christmas Islands and Seven Atolls in the Marshall Islands

In a 1977 paper compiled by Nelson, for the Laboratory of Radiation Ecology (LRE), the progress of the Pacific Radioecology Program for 1974-1975 was reported. As a result of the 66 nuclear weapons tests conducted in the vicinity of Marshall Island from 1946-1958, this program was tasked with researching the nuclides and their

distribution of radionuclides in foods, plants, animals, and soil of the Central Pacific, with particular emphasis on the Marshall Islands.

During the April 1974 to August 1975 time frame, 600 samples were collected. The samples were dried, ground, and compressed into uniformly distributed mass and density segments. Samples were first counted for gammas using NaI detectors and counts determined by the method of least squares, or with Ge (Li) detectors and counts determined by hand calculations or summing counts within the five channels under spectrum peaks. Counts were converted to pCi and values were corrected for decay to the date of sample collection. For ^{55}Fe discrimination, solvent extraction and electrodeposition with x-ray spectrometry were used. Chemical separation was used to separate ^{90}Y from ^{90}Sr and a low-level beta counting system was used to count ^{90}Y after being collected on filter paper. Alpha spectrometry was used to analyze Pu which was extracted via ion exchange and ^{242}Pu was used as a tracer to determine chemical yield.

Results indicated that the sample activity measured varied with relation to the location of the test sites, with Bikini Atoll having the highest levels of measured radioactivity and Christmas Island having the lowest levels. Bikini Atoll was the collection site of the nine species of fish collected for this study. Mullet viscera contained the highest levels of ^{90}Sr and $^{239,\ 240}$Pu, with 2.6 pCi/g (9.6 Bq/kg) and 5.6 pCi/g (20.7 Bq/kg), respectively. Levels of ^{137}Cs were generally low (< 1 pCi/g [3.7 Bq/kg]) in the sampled fish, with highest levels being found in plant life in location with the lowest levels if ^{137}Cs in soil (Nelson, 1977). The results were not presented with dose

rate estimates or indications of risk. The results do indicate that ^{137}Cs enters the food chain via plant life. The results also indicate that ^{90}Sr and $^{239,\ 240}Pu$ concentrate in the GIT, representing a potential radiological hazard to the fish itself and animals that consume them whole.

Radiological Survey of Plants, Animals, and Soil in Micronesia

In a 1979 paper, Nelson reports the findings of a joint study with the Laboratory of Radiation Ecology and Brookhaven National Laboratory in the Micronesia area which included: Majuro Atoll (Marshall Islands), Truk and Ponape (Caroline Islands), Guam (Marianas Islands), and Koror and Babelthaup (Palau Islands). This study cites the radiological sources as being the underwater and atmospheric nuclear testing done by the United States in the central Pacific and the atmospheric nuclear testing conducted by France and Great Britain from 1946-1962.

Biological and soil samples were collected in November 1975, with approximately 70% of the samples being food items common in the Marshallese diet such as fish, coconut crab, coconut, pandanus, and breadfruit. Approximately 30% of the samples were soil, which were collected for the purpose of estimating future environmental distribution of radionuclides. The samples were dried, ground, and compressed into uniformly distributed mass and density segments. Biological samples underwent gamma spectrometry using NaI detectors (thallium-drifted) and 200-channel, pulse height analyzer and Ge (Li) diode detector and 4096-channel, pulse-height analyzer. Soil samples were analyzed with just the Ge (Li) system. Those counted with NaI system

were determined by a method of least squares and those counted with the Ge (Li) system were calculated by hand calculations or summing counts within the five channels under spectrum peaks. Background was subtracted and values were corrected for decay to the date of sample collection and counts were converted to pCi.

Strontium-90 was measured using chemical separation of ^{90}Y from ^{90}Sr and a low-level beta counting system to count ^{90}Y after being collected on filter paper. Alpha spectrometry was used to analyze Pu which was extracted via ion exchange and using ^{242}Pu as a tracer to determine chemical yield.

The analysis showed that the levels of ^{137}Cs were lower than Nelson's 1977 report of the Marshall Islands, and the majority of samples contained levels that were below the levels of detectability. Strontium-90 and $^{239, 240}Pu$ in the fish tissue samples were near or below the levels of detectability with ^{90}Sr only detectable in 1 of the 15 analyzed tissues and $^{239, 240}Pu$ was not detectable in any of the samples (Nelson 1979).

Radionuclide Concentrations in Fish and Invertebrates from Bikini Atoll Between 1977 and 1984 and Radionuclide Concentrations in Fish and Invertebrates from Bikini Atoll

Research conducted by Lawrence Livermore National Laboratory investigated the radionuclide concentrations in fish and invertebrates located in the area of Bikini Atoll. Bikini Atoll is one of two sites used as nuclear testing grounds by the United States during the time period of 1946-1958. The detonations consisted of air drops, anchored barges, underwater, and surface, resulting in the dispersion of fission and activation products within the lagoon and the islands of the atoll. A 1988 published report,

compiled by Noshkin et al., summarized all available data regarding tissue concentrations of radionuclides in fish and invertebrates collected in the area from 1977 to 1984.

Throughout the studies, gills were separated, but not analyzed. The gills were found to be regularly contaminated with sediment and deemed to not be analytically important given that "gills are not eaten." Stomach contents, while not eaten, were of particular interest for obtaining data on feeding habits. Initially, studies sought to determine the radionuclide concentration in the tissues of varies species. "As the program progresses, dose assessment became an important issue, so our attention focused on the analysis of edible muscle tissue from fish collected at different locations." Samples were categorized, weighed (wet/dry), and ashed. The samples were then analyzed by gamma spectrometry using Ge (Li) diode detector systems with a count time of 1000 minutes or more per sample. With the use of GAMANAL, an analysis program, the photopeaks were compared to a radionuclide library for identification. GAMANAL applied correction factors for sample size, density, counting time, counting geometry, and decay to report the measure concentration in units of $\left[{}^{pCi}/_{g} \right]$. Following this process, selected samples underwent radiochemical analysis for ^{90}Sr, ^{137}Cs, $^{238,\ 239,\ 240}$Pu, ^{241}Am, ^{210}Po, ^{210}Pb, and ^{210}Bi, using alpha-spectrometer systems or low-background beta detectors. Results were reported per tissue or organ, as the percentage of the whole body activity.

Analysis of results focused almost exclusively on activity measured in edible flesh, and relationship to trophic position of fish sampled and the muscle burden of ^{137}Cs, of

which there was none. Specifically noted was the observation that the bulk of measured ^{90}Sr was found in non-edible segments. In goatfish and snapper, the body burden was associated with bone, while viscera contained the majority of concentration in mullet. The high concentration in viscera was attributed to bottom sediment ingested with food intake and present in the intestinal tract, which was not separated from the viscera. The report summarized that the radiological concentrations in edible tissue was not expected to exceed the upper limits determined for human consumption, reporting results in terms of estimated dose-equivalent rates to individual taken from whole body concentrations (Noshkin et al. 1988). The objectives, methods, and reported results illustrate the concept of radiation protection being focused solely on the effects to humans.

2.01.04 Previous Approaches to Modeling Non-Human Biota

Estimates of internal and external dose rates to aquatic organisms have been accomplished using computer programs such as RESRAD and CRITR2 (TVA 2012, Baker et al. 1992). CRITR2 considers a liquid radiological release to surface water and the effects to primary and secondary organisms. Users input information such as site parameters, bioaccumulation factors, biological half-lives, uptake fractions, radiological half-lives, energies for various radii, and external dose rate factors into an ASCII text file which can be output to a text file for editing (Baker et al. 1992). Data is entered in a block format:

SETUP block- Used to specify name and location of input and output files.

TITLE- Title of the scenario run.

BIOFILE- Bioaccumulation factor file.

ENERGY FILE- Dose rate factor file.

OUTFILE- File to hold summary results tables.

QAPRINT- Optional printout of results of intermediate calculations.

OUTUNITS- Selection of dose units.

TB- Time of radionuclide buildup in sediment

SOURCE block- Nuclides involved in calculation, concentration or release rate, and recirculation factor.

DILUTION block- Parameters for calculation of dilution factor for body of water in which the organism resides.

MODEL- Type of body of water: river, estuary, coastal, lake.

SALINITY- Primary water salinity: fresh or salt.

PIPE_FLOW- Volume flow rate of effluent entering and outflow.

NEAR/FARSIDE- Distance from receptor relative to source.

RIVER_FLOW- Volume flow rate of river or fresh-water component of estuary.

WIDTH- Width of river or estuary at outfall.

DEPTH- Depth of body of water.

EBB_FLOW- For estuary site: average flow of ebb tide.

FLOOD_FLOW- For estuary site: average flow of flood tide.

TIDAL_PERIOD- One tidal cycle.

COSTAL_CURRENT- For costal site: current velocity along coast.

LAKE_VOL- For lake site: volume of lake.

NET_FLOW- For lake site: inflow minus outflow.

CRITR block- Types, names, and order of organisms considered by program (Maximum of 9 organisms).

X- Distance from source to target.

DILUTION- Optional direct input of dilution factors.

MASS- Mass of organism.

RADIUS- Effective radius of organism

DIET- Primary organism that makes up diet of secondary organism: plant, fish, crustacean, or mollusk.

INTAKE RATE- Intake rates of secondary organisms.

SEDIMENT- Fraction of time exposed to sediment.

IMMERSION- fraction of time immersed in water.

SURFACE- Fraction of time floating on surface.

ROUGHNESS- geometrical roughness of organism.

By utilizing this block structure, any areas in need of revision can be easily located (Baker et al. 1992).

Quality factors are used in internal dosimetry for humans which allows for comparing exposures of various radiation types based on biological effects. This method allows for estimating probability of certain stochastic effects. While some dose

estimating programs such as RESRAD utilize weighting factors, there are currently no set standards for non-human biota (Jones et al. 2003). Lacking this standard limits the focus of studies to deterministic effects such as mortality and reproductive success. Due to the huge variety of organisms, the most common method of dose estimates is through the use of reference animals and plants. The ERICA project expands on the ICRP RAPs using simplifications to encompass a variety of exposure situations such as:

- Shapes of organisms approximated by spheres and ellipsoids
- Radioactivity distributed homogenously throughout the whole body and internal organs are not explicitly considered
- Concentration is considered to be at equilibrium throughout the body.
- Aquatic organisms are treated as though they are in a quasi-infinite medium with medium density being equal to organisms density.

The ERICA Tool accounts for daughter nuclides by truncating the decay chain at the first radionuclide with a half-life greater than 10 days and assuming all members in the decay chain to be in secular equilibrium. The ERICA Tool has the option of using relative activities of the decay chain members or using the activities at a specified time following the beginning of the parent nuclide decay. A dosimetric module was programmed in the FORTRAN language and integrated into the ERICA Tool following the module logic flowchart such as the recreated Ulanovsky chart illustrated in Figure 2. This allows internal and external exposure to be considered for a wide range of organisms

and a variety of exposure scenarios by inputting parameters such as: organism's shape and mass, habitat, biota type, and geometry of external sources (Ulanovsky et al. 2008).

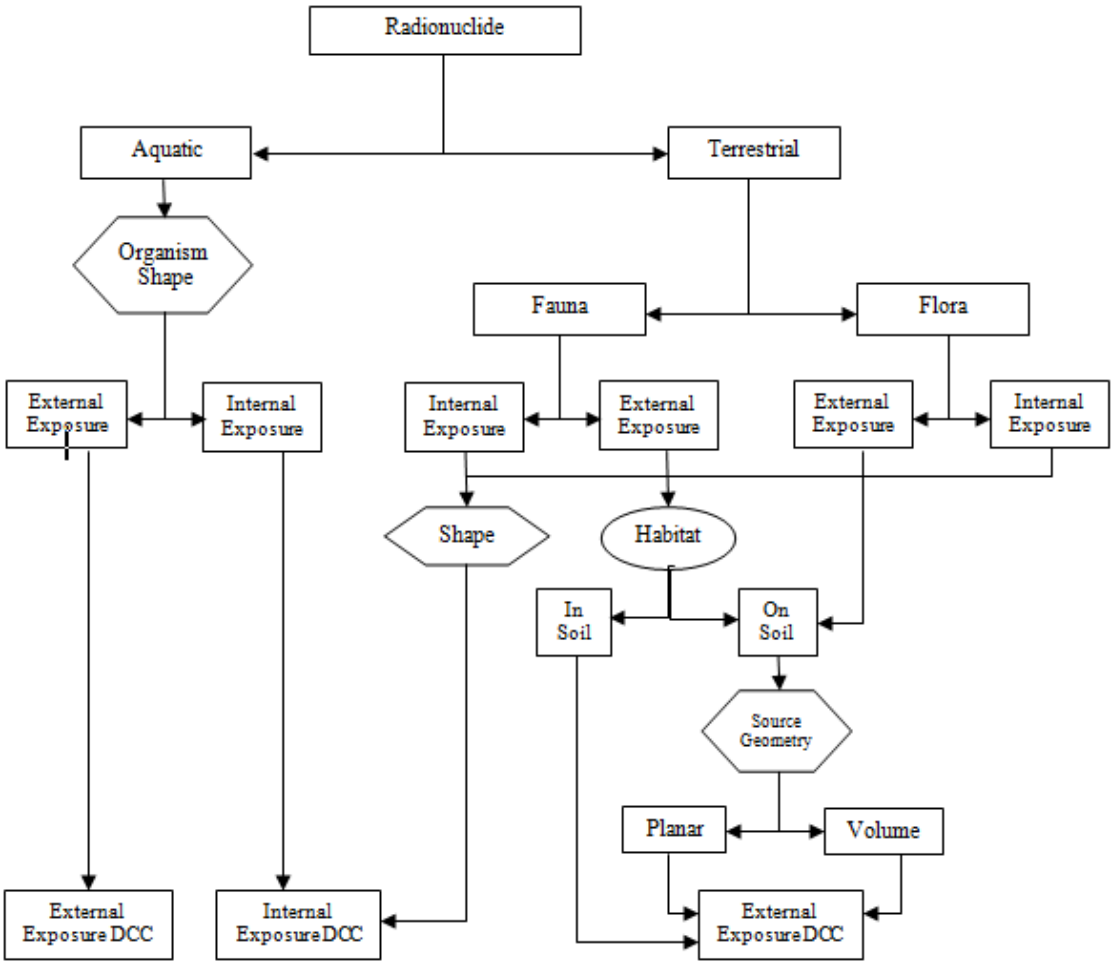

Figure 2: ERICA Tool flowchart

Doses received by individual organs from ingestion of radionuclides are dependent on several factors. In addition to the emission type (alpha, beta, gamma, neutron, proton), energy, and half-life, the chemical form (soluble or insoluble) and condition of

the tissue of the transport pathway, such as wounds, have a significant impact on dose. When ingested with soluble material, the behavior of the radionuclide can be predicted by the affinity of other elements in the same chemical group. Common examples of this are ^{137}Cs and ^{90}Sr, as they are both found in nuclear weapons fallout. Cesium-137 behaves much like potassium and is therefore expected to be transported and taken up by most tissues, while Sr-90 behaves much like calcium with the bulk of the activity depositing in bone tissue. However when ingested in insoluble form, very little of the activity enters the bloodstream for transport and consequently reduces overall dose to tissue considerably (Harrison et al. 1996).

Plutonium-239, an alpha-emitter, generally has minimal absorption within the body, but given that it can be present in a wide variety of chemical forms, the absorption characteristics within the GIT can vary. When ingested in soluble form, the absorption level is approximately 0.1% (transfer factor of $10^{-3)}$ with retention mainly occurring in bone and the liver, but less than 0.001% (transfer factor of 10^{-5}) when taken in as insoluble plutonium dioxide, resulting in an effective dose difference of about 50 times less for insoluble ^{239}Pu (Harrison et al. 1996).

Generally, the effective dose will be considerably lower for radionuclides that are ingested in particulate form or within particles, as opposed to more soluble forms. Intake of this nature can however, also lead to an extended residence time within the GIT, resulting in higher doses to regions of the GIT and associated lymphatic tissue. This extended retention time in the GIT has been shown to be generally true in neonatal

animals but varies considerably with species, diet, and particle size when the uptake is in adult animals (Hodges et al. 1995). There is considerable variance with regards to distribution and retention of radionuclides within the body. While there is currently a GI model in use for humans, there is no such model for non-human biota at this time. It is suggested that a new dosimetric model is needed to include retention in intestinal tissue for various physicochemical radiological forms. For the determination of cancer risk, studies have shown that the local irradiation that occurs with short-range emissions, such as alpha-emitters, is less effective than the same dose that is distributed uniformly, such as that which occurs with more soluble chemical forms (Harrison et al. 1996).

2.03 Deterministic and Stochastic Effects

When radioactive particles interact with biological tissue, cellular damage may occur. Depending on the extent of the cellular damage, adequate repair may not be possible and may result in cell death, inability for cellular reproduction, or cell reproduction with a mutation that is passed on to future generations. If cell death or failure to replace lost cells through cellular reproduction occurs, a determinist effect may occur. While the body can remain unaffected with minimal cell death, there can be a loss of function if the cell loss is significant enough. The probability of such an event is zero at low doses of radiation. As the dose increases, a threshold is reached and the probability increases dramatically to 100%. Additionally, the severity of impairment also increases with dose. An example of a deterministic effect is cataracts. When a cell is exposed to radiation and is damaged such that it is still capable of reproducing, however it is

mutated, a stochastic effect may occur. With stochastic effects, an excepted dose threshold does not exist, nor is the severity affected by dose. However, the probability of a stochastic effect occurring increases as dose increases. Stochastic effects are typically associated with whole body exposures leading to cancer or heritable defects (Hall and Giaccia 2012).

2.04 Acute and Late Effects

Radiological effects are typically described as acute or late and are characterized by their dose-response relationships. Acute effects, also known as early effects, are a result of significant cell death occurring within days or weeks of irradiation of tissues with a high turnover rate. Onset of early effect correlates with the short life span of the mature functional cells. This kind of effect may be seen in gastrointestinal epithelium due to a bolus containing an alpha-emitter. Late effects, which are more sensitive to fractionalization, are typically seen in slowly reproducing tissues, such as lung and liver. Repair to this tissue happens very slowly due to the slow turnover rate of cells. This kind of effect may be seen in heart tissue as a result of receiving dose from a source organ, such as the gastrointestinal tract (Hall et al. 2012).

2.05 Weaknesses

The wide range of possible exposure scenarios and vast amount of organisms, each with differing habitats, diets, reproduction patterns, and life spans make the development of detailed dosimetric models, such as the ones developed for reference humans, a very

complicated and labor intensive task. The amount of unknowns and assumptions widen the margin of uncertainty in dose rate estimations. Some of the uncertainty may be minimized by examining previous assumptions, exploring additional sources of data, and reviewing previous studies with the use of newer technology.

2.05.01 Dosimetry, Uptake, and Effects in RAPs Data Gaps

The ability to obtain data regarding the radiological effects of some animal wildlife to sufficiently represent, in relationship to varying possibilities of exposure, has limited the potential pool of reference organisms (Pentreath 2012). As seen by 12 Reference Animals and Plants, the current selection to use as a comparative standard is very limited and is not representative of all biota with applicable research potential. The fish in this study varied vastly in size and geometry from themselves as well as from the two possible reference fish, with closest similarities to the reference trout.

Brèchignac discusses the need for the development of a system that adequately address radioprotection with regards to the environment and suggests that the approached used for Ecological Risk Assessment (ERA) can be improved upon to widen the perspective of environmental radioprotection. Addressing radioecology from the same perspective used for human radioprotection does not consider the affects of differing pathway exposure and diverse sensitivities. While the ERA was originally concerned with human health issues, improvements would be required to address the complications that arise from multiple organisms. The most common approach to this problem is selecting species of various taxonomic groups to represent the global system in an effort

to obtain data on dose-effect relationships. While it has become more common to approach radioprotection of non-human biota from a reference animal and plant perspective, the concept of protecting a system as a whole (ecosystem approach), taking into consideration the framework and effects of stress and interaction within an ecosystem is emerging (Brèchignac 2003).

2.05.02 Contribution of dose from GIT

Research has found high concentrations of radionuclides in the gastrointestinal tract of bottom-feeding fish. The high concentration, relative to the remainder of the consumable fish body, has been determined to be misleading if included in whole body calculations of the fish (Noshkin, 1988). In the past, this has been negated from dose rate calculations due to the lack of effect it has on human dose rate. When considering effects to the ecosystem, such as other animals that consume the entire fish or internal dosimetry for the fish in question, excluding the GIT from estimations is misleading.

Chapter 3 - Materials and Methods

3.01 Data Source

Three species, of varying trophic positions, were collected from the Pacific Proving Ground in the years following significant radiological release as a result of various nuclear weapons testing events (Table 1). Data used in this study, provided by Mathew Johansen with Australian Nuclear Science and Technology Organization (ANSTO), was reported for dissected tissue compartments, including: muscle, bone, skin, liver, stomach contents, and viscera (all GIT and contents, kidney, and spleen).

Table 1: Data Source

Species	Trophic Position	Location	Radionuclide(s)	Reference & Year
C. crenilabis & N. chaptalii (Mullet)	Benthic Omnivores	Bikini Atoll	^{90}Sr, ^{239}Pu,^{240}Pu	Noshkin et al., 1986
		Bikini, Endrik, Lukuen, Kabelle	^{137}Cs	Nelson et al.1977, 1979
		Bikini, Nam	^{137}Cs	Held, 1969
M. samoensis (Goatfish)	Carnivorous Foragers	Bikini Atoll	^{137}Cs, ^{90}Sr, ^{239}Pu, ^{240}Pu	Noshkin et al, 1988
L. bohar & A. virescens (Snapper)	Picivorous Predators	Panape, Kit	^{137}Cs	Nelson et al. 1977, 1979
		Bikini Atoll	^{137}Cs, ^{90}Sr, ^{239}Pu, ^{240}Pu	Noshkin et al, 1988

3.02 Reference Animal Selection

ICRP 108 selected the trout and flatfish as the reference animal for fish species (2008). The variances between trout and flatfish are considerable. Trout belong to the Salmonidae family which are ray finned fish, with adult lengths ranging from 13 cm to 2 meters. They are a predatory fish that feed on small crustaceans, insects, and smaller fish. Flatfish belong to the Pleuronectidae family and are describes as having long and continuous dorsal and anal fins with the dorsal fin extending forward onto the head. They are oceanic bottom dwellers ranging in length from 20.0 cm to 4.7 meters at adulthood (Paxton & Eschmeyer 1998). The fish in this study, from within the Pacific Proving Ground, share a closer resemblance to the trout reference fish due to their body shape (geometry), as well as their swimming and eating habits. For these reason, any ICRP 108 RAP data and comparisons are referenced to the reference trout.

3.03 Heterogeneous Dose Rate Estimations

Using a heterogeneous model, dose rates to individual organs were estimated (ICRP 109 2008). This allowed for estimating the dose rate increase to various organs as a result of including concentrations from the GIT.

3.03.01 Modeling the Reference Animal

A trout was imaged at the Oregon State University College of Veterinary Medicine, using Toshiba Aquilion 64 slice Computerized Tomography (CT) as depicted in Figure 3. The CT images were processed by Catherine Hess in her Master's Thesis, Monte Carlo

Simulation of Absorbed Fractions in a Voxel-Based Trout Model. Hess used 3D Doctor, software produced by Able Software, to create a three-dimensional model to model compartments of interest that were specified from each slice of the CT images, depicted in Figure 4 and Figure 5. Once the compartments of interest were identified, also known as segmentation, the 3D Doctor software calculated each compartment's volume, mass, density, and distance to other compartments. Table 2 illustrates the organs modeled and Table 3 reports the data calculated using 3D Doctor (Hess 2013).

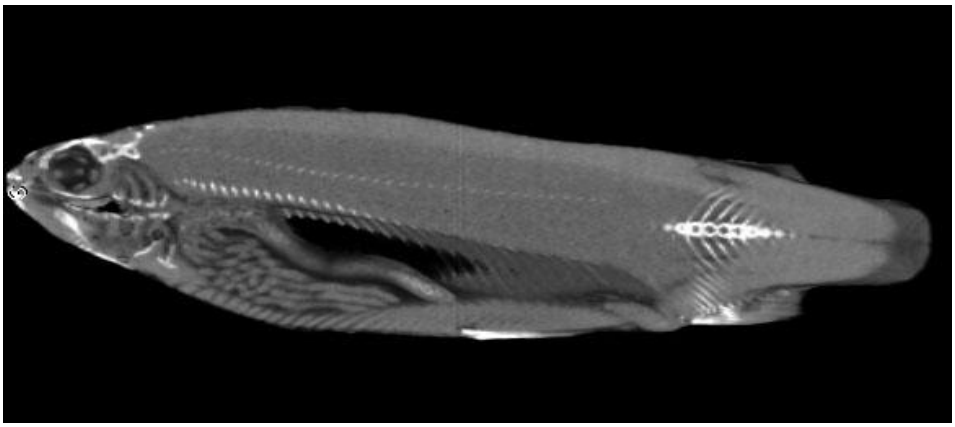

Figure 3: Sagittal Trout CT Image

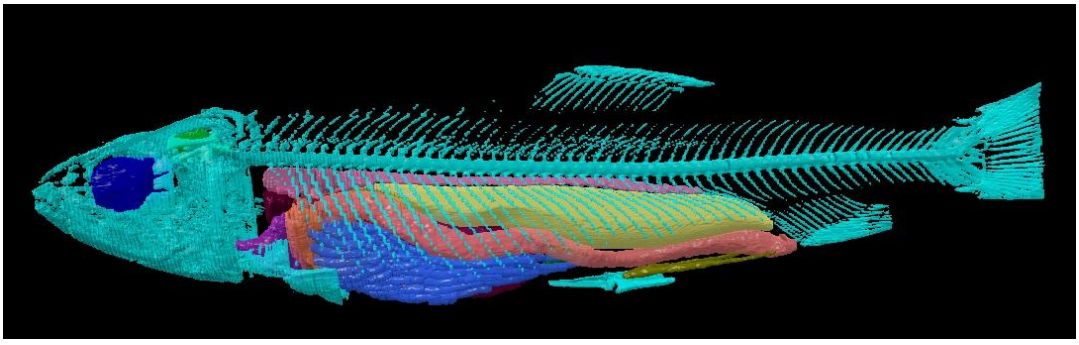

Figure 4: Sagittal Trout 3D Doctor Image

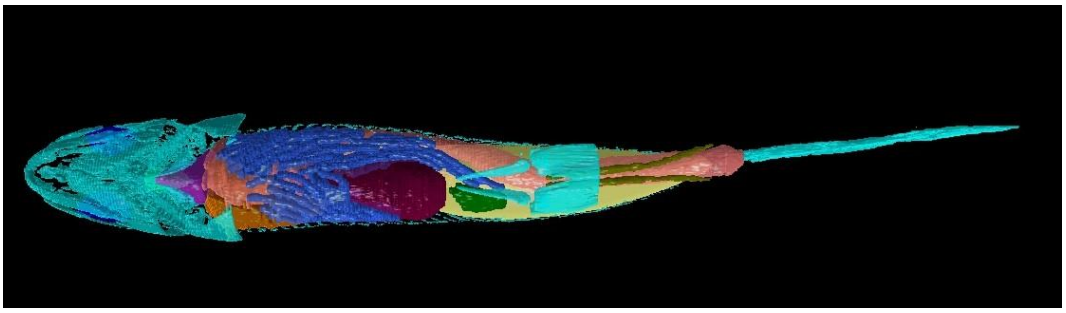

Figure 5: Coronal Trout 3D Doctor Image

Table 2: Organs Included in Modeled Segments

Modeled Segments	Organs Included in Segment
Brain	Brain
Esophagus	Esophagus and Stomach
Eyes	Eyes
Heart	Heart
Kidney	Kidney
Liver	Liver and Gallbladder
Muscle Tissue	Skin, scales, fins, pharynx and mouth region, thyroid, spinal cord, nerves, vasculature, muscle, fat and connective tissue
Pyloric Caeca	Pyloric Caeca and Pancreas
Rectum	Intestine
Skeleton	Bone and Teeth
Spleen	Spleen
Swim Bladder	Swim Bladder
Testes	Testes

Table 3: 3D Doctor Reference Trout Data

Trout Organ or Tissue	Volume (cm^3)	Mass (g)	Density Used (g/cm^3)	Reference	Referenced Organ
Brain	0.566	0.5886	1.04	ICRU-44	Brain
Esophagus	13.751	14.3698	1.045	ICRP-89	Alimentary System
Eyes	1.936	2.0715	1.07	ICRU-44	Eye Lens
Heart	1.782	1.8354	1.03	ICRP-89	Heart
Kidneys	4.02	4.221	1.05	ICRP-89	Kidney
Liver	7.145	7.5737	1.06	ICRP-89	Spleen
Muscle & Soft Tissue	554.325	582.041	1.05	ICRU-44	Muscle, Skeletal
Pyloric Caeca	7.884	8.238	1.045	ICRP-89	Alimentary System
Rectum	11.75	12.278	1.045	ICRP-89	Alimentary System
Skeleton	12.502	24.003	1.92	ICRU-44	Bone, Cortical
Spleen	0.512	0.54272	1.06	ICRP-89	Spleen
Swim Bladder	33.672	0.04044	0.001201	Saunders	Lake Trout Swim Bladder (0-16.5 Feet)
Testes	0.372	0.38688	1.04	ICRU-44	Testis

A voxel model of a reference trout was done using Voxelizer, a program created by Kevin Capello and Erick Cardenas-Mendez with the Human Monitoring Laboratory

(HML) of Health Canada's National Internal Radiation Assessment Section (Kramer et al. 2010). The boundary file (.bnd), created in 3D Doctor, was uploaded to Voxelizer. The graphical user interface (GUI) within Voxelizer is used to input the following information from the 'image information' tab within 3D Doctor: number of rows, columns, and planes, as well as pixel width and slice thickness, from 3D Doctor, taking care to do proper unit corrections. The default units in 3D Doctor are millimeters as opposed to centimeters, which is the default unit in Voxelizer and MCNP (Hess 2013).

Voxelizer utilized the 3D boundary file, created in 3D Doctor, to correlate the trout compartments specified with Monte Carlo universes. The geometry was output as a ASCII file type, which is a type of format description used by MCNP. Utilizing the densities calculate in 3D Doctor (Table 3), a generic MCNP card was used to calculate absorbed fractions of each "source to target" pair for each energy emitted by ^{137}Cs and ^{90}Sr (Ruedig 2013). ^{137}Cs and ^{90}Sr absorbed fraction data for this study was also obtained from Hess's thesis (Hess 2013). Due to ^{239}Pu and ^{240}Pu being monoenergetic alpha emitters, their absorbed fraction is equal to one (i.e. all energy emitted from source "heart" was absorbed in target "heart") (ICRP, 2008).

3.03.02 Dose Conversion Factor

Dose Conversion Factors (DCFs) are "defined as absorbed dose rate per activity concentration within the organism or externally in the medium" (ICRP 2008). Once the concentrations of radionuclides were measured, the total dose rate to each target of interest was estimated using DCFs specific for each nuclide. This was achieved with

absorbed fractions of each "source to target" pair for each energy emitted by ^{137}Cs and ^{90}Sr (β and γ) calculated in MCNP and an absorbed fraction of 1 for ^{239}Pu and ^{240}Pu, due to their monoenergetic alpha emissions (i.e. all energy emitted from source "heart" was absorbed in target "heart"). Following the method used in ICRP 108, the DCFs included the contributions from parent and daughter nuclides in cases for daughter radionuclides having a half-life of less than 10 days. Also in accordance with ICRP 108, when parent and daughter radionuclides were used, they were assumed to be in secular equilibrium. Daughters were therefore considered for ^{137}Cs and ^{90}Sr, which were ^{137}Ba and ^{90}Y respectively. Using the DCFs normalized the nuclide concentrations to 1 Bq kg^{-1}. DCFs were calculated in Microsoft Excel using conversions and the following equation:

$$S = \sum \left(1\frac{Bq}{kg}\right)\left(\frac{1\ nt}{1\ Bq * s}\right)\left(\frac{E_{avg}}{nt}\right)(AF)(BR)(Y)\left(\frac{1.602\ E-16\ J}{keV}\right)\left(\frac{1\ E6\ \mu J}{J}\right) =$$

$$\frac{\mu J}{kg\ s} = \frac{\mu Gy}{s}$$

$$DCF = S\left(\frac{86400\ s}{d}\right)M = \left[\mu Gy\ kg/_{Bq\ d}\right]$$

Where variables are defined as illustrated in Table 4:

Table 4: DCF Variable Definitions

Symbol	Definition	Units
S	Source	μGy/s
E_{avg}	Average Energy	keV
Y	Nuclear Yield	Unitless
Br	Branching Ratio	Unitless
AF	Absorbed Fraction	Unitless
M	Mass of Target	kg

While ICRP 108 calculated DCFs for the 12 RAPs, they were calculated for use in whole body dose rate estimates and were determined using the assumptions of a body shape proportion of 1 x 0.1600 x 0.12, body mass of 1.26 kg, and a homogeneous body density equal to that of water (2008). DCFs for this study were found for individual organs, using mass, density, and geometry calculated using the methods described in 3.03.01. DCFs were found for the following organs: muscle tissue, skeleton, liver, esophagus, rectum, spleen, testes, pyloric caeca, and kidney. The DCFs calculated for theses tissues are illustrated in Table 5, Table 6, Table 7, and Table 8. Activities were reported for the following organs: muscle, bone, skin, liver, stomach contents, and viscera (all GIT and contents, kidney, and spleen). Using the assumption that the tissue densities are equal, activity within skin was included with the activity within muscle tissue, and the muscle tissue DCF was utilized. Likewise, activity within the stomach

contents was included with activity within the esophagus, utilizing the esophagus DCF. Given that both the stomach and esophagus are "sac-like" organs and located in such close vicinity to each other that it was difficult to accurately distinguish on the CT scans, the assumption was made that the density of the source organs and geometry to other source organs are the same.

Table 5: Reference Trout DCFs (Cs-137)

Source $\frac{\mu Gy\ kg}{Bq\ d}$ / Target	Muscle	Skelton	Liver	Spleen	Kidney	Esophagus	Rectum	Pyloric Caeca
Muscle Tissue	5.02 x 10^{-3}	2.52 x 10^{-3}	2.18 x 10^{-3}	2.20 x 10^{-3}	3.02 x 10^{-3}	2.10 x 10^{-3}	2.21 x 10^{-3}	2.23 x 10^{-3}
Swim Bladder	3.45 x 10^{-7}	3.68 x 10^{-7}	4.05 x 10^{-7}	5.09 x 10^{-7}	4.79 x 10^{-7}	6.55 x 10^{-7}	5.66 x 10^{-7}	4.06 x 10^{-7}
Skeleton	2.05 x 10^{-4}	3.04 x 10^{-3}	2.27 x 10^{-4}	8.71 x 10^{-5}	4.16 x 10^{-4}	1.63 x 10^{-4}	1.66 x 10^{-4}	1.35 x 10^{-4}
Eyes	8.91 x 10^{-6}	1.23 x 10^{-5}	3.97 x 10^{-6}	4.21 x 10^{-7}	1.81 x 10^{-5}	2.74 x 10^{-6}	1.94 x 10^{-6}	1.01 x 10^{-6}
Heart	8.11 x 10^{-6}	9.87 x 10^{-6}	7.61 x 10^{-5}	5.69 x 10^{-6}	1.22 x 10^{-5}	3.50 x 10^{-5}	2.86 x 10^{-5}	2.42 x 10^{-5}
Liver	3.51 x 10^{-5}	4.35 x 10^{-5}	3.20 x 10^{-3}	2.73 x 10^{-5}	5.81 x 10^{-5}	1.27 x 10^{-4}	4.67 x 10^{-5}	9.70 x 10^{-5}
Brain	3.29 x 10^{-6}	6.79 x 10^{-6}	4.65 x 10^{-7}	6.61 x 10^{-8}	3.04 x 10^{-6}	3.88 x 10^{-7}	2.96 x 10^{-7}	1.39 x 10^{-7}
Esophagus	6.44 x 10^{-5}	5.68 x 10^{-5}	2.41 x 10^{-4}	4.30 x 10^{-4}	1.32 x 10^{-4}	3.32 x 10^{-3}	1.81 x 10^{-4}	2.76 x 10^{-4}
Rectum	5.80 x 10^{-5}	5.10 x 10^{-5}	7.62 x 10^{-5}	1.36 x 10^{-4}	6.39 x 10^{-5}	1.56 x 10^{-4}	3.17 x 10^{-3}	2.17 x 10^{-4}
Spleen	2.54 x 10^{-6}	1.11 x 10^{-6}	2.04 x 10^{-6}	2.83 x 10^{-3}	8.78 x 10^{-7}E-07	1.69 x 10^{-5}	6.16 x 10^{-6}	8.55 x 10^{-6}
Testes	1.73 x 10^{-6}	1.40 x 10^{-6}	4.09 x 10^{-7}	5.49 x 10^{-6}	3.97 x 10^{-7}	2.47 x 10^{-6}	6.84 x 10^{-6}	2.02 x 10^{-6}
Pyloric Caeca	4.28 x 10^{-5}	2.98 x 10^{-5}	1.16 x 10^{-4}	1.39 x 10^{-4}	2.41 x 10^{-5}	1.75 x 10^{-4}	1.60 x 10^{-4}	2.89 x 10^{-3}
Kidney	2.70 x 10^{-5}	4.70 x 10^{-5}	3.20 x 10^{-5}	6.59 x 10^{-6}	2.98 x 10^{-3}	3.83 x 10^{-5}	2.17 x 10^{-5}	1.11 x 10^{-5}

Table 6: Reference Trout DCFs (^{90}Sr)

Source $\frac{\mu Gy\ kg}{Bq\ d}$ / Target	Muscle	Skelton	Liver	Spleen	Kidney	Esophagus	Rectum	Pyloric Caeca
Muscle Tissue	2.59×10^{-3}	7.88×10^{-5}	2.29×10^{-5}	4.27×10^{-5}	4.84×10^{-5}	2.17×10^{-5}	3.03×10^{-5}	8.82×10^{-5}
Swim Bladder	1.45×10^{-7}	1.39×10^{-7}	0.00	0.00	0.00	0.00	0.00	0.00
Skeleton	5.37×10^{-6}	2.52×10^{-3}	3.37×10^{-7}	0.00	7.65×10^{-7}	1.33×10^{-7}	2.38×10^{-7}	0.00
Eyes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heart	0.00	0.00	2.68×10^{-6}	0.00	0.00	0.00	7.67×10^{-7}	0.00
Liver	3.58×10^{-7}	0.00	2.56×10^{-3}	0.00	1.24×10^{-6}	2.36×10^{-6}	2.20×10^{-6}	2.41×10^{-6}
Brain	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Esophagus	6.53×10^{-7}	0.00	4.53×10^{-6}	1.90×10^{-7}	1.33×10^{-6}	2.58×10^{-3}	2.28×10^{-7}	2.01×10^{-6}
Rectum	8.23×10^{-7}	0.00	3.50×10^{-6}	0.00	0.00	2.10×10^{-7}	2.56×10^{-3}	4.32×10^{-6}
Spleen	0.00	0.00	0.00	2.56×10^{-3}	0.00	0.00	0.00	0.00
Testes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pyloric Caeca	1.74×10^{-6}	0.00	2.74×10^{-6}	0.00	0.00	1.39×10^{-6}	3.10×10^{-6}	2.51×10^{-3}
Kidney	4.31×10^{-7}	0.00	6.67E-07	0.00	2.55×10^{-3}	3.69E-07	0.00	0.00

Table 7: Reference Trout DCFs (^{239}Pu)

Source $\frac{\mu Gy\ kg}{Bq\ d}$ / Target	Muscle	Skelton	Liver	Spleen	Kidney	Esophagus	Rectum	Pyloric Caeca
Muscle Tissue	7.26×10^{-2}	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Swim Bladder	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Skeleton	0.00	7.26×10^{-2}	0.00	0.00	0.00	0.00	0.00	0.00
Eyes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heart	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liver	0.00	0.00	7.26×10^{-2}	0.00	0.00	0.00	0.00	0.00
Brain	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Esophagus	0.00	0.00	0.00	0.00	0.00	7.26×10^{-2}	0.00	0.00
Rectum	0.00	0.00	0.00	0.00	0.00	0.00	7.26×10^{-2}	0.00
Spleen	0.00	0.00	0.00	7.26×10^{-2}	0.00	0.00	0.00	0.00
Testes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pyloric Caeca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.26×10^{-2}
Kidney	0.00	0.00	0.00	0.00	7.26×10^{-2}	0.00	0.00	0.00

Table 8: Reference Trout DCFs (^{240}Pu)

Source $\frac{\mu Gy\ kg}{Bq\ d}$ / Target	Muscle	Skelton	Liver	Spleen	Kidney	Esophagus	Rectum	Pyloric Caeca
Muscle Tissue	7.28×10^{-2}	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Swim Bladder	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Skeleton	0.00	7.28×10^{-2}	0.00	0.00	0.00	0.00	0.00	0.00
Eyes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heart	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liver	0.00	0.00	7.28×10^{-2}	0.00	0.00	0.00	0.00	0.00
Brain	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Esophagus	0.00	0.00	0.00	0.00	0.00	7.28×10^{-2}	0.00	0.00
Rectum	0.00	0.00	0.00	0.00	0.00	0.00	7.28×10^{-2}	0.00
Spleen	0.00	0.00	0.00	7.28×10^{-2}	0.00	0.00	0.00	0.00
Testes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pyloric Caeca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.28×10^{-2}
Kidney	0.00	0.00	0.00	0.00	7.28×10^{-2}	0.00	0.00	0.00

3.03.03 Organ Weighting

Radionuclide concentrations were reported for the following compartments: muscle, bone, skin, liver, stomach contents, and viscera (all GIT and contents, kidney, and spleen). To weight the concentrations for the organs contained in the viscera, the mass of each organ, as calculated in 3D Doctor was used (Table 9). This enabled the dose rate calculations to be calculated for individual organs with and without the contribution of the GIT.

Table 9: Data for Organ Weighting of Viscera (3D Doctor)

Viscera	Mass (kg)	% Viscera
GIT (Total)	0.0348858	87.99%
Esophagus	0.0143698	36.24%
Pyloric caeca	0.008238	20.78%
Rectum	0.012278	30.97%
Non GIT (Total)	0.00476372	12.01%
Spleen	0.00054272	1.37%
Kidney	0.004221	10.65%

3.03.04 Dose Rate Calculation

Due to the fact that there are no tissue-weighting factors for non-human biota at this time, internal dose rate calculations for each individual target organ were done using the following equation:

$$\dot{D}_T = \sum C_{S,X} * DCF_{x,S \to T}$$

Where C is the concentration in the source organ for radionuclide "X", and DCF is the dose conversion factor calculated for radionuclide "X" for each source to target organ pair.

3.04 Homogeneous Dose Rate Estimation

Homogeneous dose rate calculations were done utilizing tabulated data from ICRP 108 for the reference trout. The tabulated data was obtained using ellipsoidal geometry modeling assuming a homogeneous distribution of the radionuclides throughout the organisms.

3.04.01 Dose Conversion Factor

The dose conversion factor for each reference animal is tabulated in ICRP 108 for 75 specific nuclides, for both internal and external exposures. The ICRP DCF used for the homogeneous dose rate calculations for the reference trout are illustrated in Table 10 (ICRP 2008).

Table 10: ICRP 108 Reference Trout DCF

	^{137}Cs	^{90}Sr	^{239}Pu	^{240}Pu
ICRP DCF μGy kg(Bq h)$^{-1}$	1.83 x10^{-4}	6 x10^{-4}	2.96 x10^{-3}	3.00 x10^{-3}
ICRP DCF μGy kg(Bq d)$^{-1}$	4.40 x10^{-3}	1.50 x10^{-2}	7.10 x10^{-2}	7.20 x10^{-2}

As with the dose rate estimations calculated in the heterogeneous models, the activity within skin was included with the activity within muscle tissue, and the muscle tissue DCF was utilized, as well as the stomach contents included with activity within pyloric caeca, utilizing the pyloric caeca DCF.

3.04.02 Whole Body Dose Rate Calculations

The concentration for each of the sample categories (mullet, snapper, and goatfish) were separated into concentration including GIT and concentration excluding GIT. The concentration for the GIT was weighted as explained in section 3.03.03. Dose rates were then calculated for each nuclide using the following equation:

$$\dot{D} = C * DCF$$

where "C" is the concentration in tissue with units of [Bq/kg] and the DCF was that obtained from ICRP 108, listed in Table 10, converted to the units of [μGy kg/Bq h] to obtain the dose rate in units of [μGy/hr].

Chapter 4 - Results and Analysis

4.01 Radionuclide Concentrations

Concentrations for each of the three categories of fish species were measured and reported by percentage of total concentration within specified organs or compartments (Held 1969, Nelson et al.1977, 1979, Noshkin et al. 1986, 1988). Utilizing the methods specified in Chapter 3, the percentage of total measured concentration within the GIT was calculated. The values are reported below, in Tables 11, 12, and 13. It is important to note that the values do not sum to 100% due to the absence of data for gills, eyes, and reproductive organs.

Table 11: Radionuclide Concentration in Mullet

	^{137}Cs	^{90}Sr	^{239}Pu	^{240}Pu
Total Concentration [Bq/kg]	7.622	19.166	6.327	7.733
Muscle Tissue	53%	0.06%	0.09%	0.11%
Skeleton	0%	2.00%	0.23%	0.28%
Skin	13%	1.00%	0.23%	0.28%
Liver	2%	0.07%	2.39%	2.92%
Viscera	26%	82.00%	36.90%	45.10%
Stomach Contents	1%	8.00%	3.15%	3.85%
GIT	23.88%	30.88%	26.03%	26.73%

Table 12: Radionuclide Concentration in Snapper

	^{137}Cs	^{90}Sr	^{239}Pu	^{240}Pu
Total Concentration [Bq/kg]	4.551	0.703	0.0333	0.0407
Muscle Tissue	92.00%	0.90%	0.14%	0.17%
Skeleton	0.30%	63.00%	11.70%	14.30%
Skin	4.00%	34.00%	22.50%	27.50%
Liver	0.20%	0.10%	4.95%	6.05%
Viscera	0.70%	0.10%	2.70%	3.30%
Stomach Contents	10.01%	0.02%	0.14%	0.17%
GIT	10.63%	0.64%	0.75%	0.78%

Table 13: Radionuclide Concentration in Goatfish

	^{137}Cs	^{90}Sr	^{239}Pu	^{240}Pu
Total Concentration [Bq/kg]	1.739	4.033	0.7326	0.8954
Muscle Tissue	68.00%	2.00%	0.05%	0.06%
Skeleton	0.90%	40.00%	0.09%	0.11%
Skin	7.00%	29.00%	0.41%	0.50%
Liver	0.90%	0.05%	0.36%	0.44%
Viscera	17.00%	22.00%	40.50%	49.50%
Stomach Contents	0.90%	0.10%	0.05%	0.06%
GIT	15.86%	15.06%	15.00%	15.01%

4.02 Heterogeneous Dose Rate

Utilizing the tissue concentrations reported in section 4.01 and the DCFs reported in section 3.03.02, calculated from the voxel trout model, the combined dose rates to each target organ from individual source organs, were calculated for the Mullet, Snapper, and Goatfish.

4.02.01 Mullet

The total combined dose rate for each of the selected target organs for the Mullet, calculated with and without the contribution from the GIT, is displayed in Table 14. As noted, the dose rate increases when the concentration from the GIT was considered.

The esophagus, rectum, and pyloric caeca, all of which are organs included in the GIT, had a significant increase in dose rate (1.0×10^5%, 9.6×10^4%, 8.3×10^4% respectively), when their internal concentration was included. The heart had the most significant dose rate change of the non-GIT organs of over an order of magnitude (226.41%). The reproductive organs had an increase of nearly an order of magnitude, with a percentage increase of 76.03%. The changes throughout the selected target organs can be seen in Figure 6. The non-GIT organs with the most significant dose rate change with the inclusion of the GIT contributions is displayed in Figure 7.

Table 14: Total Combined Dose Rate (Mullet) using Voxel Model

Organ	Total Combined Dose Without GIT [μGy/hr]	Total Combined Dose With GIT [μGy/hr]	Δ Dose Rate (μGy/hr)	With to Without GIT Ratio
Muscle Tissue	3.75×10^{-2}	5.08×10^{-2}	1.33×10^{-2}	1.35:1
Swim Bladder	3.01×10^{-6}	7.71×10^{-6}	4.70×10^{-6}	2.56:1
Skeleton	9.88×10^{-3}	1.02×10^{-2}	3.10×10^{-4}	1.03:1
Eyes	5.01×10^{-5}	5.38×10^{-5}	3.78×10^{-6}	1.08:1
Heart	5.61×10^{-5}	1.83×10^{-4}	1.27×10^{-4}	3.26:1
Liver	5.50×10^{-2}	5.57×10^{-2}	7.34×10^{-4}	1.01:1
Brain	1.77×10^{-5}	1.82×10^{-5}	5.47×10^{-7}	1.03:1
Esophagus	4.41×10^{-4}	4.53×10^{-1}	4.53×10^{-1}	1.03×10^{3}:1
Rectum	3.26×10^{-4}	3.12×10^{-1}	3.11×10^{-1}	9.56×10^{2}:1
Spleen	1.37×10^{-2}	1.37×10^{-2}	2.12×10^{-5}	1:1
Testes	9.20×10^{-6}	1.62×10^{-5}	6.99×10^{-6}	1.76:1
Pyloric Caeca	2.49×10^{-4}	2.06×10^{-1}	2.06×10^{-1}	8.29×10^{2}:1
Kidney	1.07×10^{-1}	1.07×10^{-1}	9.44×10^{-5}	1:1

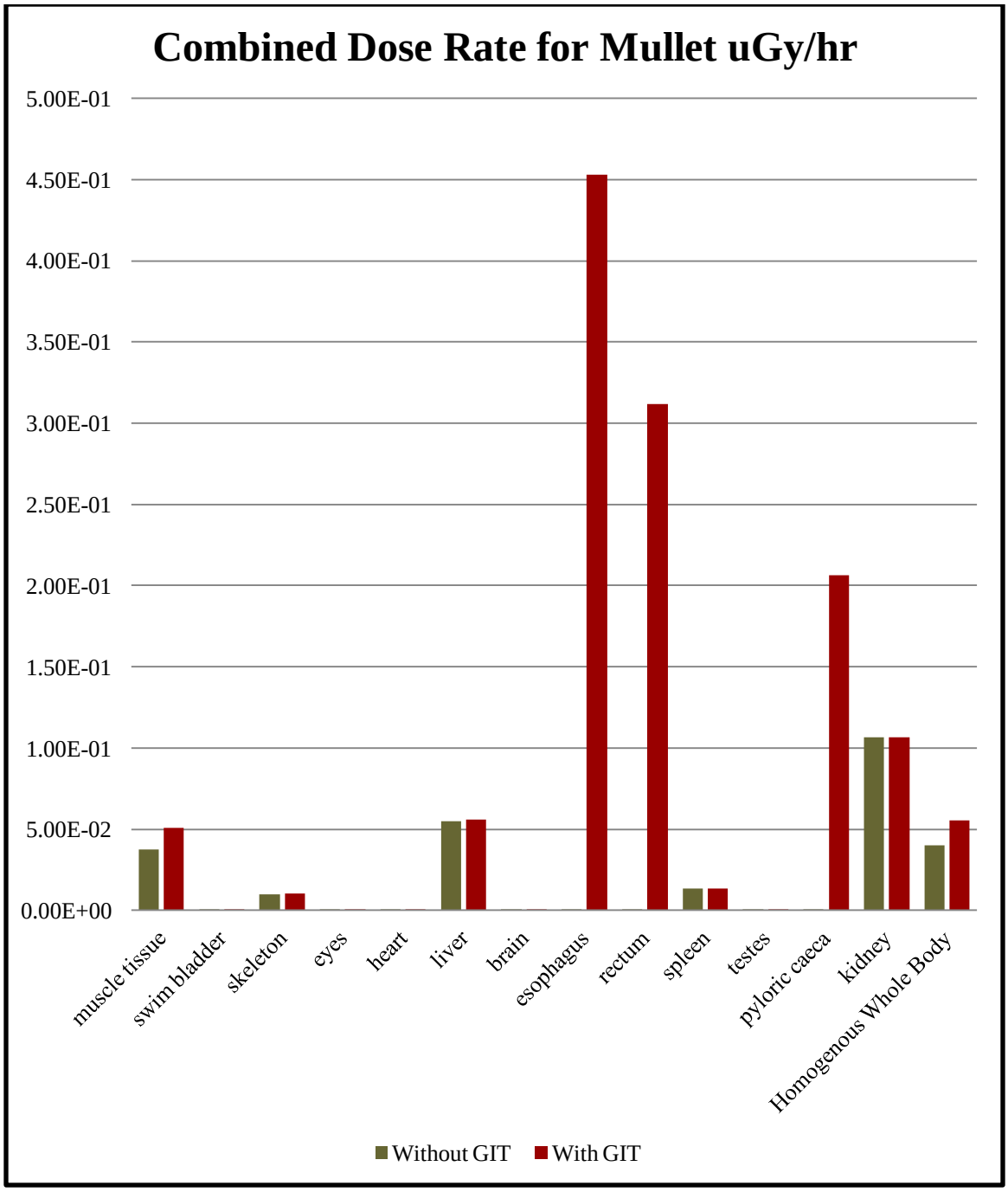

Figure 6: Combined Dose Rate (Mullet)

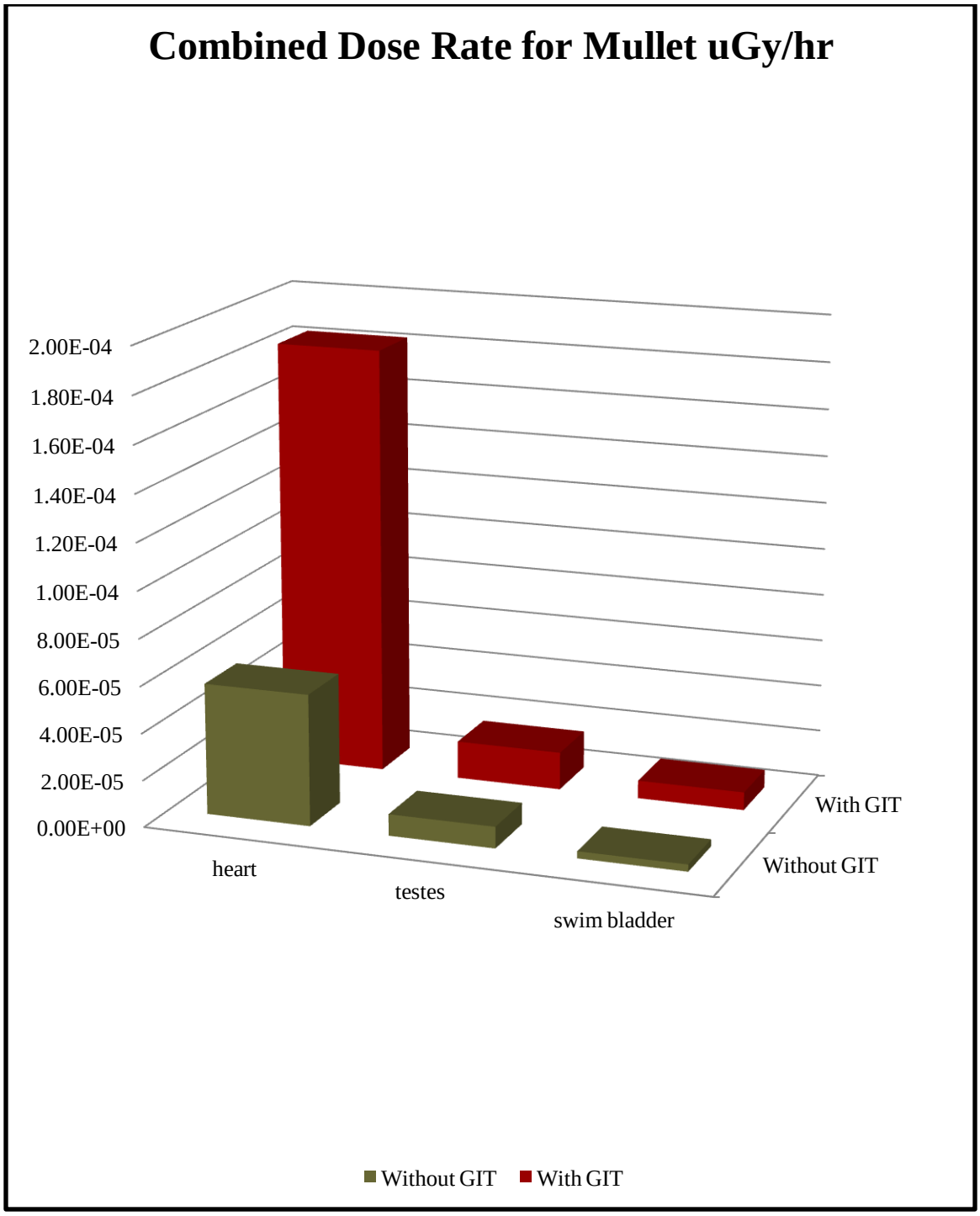

Figure 7: Combined Dose Rate Organs of Interest (Mullet)

4.02.02 Snapper

The total combined dose rate for each of the selected target organs for the Snapper, calculated with and without the contribution from the GIT is displayed in Table 15. As noted, the dose rate increases when the concentration from the GIT was included in the calculations.

The esophagus, rectum, and pyloric caeca, all of which are organs included in the GIT, had a significant increase in dose rate (588%, 80.3%, 87.5% respectively), when their internal concentration was included. The heart had the most significant dose rate change of the non-GIT organs, although considerably lower than that which was observed in the Mullet (45.6%). The spleen also showed an increase with the inclusion of the concentration from within the GIT, and was also not as significant as that which was observed in the Mullet (46.9%). The changes throughout the selected target organs can be seen in Figure 8. The non-GIT organs with the most significant dose rate change with the inclusion of the GIT contributions is displayed in Figure 9.

Table 15: Total Combined Dose (Snapper) using Voxel Model

Organ	Total Combined Dose Without GIT [μGy/hr]	Total Combined Dose With GIT [μGy/hr]	Δ Dose Rate (μGy/hr)	With to Without GIT Ratio
Muscle Tissue	2.79×10^{-2}	2.89×10^{-2}	1.02×10^{-3}	1.04:1
Swim Bladder	2.00×10^{-6}	2.31×10^{-6}	3.14×10^{-7}	1.16:1
Skeleton	6.49×10^{-3}	6.57×10^{-3}	7.87×10^{-5}	1.01:1
Eyes	4.01×10^{-5}	4.14×10^{-5}	1.31×10^{-6}	1.03:1
Heart	3.68×10^{-5}	5.36×10^{-5}	1.68×10^{-5}	1.46:1
Liver	7.84×10^{-4}	8.44×10^{-4}	6.05×10^{-5}	1.08:1
Brain	1.49×10^{-5}	1.51×10^{-5}	1.85×10^{-7}	1.01:1
Esophagus	2.88×10^{-4}	1.98×10^{-3}	1.69×10^{-3}	6.88:1
Rectum	2.59×10^{-4}	4.66×10^{-4}	2.08×10^{-4}	1.8:1
Spleen	1.71×10^{-5}	2.51×10^{-5}	8.01×10^{-6}	1.47:1
Testes	7.82×10^{-6}	9.05×10^{-6}	1.23×10^{-6}	1.16:1
Pyloric Caeca	1.95×10^{-4}	3.66×10^{-4}	1.71×10^{-4}	1.87:1
Kidney	1.66×10^{-4}	1.85×10^{-4}	1.82×10^{-6}	1.11:1

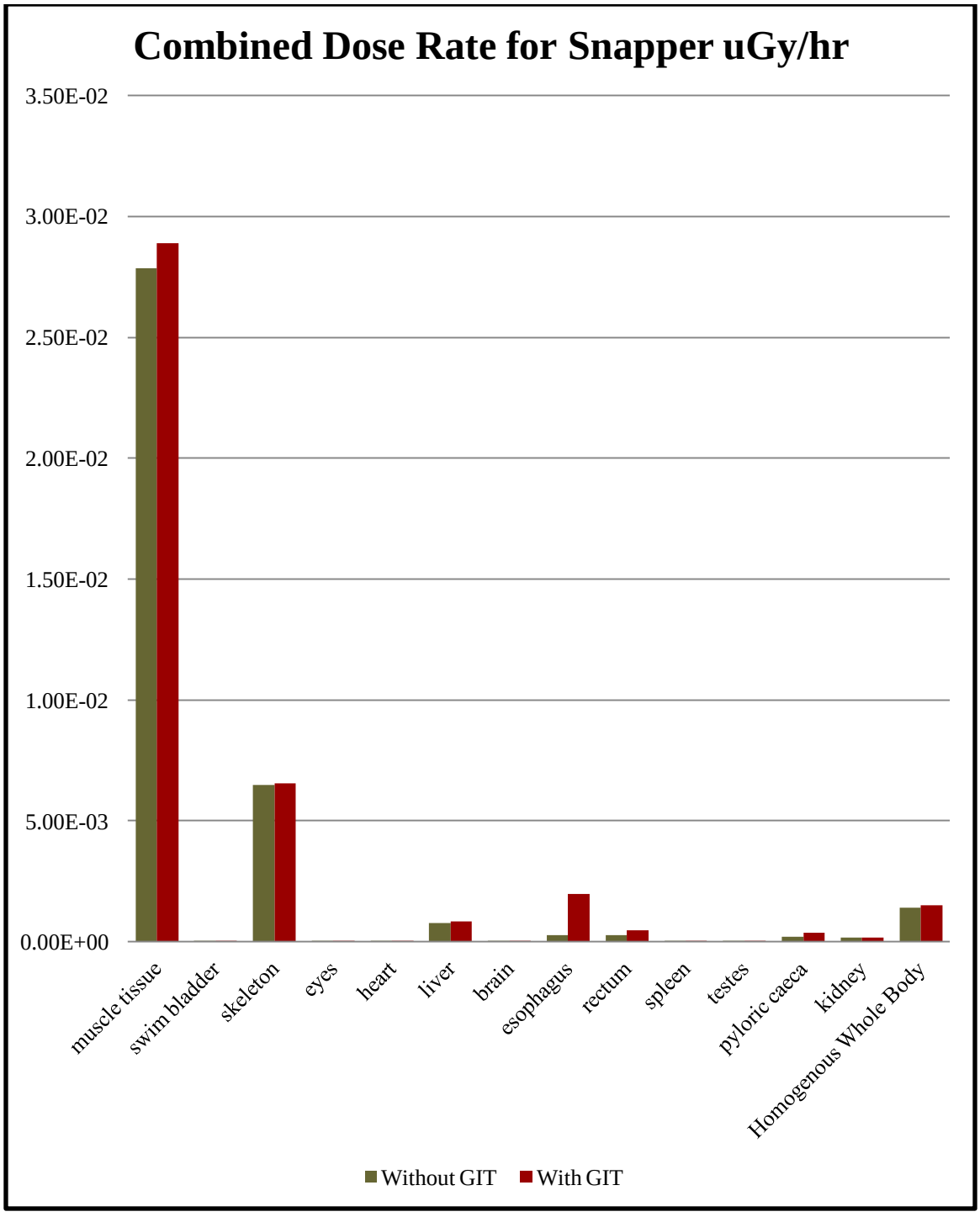

Figure 8: Combined Dose Rate (Snapper)

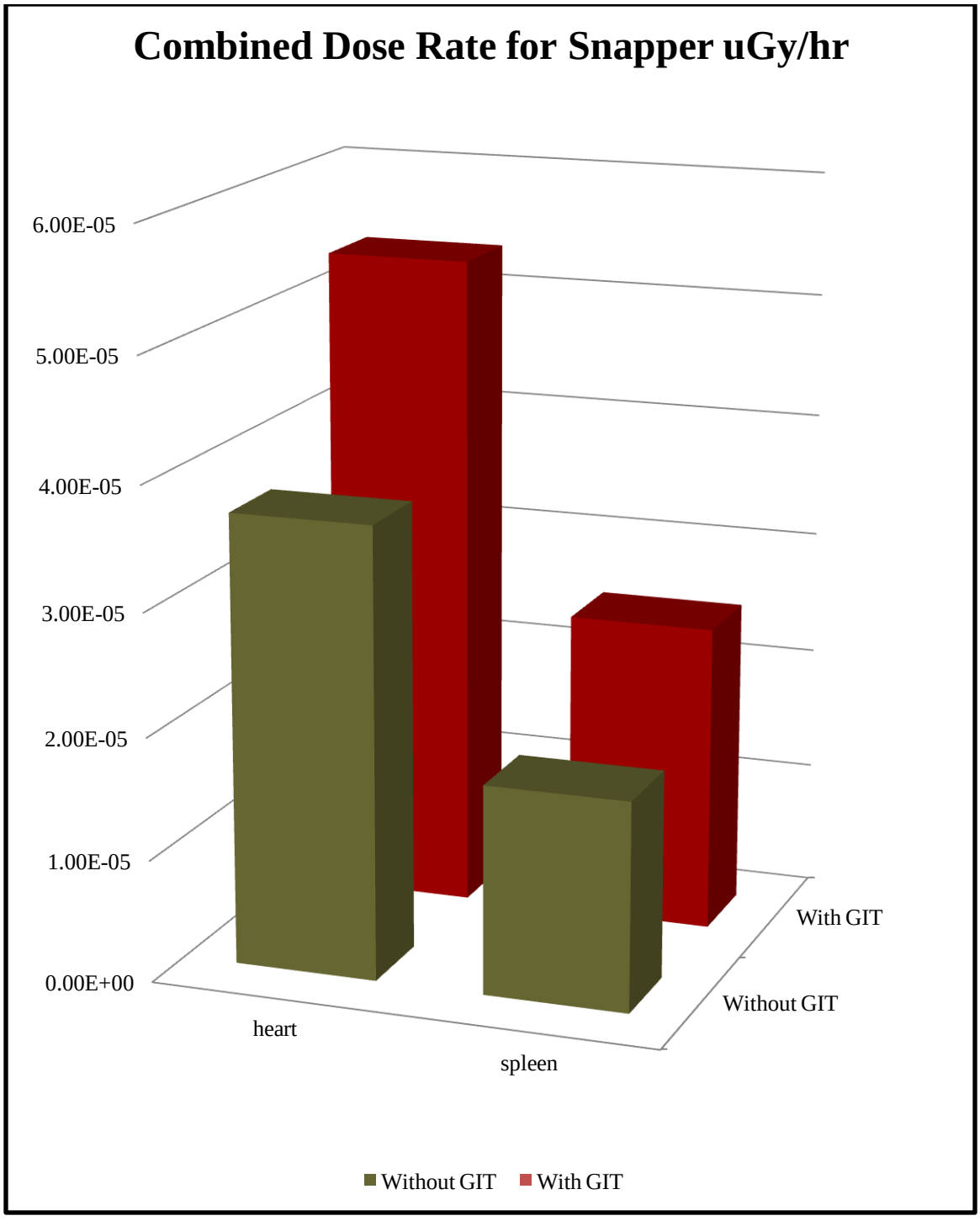

Figure 9: Combined Dose Rate Organs of Interest (Snapper)

4.02.03 Goatfish

The total combined dose rate for each of the selected target organs for the Goatfish, calculated with and without the contribution from the GIT is displayed in Table 16. As noted, the dose rate increases when the concentration from the GIT was considered.

As with the Snapper and the Mullet, the esophagus, rectum, and pyloric caeca, all of which are organs included in the GIT, had a significant increase in dose rate (3.84 x 10^4%, 3.68 x 10^4%, 2.57 x 10^4% respectively), when their internal concentration was included for the Goatfish dose rate calculations. The heart and the reproductive organ had the most significant dose rate change of the non-GIT organs, with an increase of 83.5% and 29.9%, respectively. The changes throughout the selected target organs can be seen in Figure 10. The non-GIT organs with the most significant dose rate change with the inclusion of the GIT contributions is displayed in Figure 11.

Table 16: Total Combined Dose (Goatfish) using Voxel Model

Organ	Total Combined Dose Rate Without GIT [µGy/hr]	Total Combined Dose Rate With GIT [µGy/hr]	Δ Dose Rate (µGy/hr)	With to Without GIT Ratio
Muscle Tissue	2.32×10^{-2}	2.43×10^{-2}	1.10×10^{-3}	1.05:1
Swim Bladder	2.50×10^{-6}	2.85×10^{-6}	3.46×10^{-7}	1.14:1
Skeleton	1.57×10^{-2}	1.58×10^{-2}	4.47×10^{-5}	1:1
Eyes	1.67×10^{-5}	1.73×10^{-5}	5.76×10^{-7}	1.03:1
Heart	1.48×10^{-5}	2.72×10^{-5}	1.24×10^{-5}	1.83:1
Liver	1.08×10^{-3}	1.13×10^{-3}	5.46×10^{-5}	1.05:1
Brain	6.45×10^{-6}	6.53×10^{-6}	8.33×10^{-8}	1.01:1
Esophagus	1.11×10^{-4}	4.26×10^{-2}	4.25×10^{-2}	3.85×10^{2}:1
Rectum	9.81×10^{-5}	3.62×10^{-2}	3.61×10^{-2}	3.69×10^{2}:1
Spleen	1.60×10^{-3}	1.60×10^{-3}	3.18×10^{-6}	1:1
Testes	3.52×10^{-6}	4.57×10^{-6}	1.05×10^{-6}	1.3:1
Pyloric Caeca	9.37×10^{-5}	2.41×10^{-2}	2.41×10^{-2}	2.58×10^{2}:1
Kidney	1.24×10^{-2}	1.24×10^{-2}	9.45×10^{-6}	1:1

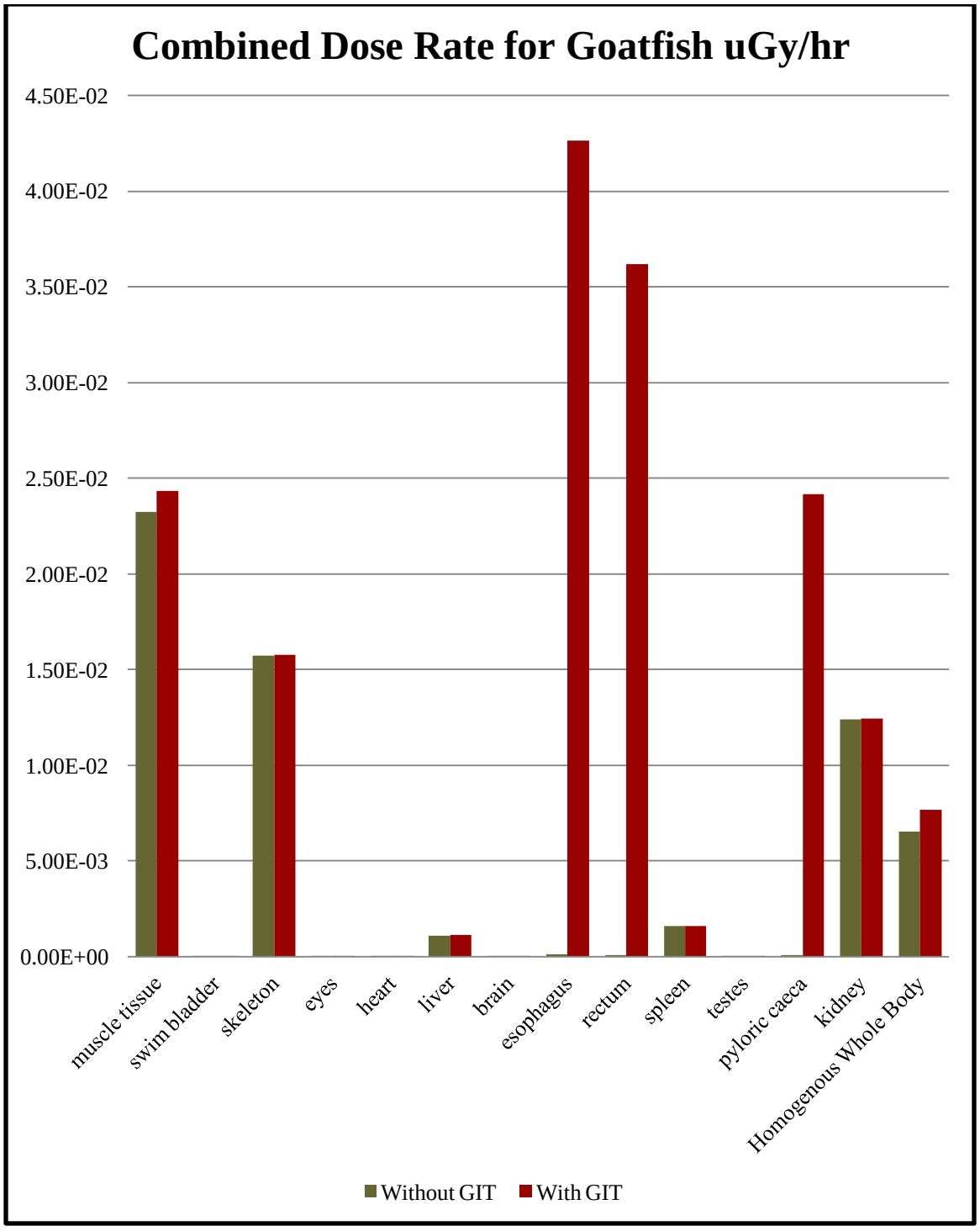

Figure 10: Combined Dose Rate (Goatfish)

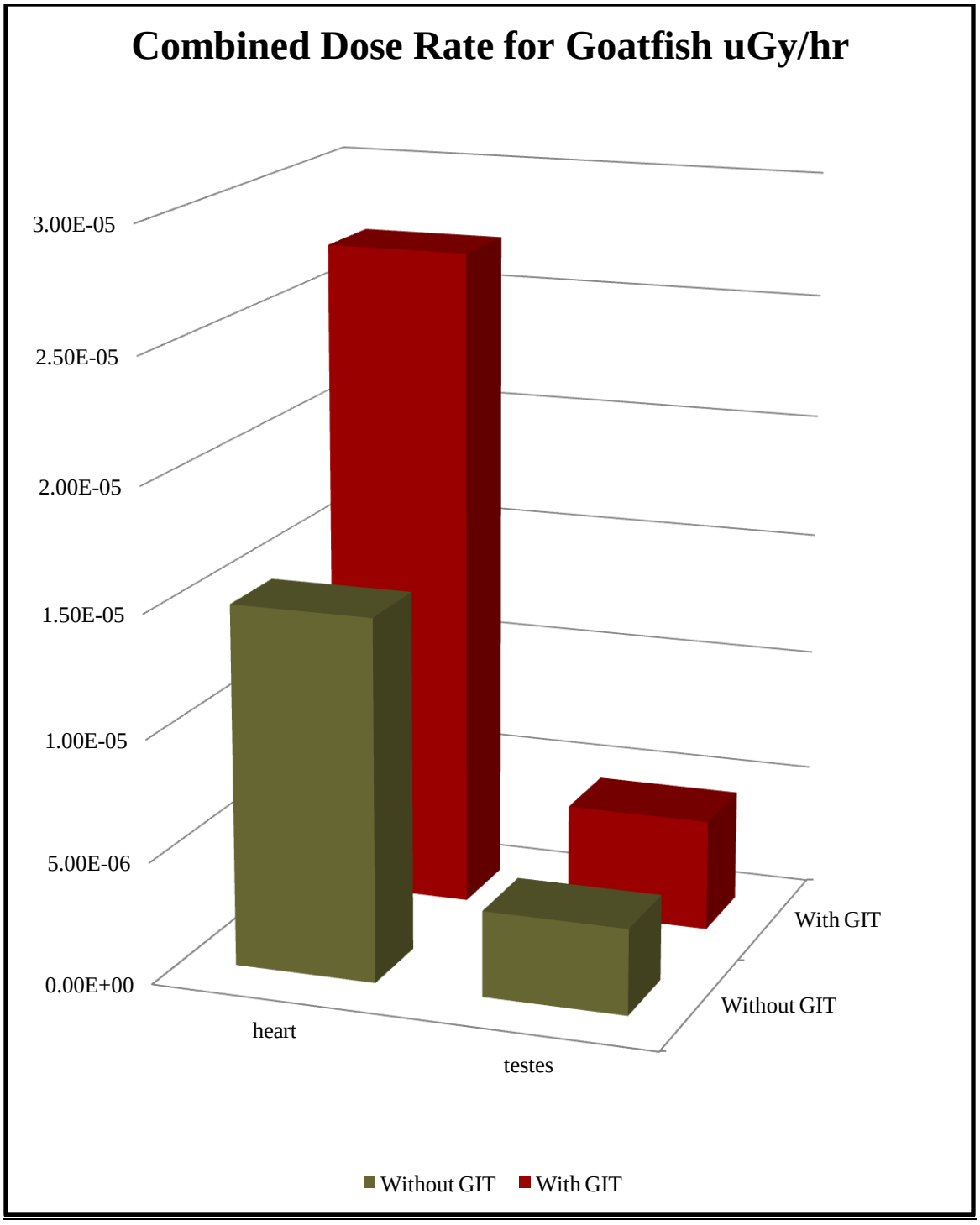

Figure 11: Combined Dose Rate Organs of Interest (Goatfish)

4.03 Homogeneous Dose Rate

Utilizing the tissue concentrations reported in section 4.02 and the DCFs reported in section 3.04.01, obtained from ICRP 108 for the Reference Trout, the combined dose rates were calculated for the Mullet, Snapper, and Goatfish using the historical homogeneous distribution method.

The dose rates with and without the inclusion of the concentrations within the GIT, as well as the percentage change is reported for the Mullet, Snapper, and Goatfish in Table 17, Table 18, and Table 19, respectively. As with the heterogeneous models, the homogenized calculations also reflected a dose rate increase with the inclusion of the concentration of the GIT. Also like the heterogeneous model, the highest percentage change was observed in the Mullet (38% of total combined dose rate), followed by the Goatfish (18% of total combined dose rate), with the most minimal change seen in the Snapper (7% of total combined dose rate).

Table 17: Homogenized Dose Rate (Mullet)

Nuclide	**Dose Rate Without GIT [µGy/hr]**	**Dose Rate With GIT [µGy/hr]**	**Δ Dose Rate (µGy/hr)**	**Percent Change**
Cs-137	1.06×10^{-3}	1.40×10^{-3}	3.34×10^{-4}	31%
Sr-90	8.28×10^{-3}	1.20×10^{-2}	3.70×10^{-3}	45%
Pu-239	2.93×10^{-3}	3.95×10^{-3}	4.87×10^{-3}	35%
Pu-240	3.54×10^{-3}	4.83×10^{-3}	6.20×10^{-3}	36%
Total	4.02×10^{-2}	5.53×10^{-2}	1.51×10^{-2}	38%

Table 18: Homogenized Dose Rate (Snapper)

Nuclide	Dose Rate Without GIT [µGy/hr]	Dose Rate With GIT [µGy/hr]	Δ Dose Rate (µGy/hr)	Percent Change
Cs-137	7.46×10^{-4}	8.34×10^{-4}	8.87×10^{-5}	12%
Sr-90	4.37×10^{-4}	4.39×10^{-4}	2.79×10^{-6}	1%
Pu-239	9.78×10^{-5}	9.85×10^{-5}	7.40×10^{-7}	1%
Pu-240	1.21×10^{-4}	1.22×10^{-4}	9.53×10^{-4}	1%
Total	1.40×10^{-3}	1.49×10^{-3}	9.31×10^{-5}	7%

Table 19: Homogenized Dose Rate (Goatfish)

Nuclide	Dose Rate Without GIT [µGy/hr]	Dose Rate With GIT [µGy/hr]	Δ Dose Rate (µGy/hr)	Percent Change
Cs-137	2.68×10^{-4}	3.19×10^{-4}	5.06×10^{-5}	19%
Sr-90	2.14×10^{-3}	2.52×10^{-3}	3.80×10^{-4}	18%
Pu-239	1.84×10^{-3}	2.17×10^{-3}	3.25×10^{-4}	18%
Pu-240	2.28×10^{-3}	2.69×10^{-3}	4.03×10^{-4}	18%
Total	6.53×10^{-3}	7.69×10^{-3}	1.16×10^{-3}	18%

Chapter 5 - Conclusion

The data calculated with the use of the voxel models shows that the organs which regularly experienced the greatest increase in dose with the inclusion of the GIT were the heart and testes. Figure 12 illustrates the positioning of the GIT organs of the Voxel-Based Trout Model created using 3D Doctor software. Figure 13 illustrates the location of the heart and testes relative to the GIT organs. The geometry of the source to target organs offers a possible explanation of the dramatic dose rate increase to the heart and testes. Determinations regarding the necessity of the inclusion of the GIT in dose rate in reference animals need to consider organs likely to receive significant dose due to geometry of the target organ from the GIT as the source as well as the target organ's radiosensitivity.

Figure 12: 3D Doctor Reference Trout GIT

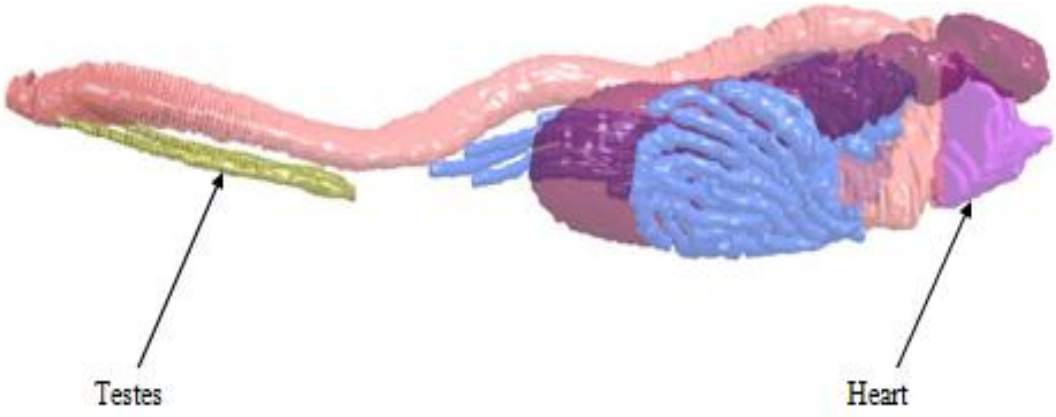

Figure 13: 3D Doctor Reference Trout GIT with Testes and Heart

Dosimetry for nonhuman biota has historically been approached with the assumption that the level of protection for humans is likely adequate to protect other species. This approach is seen in models like the homogenized model used for ICRP 108 reference animals and plants, which results in the misrepresentation of dose rate with respect to specific organs. The widely accepted standard procedure of calculating a whole body dose rate of beings with ellipsoidal geometries, homogeneous body density, and homogeneous distribution of radionuclides results in dose rates that are typically much higher than found when compared to calculations done with voxel modeling.

When comparing the individual organ dose rates calculated using the voxel models to whole body dose rates calculated using the homogeneous model, as illustrated in Table 20, Table 21, and Table 22, dose rates were over estimated by as much as a magnitude of four, and in a few instances, the dose rates were under-estimated by a magnitude of one. This can have significant impact when attempting to determine dose to risk relationships, with respect to determining deterministic effects, as the effect being observed may actually be due to a dose rate that is significantly lower, and in some cases higher, than the dose rate being attributed to the effect. When determining where to focus resources and remediation efforts, the ability to identify risks that may affect populations is essential to the decision making process regarding public health and environmental protection

Table 20: Heterogeneous vs. Homogeneous Dose Rate Comparison (Mullet)

Organ	*Without GIT [μGy/hr] (Voxel)*	*Without GIT [μGy/hr] (Homogenized)*	*% Change*	*With GIT [μGy/hr] (Voxel)*	*With GIT [μGy/hr] (Homogenized)*	*% Change*
Muscle Tissue	3.75×10^{-2}	4.02×10^{-2}	-7.1%	5.08×10^{-2}	5.53×10^{-2}	-8.9%
Swim Bladder	3.01×10^{-6}	4.02×10^{-2}	-1.3×10^{6}%	7.71×10^{-6}	5.53 x 10	-7.2×10^{5}%
Skeleton	9.88×10^{-3}	4.02×10^{-2}	-3.4×10^{2}%	1.02×10^{-2}	5.53 x 10	-4.4×10^{2}%
Eyes	5.01×10^{-5}	4.02×10^{-2}	-8.0×10^{4}%	5.38×10^{-5}	5.53 x 10	-1.0×10^{5}%
Heart	5.61×10^{-5}	4.02×10^{-2}	-7.1×10^{4}%	1.83×10^{-4}	5.53 x 10	-3.0×10^{4}%
Liver	5.50×10^{-2}	4.02×10^{-2}	27%	5.57×10^{-2}	5.53 x 10	0.81%
Brain	1.77×10^{-5}	4.02×10^{-2}	-2.7×10^{5}%	1.82×10^{-5}	5.53 x 10	-3.0×10^{5}%
Esophagus	4.41×10^{-4}	4.02 x 10	-9.0×10^{3}%	4.53×10^{-1}	5.53 x 10	88%
Rectum	3.26×10^{-4}	4.02 x 10	-1.2×10^{4}%	3.12×10^{-1}	5.53 x 10	82%
Spleen	1.37×10^{-2}	4.02 x 10	-1.9×10^{2}%	1.37×10^{-2}	5.53 x 10	-3.0×10^{2}%
Testes	9.20×10^{-6}	4.02 x 10	-4.4×10^{5}%	1.62×10^{-5}	5.53 x 10	-3.4×10^{5}%
Pyloric Caeca	2.49×10^{-4}	4.02 x 10	-1.6×10^{4}%	2.06×10^{-1}	5.53 x 10	73%
Kidney	1.07×10^{-1}	4.02x10	62%	1.0×10^{-5}	5.53 x 10	48%

Table 21: Heterogeneous vs. Homogeneous Dose Rate Comparison (Snapper)

Organ	*Without GIT [μGy/hr] (Voxel)*	*Without GIT [μGy/hr] (Homogenized)*	*% Change*	*With GIT [μGy/hr] (Voxel)*	*With GIT [μGy/hr] (Homogenized)*	*% Change*
Muscle Tissue	2.79×10^{-2}	1.40×10^{-3}	95%	2.89×10^{-2}	1.49×10^{-3}	95%
Swim Bladder	2.00×10^{-6}	1.40×10^{-3}	-7.0×10^{4}%	2.31×10^{-6}	1.49×10^{-3}	-6.4×10^{4}%
Skeleton	6.49×10^{-3}	1.40×10^{-3}	78%	6.57×10^{-3}	1.49×10^{-3}	77%
Eyes	4.01×10^{-5}	1.40×10^{-3}	-3.4×10^{3} %	4.14×10^{-5}	1.49×10^{-3}	-3.5×10^{3}%
Heart	3.68×10^{-5}	1.40×10^{-3}	-3.7×10^{3} %	5.36×10^{-5}	1.49×10^{-3}	-2.7×10^{3}%
Liver	7.84×10^{-4}	1.40×10^{-3}	-79%	8.44×10^{-4}	1.49×10^{-3}	-77%
Brain	1.49×10^{-5}	1.40×10^{-3}	-9.3×10^{3} %	1.51×10^{-5}	1.49×10^{-3}	-9.8×10^{3}%
Esophagus	2.88×10^{-4}	1.40×10^{-3}	-3.9×10^{2} %	1.98×10^{-3}	1.49×10^{-3}	25%
Rectum	2.59×10^{-4}	1.40×10^{-3}	-4.4×10^{2} %	4.66×10^{-4}	1.49×10^{-3}	-2.2×10^{2}%
Spleen	1.71×10^{-5}	1.40×10^{-3}	-8.1×10^{3} %	2.51×10^{-5}	1.49×10^{-3}	-5.9×10^{3}%
Testes	7.82×10^{-6}	1.40×10^{-3}	-1.8×10^{4} %	9.05×10^{-6}	1.49×10^{-3}	-1.6×10^{4}%
Pyloric Caeca	1.95×10^{-4}	1.40×10^{-3}	-6.1×10^{2}%	3.66×10^{-4}	1.49×10^{-3}	-3.1×10^{2}%
Kidney	1.66×10^{-4}	1.40×10^{-3}	-7.4×10^{2}%	1.85×10^{-4}	1.49×10^{-3}	-7.1×10^{2}%

Table 22: Heterogeneous vs. Homogeneous Dose Rate Comparison (Goatfish)

Organ	*Without GIT [μGy/hr] (Voxel)*	*Without GIT [μGy/hr] (Homogenized)*	*% Change*	*With GIT [μGy/hr] (Voxel)*	*With GIT [μGy/hr] (Homogenized)*	*% Change*
Muscle Tissue	2.32×10^{-2}	6.53×10^{-3}	72%	2.43×10^{-2}	7.69×10^{-3}	68%
Swim Bladder	2.50×10^{-6}	6.53×10^{-3}	-2.6×10^{5} %	2.85×10^{-6}	7.69×10^{-3}	-2.7×10^{5}%
Skeleton	1.57×10^{-2}	6.53×10^{-3}	58%	1.58×10^{-2}	7.69×10^{-3}	51%
Eyes	1.67×10^{-5}	6.53×10^{-3}	-3.9×10^{4}%	1.73×10^{-5}	7.69×10^{-3}	-4.4×10^{4}%
Heart	1.48×10^{-5}	6.53×10^{-3}	-4.4×10^{4}%	2.72×10^{-5}	7.69×10^{-3}	-2.8×10^{4}%
Liver	1.08×10^{-3}	6.53×10^{-3}	-5.1×10^{2}%	1.13×10^{-3}	7.69×10^{-3}	-5.8×10^{2}%
Brain	6.45×10^{-6}	6.53×10^{-3}	-1.0×10^{5}%	6.53×10^{-6}	7.69×10^{-3}	-1.2×10^{5}%
Esophagus	1.11×10^{-4}	6.53×10^{-3}	-5.8×10^{3}%	4.26×10^{-2}	7.69×10^{-3}	82%
Rectum	9.81×10^{-5}	6.53×10^{-3}	-6.6×10^{3}%	3.62×10^{-2}	7.69×10^{-3}	79%
Spleen	1.60×10^{-3}	6.53×10^{-3}	-3.1×10^{2}%	1.60×10^{-3}	7.69×10^{-3}	-3.8×10^{2}%
Testes	3.52×10^{-6}	6.53×10^{-3}	-1.9×10^{5}%	4.57×10^{-6}	7.69×10^{-3}	-1.7×10^{5}%
Pyloric Caeca	9.37×10^{-5}	6.53×10^{-3}	-6.9×10^{3}%	2.41×10^{-2}	7.69×10^{-3}	68%
Kidney	1.24×10^{-2}	6.53×10^{-3}	47%	1.24×10^{-2}	7.69×10^{-3}	38%

The historical approach of viewing the protection of species being primarily for the purposes of human protection led to such practices as discarding the gastrointestinal tract for the purposes of determining internal dose rate. This practice can result in an underestimate of dose rate by more than an order of magnitude. It is unclear at this time what the consequence of this is. To better understand the deterministic effects, particularly to organs which can have significant effects to populations (i.e. reproductive organs), similar voxel models will need to be done on the remaining reference animals and plants, as well as potentially expanding the categories of reference plants and animals. This will also aid in our understanding of radiation protection, which can be used to improve the measures taken to prevent releases and remediation techniques.

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Appendix

Table 23: Cs-137 Absorbed Fraction

#1 Energy (keV): 661 Average Energy (keV): 661.0 Yield: 0.851 Type: Gamma

TARGET												
SOURCE	Muscle Tissue	Swim Bladder	Skeleton	Eyes	Heart	Liver	Brain	Esophagus	Rectum	Spleen	Testes	Pyloric Caeca	Kidney
Muscle Tissue	3.59E-01	2.89E-05	2.53E-02	1.14E-03	1.04E-03	4.48E-03	4.22E-04	8.21E-03	7.37E-03	3.26E-04	2.23E-04	5.33E-03	3.43E-03
Skeleton	3.12E-01	3.06E-05	7.59E-02	1.58E-03	1.27E-03	5.59E-03	8.72E-04	7.29E-03	6.53E-03	1.43E-04	1.80E-04	3.83E-03	6.03E-03
Liver	2.77E-01	5.21E-05	2.91E-02	5.10E-04	9.39E-03	9.06E-02	5.97E-05	3.03E-02	9.29E-03	2.62E-04	5.25E-05	1.45E-02	4.02E-03
Esophagus	2.67E-01	8.41E-05	2.09E-02	3.52E-04	4.50E-03	1.59E-02	4.99E-05	1.04E-01	2.01E-02	2.17E-03	3.18E-04	2.23E-02	4.87E-03
Rectum	2.80E-01	7.10E-05	2.13E-02	2.49E-04	3.56E-03	5.69E-03	3.81E-05	2.33E-02	8.65E-02	7.91E-04	8.78E-04	2.02E-02	2.78E-03
Spleen	2.77E-01	6.54E-05	1.12E-02	5.41E-05	7.30E-04	3.50E-03	8.49E-06	5.52E-02	1.74E-02	4.38E-02	7.03E-04	1.79E-02	8.46E-04
Testes	2.40E-01	2.49E-05	1.63E-02	2.94E-05	2.51E-04	9.16E-04	8.34E-06	1.06E-02	2.58E-02	9.15E-04	3.52E-02	5.50E-03	4.80E-04
Pyloric Caeca	2.74E-01	5.21E-05	1.73E-02	1.30E-04	3.10E-03	1.21E-02	1.78E-05	3.52E-02	2.73E-02	1.10E-03	2.60E-04	5.92E-02	1.43E-03
Kidney	3.81E-01	6.00E-05	5.53E-02	2.32E-03	1.57E-03	7.29E-03	3.91E-04	1.68E-02	8.21E-03	1.13E-04	5.10E-05	3.09E-03	6.43E-02

#2 Energy (keV): 513 Average Energy (keV): 171.0 Yield: 0.944 Type: Beta

TARGET												
SOURCE	Muscle Tissue	Swim Bladder	Skeleton	Eyes	Heart	Liver	Brain	Esophagus	Rectum	Spleen	Testes	Pyloric Caeca	Kidney
Muscle Tissue	9.95E-01	5.35E-05	1.80E-03	0.00E+00	0.00E+00	1.20E-04	0.00E+00	2.19E-04	2.76E-04	0.00E+00	0.00E+00	5.83E-04	1.45E-04
Skeleton	2.63E-02	4.95E-05	9.72E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Liver	7.67E-03	0.00E+00	1.14E-04	0.00E+00	9.03E-04	9.87E-01	0.00E+00	1.52E-03	1.17E-03	0.00E+00	0.00E+00	9.12E-04	2.21E-04
Esophagus	7.27E-03	0.00E+00	4.61E-05	0.00E+00	0.00E+00	7.88E-04	0.00E+00	9.91E-01	7.16E-05	0.00E+00	0.00E+00	4.66E-04	1.23E-04
Rectum	1.02E-02	0.00E+00	8.03E-05	0.00E+00	2.59E-04	7.39E-04	0.00E+00	7.70E-05	9.87E-01	0.00E+00	0.00E+00	1.03E-03	0.00E+00
Spleen	1.43E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.67E-05	0.00E+00	9.85E-01	0.00E+00	0.00E+00	0.00E+00
Testes	2.34E-02	0.00E+00	3.70E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.30E-04	0.00E+00	9.76E-01	0.00E+00	0.00E+00
Pyloric Caeca	2.95E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.06E-04	0.00E+00	6.71E-04	1.45E-03	0.00E+00	0.00E+00	9.67E-01	0.00E+00
Kidney	1.62E-02	0.00E+00	2.60E-04	0.00E+00	0.00E+00	4.15E-04	0.00E+00	4.45E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.82E-01

#3 Energy (keV): 1175 Average Energy (keV): 397.1 Yield: 0.036 Type: Beta

TARGET												
SOURCE	Muscle Tissue	Swim Bladder	Skeleton	Eyes	Heart	Liver	Brain	Esophagus	Rectum	Spleen	Testes	Pyloric Caeca	Kidney
Muscle Tissue	9.83E-01	5.74E-05	6.00E-03	1.92E-04	1.46E-04	4.07E-04	7.39E-05	7.80E-04	9.14E-04	6.07E-05	7.90E-05	1.94E-03	4.86E-04
Skeleton	9.07E-02	6.29E-05	9.04E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.35E-05
Liver	2.59E-02	0.00E+00	2.90E-04	0.00E+00	3.05E-03	9.57E-01	0.00E+00	5.17E-03	4.02E-03	0.00E+00	0.00E+00	3.29E-03	7.84E-04
Esophagus	2.45E-02	0.00E+00	9.44E-05	0.00E+00	0.00E+00	2.67E-03	0.00E+00	9.70E-01	2.30E-04	0.00E+00	0.00E+00	1.57E-03	4.27E-04
Rectum	3.44E-02	4.31E-05	2.14E-04	0.00E+00	8.64E-04	2.48E-03	0.00E+00	2.50E-04	9.57E-01	0.00E+00	0.00E+00	3.38E-03	0.00E+00
Spleen	4.87E-02	0.00E+00	3.73E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.29E-04	3.12E-05	9.50E-01	0.00E+00	1.84E-04	0.00E+00
Testes	7.89E-02	0.00E+00	7.38E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.35E-04	0.00E+00	9.20E-01	0.00E+00	0.00E+00
Pyloric Caeca	1.00E-01	0.00E+00	1.05E-04	0.00E+00	0.00E+00	2.75E-03	0.00E+00	2.36E-03	4.94E-03	0.00E+00	0.00E+00	8.89E-01	0.00E+00
Kidney	5.49E-02	3.99E-05	7.78E-04	0.00E+00	0.00E+00	1.43E-03	0.00E+00	1.44E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.41E-01

Table 24: Sr-90 Absorbed Fraction

#1	Energy (keV): 564		Average Energy (keV): 188.0				Yield: 1					Type: Beta	
	TARGET												
SOURCE	Muscle Tissue	Swim Bladde	Skeleton	Eyes	Heart	Liver	Brain	Esophagus	Rectum	Spleen	Testes	Pyloric Caeca	Kidney
Muscle Tissue	9.94E-01	5.57E-05	2.06E-03	0.00E+00	0.00E+00	1.38E-04	0.00E+00	2.51E-04	3.16E-04	0.00E+00	0.00E+00	6.70E-04	1.66E-04
Skeleton	3.03E-02	5.34E-05	9.68E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Liver	8.81E-03	0.00E+00	1.29E-04	0.00E+00	1.03E-03	9.85E-01	0.00E+00	1.74E-03	1.35E-03	0.00E+00	0.00E+00	1.05E-03	2.56E-04
Esophagus	8.34E-03	0.00E+00	5.12E-05	0.00E+00	0.00E+00	9.05E-04	0.00E+00	9.90E-01	8.07E-05	0.00E+00	0.00E+00	5.34E-04	1.42E-04
Rectum	1.17E-02	0.00E+00	9.13E-05	0.00E+00	2.95E-04	8.46E-04	0.00E+00	8.76E-05	9.85E-01	0.00E+00	0.00E+00	1.19E-03	0.00E+00
Spleen	1.64E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.29E-05	0.00E+00	9.83E-01	0.00E+00	0.00E+00	0.00E+00
Testes	2.69E-02	0.00E+00	4.06E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.48E-04	0.00E+00	9.73E-01	0.00E+00	0.00E+00
Pyloric Caeca	3.39E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.26E-04	0.00E+00	7.73E-04	1.66E-03	0.00E+00	0.00E+00	9.62E-01	0.00E+00
Kidney	1.86E-02	0.00E+00	2.94E-04	0.00E+00	0.00E+00	4.78E-04	0.00E+00	5.10E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.80E-01

Table 25: Pu-239 Absorbed Fraction

#1	Energy (keV): 5.245 E+3		Average Energy (keV): 5.245 E+3				Yield: 1					Type: Alpha	
	TARGET												
SOURCE	Muscle Tissue	Swim Bladder	Skeleton	Eyes	Heart	Liver	Brain	Esophagus	Rectum	Spleen	Testes	Pyloric Caeca	Kidney
Muscle Tissue	1	0	0	0	0	0	0	0	0	0	0	0	0
Skeleton	0	0	1	0	0	0	0	0	0	0	0	0	0
Liver	0	0	0	0	0	1	0	0	0	0	0	0	0
Esophagus	0	0	0	0	0	0	0	1	0	0	0	0	0
Rectum	0	0	0	0	0	0	0	0	1	0	0	0	0
Spleen	0	0	0	0	0	0	0	0	0	1	0	0	0
Testes	0	0	0	0	0	0	0	0	0	0	1	0	0
Pyloric Caeca	0	0	0	0	0	0	0	0	0	0	0	1	0
Kidney	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 26: Pu-240 Absorbed Fraction

#1	Energy (keV): 5.256 E+3		Average Energy (keV): 5.256 E+3				Yield: 1					Type: Alpha	
	TARGET												
SOURCE	Muscle Tissue	Swim Bladder	Skeleton	Eyes	Heart	Liver	Brain	Esophagus	Rectum	Spleen	Testes	Pyloric Caeca	Kidney
Muscle Tissue	1	0	0	0	0	0	0	0	0	0	0	0	0
Skeleton	0	0	1	0	0	0	0	0	0	0	0	0	0
Liver	0	0	0	0	0	1	0	0	0	0	0	0	0
Esophagus	0	0	0	0	0	0	0	1	0	0	0	0	0
Rectum	0	0	0	0	0	0	0	0	1	0	0	0	0
Spleen	0	0	0	0	0	0	0	0	0	1	0	0	0
Testes	0	0	0	0	0	0	0	0	0	0	1	0	0
Pyloric Caeca	0	0	0	0	0	0	0	0	0	0	0	1	0
Kidney	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 27: Cs-137 Voxelized DCFs

Source	Target	DCF (uGy/kg/Bq d)
Muscle	muscle tissue	5.02E-03
	swim bladder	3.45E-07
	skeleton	2.05E-04
	eyes	8.91E-06
	heart	8.11E-06
	liver	3.51E-05
	brain	3.29E-06
	esophagus	6.44E-05
	rectum	5.80E-05
	spleen	2.54E-06
	testes	1.73E-06
	pyloric caeca	4.28E-05
	kidney	2.70E-05
Skeleton	muscle tissue	2.52E-03
	swim bladder	3.68E-07
	skeleton	3.04E-03
	eyes	1.23E-05
	heart	9.87E-06
	liver	4.35E-05
	brain	6.79E-06
	esophagus	5.68E-05
	rectum	5.10E-05
	spleen	1.11E-06
	testes	1.40E-06
	pyloric caeca	2.98E-05
	kidney	4.70E-05
Liver	muscle tissue	2.18E-03
	swim bladder	4.05E-07
	skeleton	2.27E-04
	eyes	3.97E-06
	heart	7.61E-05
	liver	3.20E-03
	brain	4.65E-07
	esophagus	2.41E-04
	rectum	7.62E-05
	spleen	2.04E-06
	testes	4.09E-07
	pyloric caeca	1.16E-04
	kidney	3.20E-05
Spleen	muscle tissue	2.20E-03
	swim bladder	5.09E-07
	skeleton	8.71E-05
	eyes	4.21E-07
	heart	5.69E-06
	liver	2.73E-05
	brain	6.61E-08
	esophagus	4.30E-04
	rectum	1.36E-04
	spleen	2.83E-03
	testes	5.49E-06
	pyloric caeca	1.39E-04
	kidney	6.59E-06

Source	Target	DCF (uGy/kg/Bq d)
Kidney	muscle tissue	3.02E-03
	swim bladder	4.79E-07
	skeleton	4.16E-04
	eyes	1.81E-05
	heart	1.22E-05
	liver	5.81E-05
	brain	3.04E-06
	esophagus	1.32E-04
	rectum	6.39E-05
	spleen	8.78E-07
	testes	3.97E-07
	pyloric caeca	2.41E-05
	kidney	2.98E-03
Esophagus	muscle tissue	2.10E-03
	swim bladder	6.55E-07
	skeleton	1.63E-04
	eyes	2.74E-06
	heart	3.50E-05
	liver	1.27E-04
	brain	3.88E-07
	esophagus	3.32E-03
	rectum	1.56E-04
	spleen	1.69E-05
	testes	2.47E-06
	pyloric caeca	1.75E-04
	kidney	3.83E-05
Rectum	muscle tissue	2.21E-03
	swim bladder	5.66E-07
	skeleton	1.66E-04
	eyes	1.94E-06
	heart	2.86E-05
	liver	4.67E-05
	brain	2.96E-07
	esophagus	1.81E-04
	rectum	3.17E-03
	spleen	6.16E-06
	testes	6.84E-06
	pyloric caeca	1.60E-04
	kidney	2.17E-05
Pyloric Caeca	muscle tissue	2.23E-03
	swim bladder	4.06E-07
	skeleton	1.35E-04
	eyes	1.01E-06
	heart	2.42E-05
	liver	9.70E-05
	brain	1.39E-07
	esophagus	2.76E-04
	rectum	2.17E-04
	spleen	8.55E-06
	testes	2.02E-06
	pyloric caeca	2.89E-03
	kidney	1.11E-05

Table 28: Sr-90 Voxelized DCFs

Source	Target	DCF (uGy kg/ Bq d)
Muscle	muscle tissue	2.59E-03
	swim bladder	1.45E-07
	skeleton	5.37E-06
	eyes	0.00E+00
	heart	0.00E+00
	liver	3.58E-07
	brain	0.00E+00
	esophagus	6.53E-07
	rectum	8.23E-07
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	1.74E-06
	kidney	4.31E-07
Skeleton	muscle tissue	7.88E-05
	swim bladder	1.39E-07
	skeleton	2.52E-03
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Liver	muscle tissue	2.29E-05
	swim bladder	0.00E+00
	skeleton	3.37E-07
	eyes	0.00E+00
	heart	2.68E-06
	liver	2.56E-03
	brain	0.00E+00
	esophagus	4.53E-06
	rectum	3.50E-06
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	2.74E-06
	kidney	6.67E-07
Spleen	muscle tissue	4.27E-05
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	1.90E-07
	rectum	0.00E+00
	spleen	2.56E-03
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00

Source	Target	DCF (uGy kg/ Bq d)
Kidney	muscle tissue	4.84E-05
	swim bladder	0.00E+00
	skeleton	7.65E-07
	eyes	0.00E+00
	heart	0.00E+00
	liver	1.24E-06
	brain	0.00E+00
	esophagus	1.33E-06
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	2.55E-03
Esophagus	muscle tissue	2.17E-05
	swim bladder	0.00E+00
	skeleton	1.33E-07
	eyes	0.00E+00
	heart	0.00E+00
	liver	2.36E-06
	brain	0.00E+00
	esophagus	2.58E-03
	rectum	2.10E-07
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	1.39E-06
	kidney	3.69E-07
Rectum	muscle tissue	3.03E-05
	swim bladder	0.00E+00
	skeleton	2.38E-07
	eyes	0.00E+00
	heart	7.67E-07
	liver	2.20E-06
	brain	0.00E+00
	esophagus	2.28E-07
	rectum	2.56E-03
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	3.10E-06
	kidney	0.00E+00
Pyloric Caeca	muscle tissue	8.82E-05
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	2.41E-06
	brain	0.00E+00
	esophagus	2.01E-06
	rectum	4.32E-06
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	2.51E-03
	kidney	0.00E+00

Table 29: Pu-239 Voxelized DCFs

Source	Target	DCF (uGy/kg/Bq/d)
Muscle	muscle tissue	7.26E-02
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Skeleton	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	7.26E-02
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Liver	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	7.26E-02
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Spleen	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	7.26E-02
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00

Source	Target	DCF (uGy/kg/Bq/d)
Kidney	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	7.26E-02
Esophagus	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	7.26E-02
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Rectum	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	7.26E-02
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Pyloric Caeca	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	7.26E-02
	kidney	0.00E+00

Table 30: Pu240 Voxelized DCFs

Source	Target	DCF (uGy kg/ Bq d)
Muscle	muscle tissue	7.28E-02
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Skeleton	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	7.28E-02
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Liver	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	7.28E-02
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Spleen	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	7.28E-02
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00

Source	Target	DCF (uGy kg/ Bq d)
Kidney	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	7.28E-02
Esophagus	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	7.28E-02
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Rectum	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	7.28E-02
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	0.00E+00
	kidney	0.00E+00
Pyloric Caeca	muscle tissue	0.00E+00
	swim bladder	0.00E+00
	skeleton	0.00E+00
	eyes	0.00E+00
	heart	0.00E+00
	liver	0.00E+00
	brain	0.00E+00
	esophagus	0.00E+00
	rectum	0.00E+00
	spleen	0.00E+00
	testes	0.00E+00
	pyloric caeca	7.28E-02
	kidney	0.00E+00

Table 31: Voxelized Combined Dose (Mullet)

^{137}Cs Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	2.63E-02	3.02E-02
Swim Bladder	1.91E-06	2.93E-06
Skeleton	1.16E-03	1.45E-03
Eyes	4.93E-05	5.29E-05
Heart	5.51E-05	1.10E-04
Liver	6.77E-04	8.45E-04
Brain	1.73E-05	1.78E-05
Esophagus	4.00E-04	3.03E-03
Rectum	3.21E-04	2.48E-03
Spleen	9.00E-05	1.10E-04
Testes	9.00E-06	1.60E-05
Pyloric caeca	2.42E-04	1.88E-03
Kidney	7.70E-04	8.16E-04
^{90}Sr Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	6.46E-04	1.34E-03
Swim Bladder	8.26E-08	8.26E-08
Skeleton	9.68E-04	9.70E-04
Eyes	0.00E+00	0.00E+00
Heart	3.60E-08	3.77E-06
Liver	3.66E-05	7.22E-05
Brain	0.00E+00	0.00E+00
Esophagus	2.46E-06	1.47E-02
Rectum	2.14E-07	1.25E-02
Spleen	5.50E-04	5.50E-04
Testes	0.00E+00	0.00E+00
Pyloric caeca	3.91E-07	1.20E-02
Kidney	4.27E-03	4.27E-03
^{239}Pu Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	3.22E-03	3.22E-03
Swim Bladder	0.00E+00	0.00E+00
Skeleton	2.30E-03	2.30E-03
Eyes	0.00E+00	0.00E+00
Heart	0.00E+00	0.00E+00
Liver	2.43E-02	2.43E-02
Brain	0.00E+00	0.00E+00
Esophagus	0.00E+00	1.37E-01
Rectum	0.00E+00	1.17E-01
Spleen	5.16E-03	5.16E-03
Testes	0.00E+00	0.00E+00
Pyloric caeca	0.00E+00	1.10E-01
Kidney	4.01E-02	4.01E-02
Muscle Tissue	3.22E-03	3.22E-03
Swim Bladder	0.00E+00	0.00E+00
^{240}Pu Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	3.94E-03	3.94E-03
Swim Bladder	0.00E+00	0.00E+00
Skeleton	2.81E-03	2.81E-03
Eyes	0.00E+00	0.00E+00
Heart	0.00E+00	0.00E+00
Liver	2.98E-02	2.98E-02
Brain	0.00E+00	0.00E+00
Esophagus	0.00E+00	1.67E-01
Rectum	0.00E+00	1.43E-01
Spleen	6.31E-03	6.31E-03
Testes	0.00E+00	0.00E+00
Pyloric caeca	0.00E+00	1.35E-01
Kidney	4.91E-02	4.91E-02

Table 32: Voxelized Combined Dose (Snapper)

^{137}Cs Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	2.20E-02	2.31E-02
Swim Bladder	1.52E-06	1.72E-06
Skeleton	9.41E-04	1.01E-03
Eyes	3.92E-05	3.97E-05
Heart	3.63E-05	4.82E-05
Liver	1.83E-04	2.30E-04
Brain	1.45E-05	1.46E-05
Esophagus	2.85E-04	4.53E-04
Rectum	2.55E-04	3.88E-04
Spleen	1.24E-05	1.66E-05
Testes	7.58E-06	8.61E-06
Pyloric caeca	1.89E-04	1.53E-03
Kidney	1.29E-04	1.35E-04
^{90}Sr Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	6.70E-04	6.70E-04
Swim Bladder	9.70E-08	9.70E-08
Skeleton	1.12E-03	1.12E-03
Eyes	0.00E+00	0.00E+00
Heart	1.88E-09	2.05E-09
Liver	1.89E-06	1.89E-06
Brain	0.00E+00	0.00E+00
Esophagus	1.63E-07	8.20E-07
Rectum	2.04E-07	7.64E-07
Spleen	2.46E-08	2.46E-08
Testes	0.00E+00	0.00E+00
Pyloric caeca	4.30E-07	1.15E-06
Kidney	2.97E-07	2.97E-07
^{239}Pu Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	1.22E-03	1.22E-03
Swim Bladder	0.00E+00	0.00E+00
Skeleton	6.29E-04	6.29E-04
Eyes	0.00E+00	0.00E+00
Heart	0.00E+00	0.00E+00
Liver	2.66E-04	2.66E-04
Brain	0.00E+00	0.00E+00
Esophagus	0.00E+00	5.26E-05
Rectum	0.00E+00	4.49E-05
Spleen	1.99E-06	1.99E-06
Testes	0.00E+00	0.00E+00
Pyloric caeca	0.00E+00	3.74E-05
Kidney	1.54E-05	1.54E-05
Muscle Tissue	1.22E-03	1.22E-03
Swim Bladder	0.00E+00	0.00E+00
^{240}Pu Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	1.49E-03	1.49E-03
Swim Bladder	0.00E+00	0.00E+00
Skeleton	7.70E-04	7.70E-04
Eyes	0.00E+00	0.00E+00
Heart	0.00E+00	0.00E+00
Liver	3.26E-04	3.26E-04
Brain	0.00E+00	0.00E+00
Esophagus	0.00E+00	6.44E-05
Rectum	0.00E+00	5.50E-05
Spleen	2.43E-06	2.43E-06
Testes	0.00E+00	0.00E+00
Pyloric caeca	0.00E+00	4.58E-05
Kidney	1.89E-05	1.89E-05

Table 33: Voxelized Combined Dose (Goatfish)

^{137}Cs Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	6.72E-03	7.32E-03
Swim Bladder	4.79E-07	6.32E-07
Skeleton	3.32E-04	3.75E-04
Eyes	1.24E-05	1.30E-05
Heart	1.23E-05	2.06E-05
Liver	9.85E-05	1.24E-04
Brain	4.50E-06	4.58E-06
Esophagus	9.45E-05	4.88E-04
Rectum	8.02E-05	4.04E-04
Spleen	1.48E-05	1.79E-05
Testes	2.32E-06	3.37E-06
Pyloric caeca	5.94E-05	3.16E-04
Kidney	1.30E-04	1.37E-04
^{90}Sr Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	3.37E-03	3.40E-03
Swim Bladder	4.05E-07	4.05E-07
Skeleton	4.07E-03	4.07E-03
Eyes	0.00E+00	0.00E+00
Heart	5.41E-09	2.16E-07
Liver	5.74E-06	7.55E-06
Brain	0.00E+00	0.00E+00
Esophagus	9.53E-07	8.30E-04
Rectum	1.04E-06	7.06E-04
Spleen	3.11E-05	3.11E-05
Testes	0.00E+00	0.00E+00
Pyloric caeca	2.19E-06	4.75E-04
Kidney	2.41E-04	2.42E-04
^{239}Pu Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	5.32E-04	5.32E-04
Swim Bladder	0.00E+00	0.00E+00
Skeleton	1.06E-04	1.06E-04
Eyes	0.00E+00	0.00E+00
Heart	0.00E+00	0.00E+00
Liver	4.26E-04	4.26E-04
Brain	0.00E+00	0.00E+00
Esophagus	0.00E+00	1.73E-02
Rectum	0.00E+00	1.48E-02
Spleen	6.55E-04	6.55E-04
Testes	0.00E+00	0.00E+00
Pyloric caeca	0.00E+00	1.00E-02
Kidney	5.10E-03	5.10E-03
Muscle Tissue	5.32E-04	5.32E-04
Swim Bladder	0.00E+00	0.00E+00
^{240}Pu Combined Dose (µGy/hr)		
Organ	**Without GIT**	**With GIT**
Muscle Tissue	6.51E-04	6.51E-04
Swim Bladder	0.00E+00	0.00E+00
Skeleton	1.30E-04	1.30E-04
Eyes	0.00E+00	0.00E+00
Heart	0.00E+00	0.00E+00
Liver	5.21E-04	5.21E-04
Brain	0.00E+00	0.00E+00
Esophagus	0.00E+00	2.12E-02
Rectum	0.00E+00	1.82E-02
Spleen	8.03E-04	8.03E-04
Testes	0.00E+00	0.00E+00
Pyloric caeca	0.00E+00	1.22E-02
Kidney	6.24E-03	6.24E-03