ASSESSING THE DOSE AFTER A RADIOLOGICAL DISPERSAL DEVICE (RDD) ATTACK USING A MILITARY RADIAC INSTRUMENT

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ASSESSING THE DOSE AFTER A RADIOLOGICAL DISPERSAL DEVICE (RDD) ATTACK USING A MILITARY RADIAC INSTRUMENT

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LIST OF SYMBOLS AND ABBREVIATIONS

AN/PDR	Army, Navy/Portable Detector Radiation
AN/VDR	Army, Navy/Vehicular (Ground), RADIAC, Passive Detecting
CBRNE	Chemical Biological Radiological Nuclear and high yield Explosives
CST	Civil Support Teams
CDL	Command Decision Level
EOD	Explosive Ordnance Disposal
IED	Improvised Explosive Device
MTOE	Modified Table of Organization and Equipment
RPO	Radiation Protection Officer
WMD	Weapons of Mass Destruction

SUMMARY

This research examines the assessment of military personnel for internal contamination after the detonation of a radiological dispersal device (RDD) in a combat environment. Due to limited medical infrastructure in forward deployed and combat areas, the process of triaging personnel who receive contamination may be extremely difficult. The lack of resources and equipment to analyze samples and test personnel makes for a very time consuming process.

Nearly all deployable Army units are equipped with AN/VDR-2 or AN/PDR-77 military radiac detectors. These detectors are capable of measuring the dose and dose rate for both gamma and beta radiation. They can readily be used in combat environments to detect radiation since they are widely fielded and Army units already have a training requirement for their usage.

In order to assess these detectors, a Monte Carlo radiation transport model was developed using specifications provided by Canberra, the instrument manufacturer [1]. The Los Alamos National Laboratory Monte Carlo N-Particle Transport Code (MCNP) Version 5 was used [2]. This model was validated against experimental measurements using a polymethyl methacrylate (PMMA) slab phantom, and then used in simulations with Medical Internal Radiation Dose (MIRD) phantoms [3]. Four locations were evaluated on the MIRD phantoms: the posterior upper right torso, the anterior upper right torso, the lateral upper thigh, and the anterior of the neck. Since this study targets military age males and females in satisfactory physical condition, only the reference male and reference female phantoms were considered in the analysis.

Three isotopes, ^{137}Cs, ^{60}Co, and ^{92}Ir, were selected and evaluated due to their assessment as candidate battlefield RDD isotopes, as well as their ability to be detected using an AN/VDR-2 and AN/PDR-77 [4]. The distribution and kinetic transport of these isotopes throughout the body, over a period of time, was determined using the Oak Ridge National Laboratory Dose Calculation and Risk Software (DCAL) [5]. Using Monte Carlo simulations, the radiac dose rate reading was determined for each isotope, at each location on the phantom for a period of two weeks after intake. The key assumptions for this analysis include all external contamination has been removed/decontaminated, only one isotope has been used in the RDD and the suspect isotope is known.

Based on medical guidance for commanders taken from the military handbook, Medical Management of Radiological Casualties [6], a Command Decision Level (CDL) was established to determine a threshold dose at which personnel would require further dosimetric evaluation. For the analysis, the CDL was set to 25 cGy. At this dose, expedited evacuation from theater would be considered based on commander's operational guidance.

Similar studies were conducted at Georgia Tech using commercial off-the-shelf radiation detectors and were directed at internal radiation exposure from an RDD to the general public. These studies involved using a Geiger-Mueller-based detector by Manger [7], and using NaI detectors by Lorio [8], Scarboro [9] and Dewji [10].

CHAPTER 1

INTRODUCTION

Radiological dispersal devices (RDDs) “are devices, other than a nuclear explosives device designed to disseminate radioactive material in order to cause destruction, damage, or injury” [11]. One type of RDD, commonly called a “dirty bomb,” uses conventional explosives to disperse radioactive contamination. Dirty bombs can produce immediate casualties from the effects of the conventional explosion including blast injuries and trauma. These effects were not considered in this analysis. In general, RDDs scatter radiological material creating a large area of contamination. The dose and dose rate are dependent on the type and amount of radioactive material used, which may not necessarily be uniformly distributed over the area. An RDD may serve as an area denial weapon, posing a danger of external and internal radiological contamination [12]. Although external contamination may be removed by surface cleaning and removing contaminated clothing, internal contamination is more difficult to remove. When the contaminants are ingested and/or inhaled, a high intensity prolonged radiation exposure may occur.

Over the past few decades, there has been an increase in the threat of use of Weapons of Mass Destruction (WMD). Several small scale attacks over the past 20 years utilized biological and chemical agents. Although there are no accounts of the true use of an RDD, the potential clearly exists. In Chechnya, there were two cases of potential dirty bombs containing ^{137}Cs. In November 1995, a group of Chechen separatists buried a ^{137}Cs source wrapped in explosives at the Izmaylovsky Park in Moscow. A group of

Chechen rebels contacted a Russian television station and reported their ability to construct a radioactive bomb. Neither the Chechens who planted the ^{137}Cs, nor the origin of the source, were ever identified. In December 1998, the Russian-backed Chechen Security Service announced that a team had found a container filled with ^{137}Cs attached to an explosive mine hidden near a railway line. The Security Service was able to safely defuse the bomb [13].

Radiation sources are used extensively in industrial and medical applications. Worldwide, accountability of these sources is poor. Numerous radioactive materials have gone missing and are unaccounted for, many from Former Soviet Union (FSU) nations. In addition to former weapons programs, radioactive sources obtained from laboratories, medical facilities, and industry, also have the potential for use in a RDD.

In Iraq and Afghanistan, there have been numerous reports of attacks on coalition forces in the form of small arms fire, improvised explosive devices (IEDs), as well as mortar and rocket attacks. There have been instances of radioactive sources being reported to coalition forces in Iraq, albeit mostly low levels of radiation. These isotopes could potentially be used in IEDs to produce an RDD to attack US and coalition forces.

Immediately after an IED attack, military forces secure the area unless otherwise dictated by the security of the area or the current mission. An explosive ordnance disposal (EOD) team may conduct a post blast assessment, often identifying the materials used in an attack. The EOD team is equipped with a military radiac detector, either an AN/VDR-2 or and AN/PDR-77 [14]. If significant levels of radiation are detected, the unit would also need to identify personnel who have received contamination. Decontamination procedures would then be conducted to remove external contamination. Management and treatment of internal contamination is more complex, requiring the need to identify personnel who have been contaminated. Triaging must be conducted in order to identify and treat these individuals. The ability to triage personnel in combat areas is limited due to the lack of resources readily available.

One method to assess casualties is through the use of gamma cameras, which are capable of assessing the activity of a known isotope inhaled by an individual when the time and duration of exposure are known [15]. Previously conducted research using anthropomorphic phantoms evaluated the response of a gamma camera with five isotopes distributed in the lungs [16]. Due to their size, and inability to readily transport them on short notice, it would not be feasible to utilize these instruments in the event of an RDD in a combat environment.

A Whole Body Counter (WBC), such as the one used to identify casualties following the ^{137}Cs accident in Goiania, Brazil, is another piece of equipment that may be used [17]. As with the gamma camera, this is also a large and complicated piece of equipment. Furthermore, WBCs are not available for use in a combat environment, therefore other triage alternatives need to be evaluated.

Nearly all deployable Army units are equipped with radiation detection equipment, including the AN/VDR-2. This instrument is ideal to measure radiation within Army units, as it has been widely fielded and operator-level training is mandatory. The present research provides a method for using this instrument to triage soldiers who have received internal contamination from isotopes producing high-energy gamma radiation, in an effort to identify soldiers requiring further dosimetric evaluation.

A methodology to categorize radioactive isotopes was developed by the Armed Forces Radiobiology Research Institute (AFRRI). Using this schema, radioactive isotopes fall under the following categories: university seven, military four, fission products, and the industrial three. The “university seven” consist of ^{3}H, ^{14}C, ^{32}P, ^{60}Co, ^{125}I, ^{131}I, and ^{252}Cf. These sources are often used in medicine and isotropic labeling in laboratories. The “military four” consist of ^{3}H, ^{235}U, ^{239}Pu and ^{241}Am, and are primarily used in the nuclear weapons complex. Fission products are a result of a fission event (i.e. a weapon detonation), and have the potential for a significant risk to the public. Finally, the “industrial three”, which have been evaluated in this research, consist of ^{60}Co, ^{137}Cs and ^{192}Ir. ^{137}Cs and ^{60}Co are used in widely industry for their penetrating gamma rays. ^{192}Ir is a medical source and is widely used in radiography [18].

CHAPTER 2

BACKGROUND

The detonation of IEDs is a daily experience for some combat units in both Iraq and Afghanistan. IEDs are made from a wide variety of materials and explosives. The common procedures for reacting to an IED include assessing and treating casualties, securing the area, and reporting the contact to the higher command. Unless there is a major security threat in the area, or the mission dictates that the convoy should continue movement, the unit will remain on site. An Explosive Ordnance Disposal (EOD) team will often conduct a post blast analysis of the site. During this assessment, the EOD team will use an AN/VDR-2 or AN/PDR-77 radiac detector to identify any potential radiological contamination. The team will collect shrapnel and remnants of the IED and assess any damage caused to the surrounding area, including assessing the size of the crater produced, in an effort to identify the amount of materials used. Although the EOD team would be able to detect contamination on site, they do not have the capability to identify the isotope [14]. In order to identify the isotope, a CBRNE (Chemical, Biological, Radiological, Nuclear, and high-yield Explosive) response team would respond to the site to analyze the sample. The team would use a DTECH Rad-ID isotope identifier to obtain spectra from the sample to analyze the energy levels of particles emitted from the sample. The spectral results are then sent to Department of Energy (DOE) Laboratories to verify the isotope present. Depending on the location of the RDD and the response time from DOE, it would take approximately six hours from the time the EOD team detected radiation to identification of the sample [18].

In a combat situation, an RDD could easily be mistaken for a simple poorly-made IED. The device may have resulted in minimal damage and minimal initial casualties. Although soldiers may not have received any external wounds from the detonation of the device, they could be receiving radiation through absorption, ingestion and inhalation. While securing the area and waiting for EOD to complete the investigation of the site, the soldiers would continuously be inhaling a radioactive source.

There have been no events involving the use of radioactive material in an IED, nor has there been any open source intelligence identifying insurgents intending to use radioactive material to produce an RDD. However, if radioactive materials are employed, soldiers would be ill prepared to respond to such a threat. In the event that the EOD team had discovered radioactive material during their post blast assessment, or soldiers started exhibiting symptoms of exposure to radiation, there would be a need to triage soldiers who may have been affected, and treat accordingly.

The military publication FM 4-02.283, Treatment of Nuclear and Radiological Casualties, is a guide for military medical personnel to recognize and treat nuclear and radiological casualties. The manual applies to the nuclear battlefield and other operations where radiation hazards exist. In order to estimate the radiological dose received, there are several different methods outlined. The approximate severity of exposure can be estimated based on symptoms and their onset as seen in Table 2.1.1 [19].

Table 2.1.1 Dose, Onset and Duration of Symptoms

DOSE (cGy)	SYMPTOMS	ONSET	DURATION
0–35	None	N/A	N/A
35–75	Mild Nausea, Headache	6 Hours	12 Hours
75–125	Nausea/Vomiting (30%)	3–5 Hours	24 Hours
125–300	Nausea/Vomiting (70%)	2–3 Hours	3–4 Days
300–530	Nausea/Vomiting (90%) Diarrhea (10%)	2 Hours 2–6 Hours	3–4 Days 2–3 Weeks
530–830	Severe Nausea/Vomiting (90%) Diarrhea (10%)	1 Hour 1–8 Hours	Direct Transit into GI Syndrome
830–3000	Severe Nausea/Vomiting (90%) Disorientation (100%)	3–10 Min 3–10 Min	Persists Until Death 30 Min–10 Hours

Estimating radiation dose based on clinical symptoms has limited accuracy. In addition, personnel may exhibit these symptoms under other battlefield or medical conditions including dehydration and food poisoning, which are more likely to occur in a foreign and arid environment. Medical assays can also be used to determine the severity of the exposure. There are a variety of these tests that can be performed at the decontamination point up through tertiary care facilities as shown in Table 2.1.2 [19].

Table 2.1.2 Medical Assay of the Radiological Patient

TEST	LOCATION/FACILITY			
	DECONTAMINATION POINT	MEDICAL TREATMENT UNIT (LEVEL 2)	HOSPITAL (LEVEL 3)	TERTIARY CARE (LEVEL 4)
Nasal swabs for inhalation of contaminants	+			
External contamination	+		+	
Urine and stool sample for internal contamination		Baseline sample	24 hour sample	+
Complete Blood Count (CBC)/platelets	If practical	Baseline sample and then daily	Daily for 2 weeks	Daily for 2 weeks
Absolute Lymphocyte Count		Every 4–12 hours for 3 days	Every 4–12 hours	
Human Leukocyte Antigen (HLA) subtyping		Draw sample	Draw sample before lymphocyte count falls	Draw sample before lymphocyte count falls
Cytomegalovirus (CMV)			+	+
Hemoglobin Agglutinin			+	+
Human Syncytial Cell Virus Antibodies				+
Human Immunovirus			+	+
Vesiculovirus				+
Lymphocyte Cytogenetics		Draw sample	Draw sample before lymphocyte count falls	+

+ Indicates test should be performed at this location/level of care.

Currently, there is no capability to analyze bioassays within Iraq and Afghanistan. As a result, any samples obtained would need to be evacuated out of theater to determine if soldiers require additional dosimetric evaluation. This process would be extremely time consuming, and would result in delaying treatment. The Army does possess gamma cameras that are available in Germany, but not deployed in the Middle East. Personnel suspected of receiving contamination would need to be evacuated in order to utilize a gamma camera to assess the dose received [20]. By using a piece of equipment widely available to all units, triaging and identification of soldiers requiring any treatment and follow-on evaluation can be a local and less time-consuming process. Overall, a sustainment of a commander's combat power would be possible.

In addition to use in combat zones, the methodology developed in this study could also be used to assist military units which are responding to a domestic event. National Guard units contain WMD-CSTs (Weapons of Mass Destruction Civil Support Teams) which provide support to domestic CBRNE consequence management events. The teams are military first responders and advise civilian first responders regarding appropriate medical and technical advice. These teams may also be deployed as an element of a response task force in support of the Lead Federal Agency [21].

For example, the 4th WMD CST, based at Dobbins Air Force Base in Marietta, Georgia, provides support within the state of Georgia. The team consists of 22 personnel, including a physician assistant, an environmental science officer, and a medical operations officer. The team possesses both civilian and military radiac equipment including two AN/VDR-2s and three AN/PDR-77s. When assessing an area that is a potential radiological hazard, personnel are required to wear personnel monitoring devices including thermoluminescent dosimeters (TLD) and direct reading pocket dosimeters. Bioassays may also be obtained to monitor for deposited radioactive materials [22]. In the event of an RDD and radiological exposure, the CST would work to provide decontamination support and care for soldiers on the team. The physician assistant would treat a soldier based on symptoms of radiological exposure, and follow-up with bioassays. Unless exposed personnel possessed a monitoring device at the time of the incident (which is not always possible), they would need to wait until the results from the bioassay were returned in order to determine the extent of radiological exposure. By utilizing the military radiac equipment within the unit, the CST would be able to assist in triage following an RDD [23].

CHAPTER 3

METHODOLOGY

3.1 Overview

The AN/VDR-2 and AN/PDR-77 use an identical handheld probe, the DT-616, which was modeled using MCNP. The DT-616 probe model was used in conjunction with a PMMA slab phantom model using MCNP to verify the detector model. The model was validated using experimental data obtained using the probe and radioactive sources in a laboratory. Upon verification of the detector model, the detector model was placed in two MIRD phantom models representing the military population. Simulations were run using MCNP with ^{137}Cs, ^{60}Co, and ^{192}Ir distributed throughout various organs. The results from MCNP were used in conjunction with DCAL and International Commission on Radiological Protection (ICRP) dose coefficients to estimate the reading obtained using the detector that would indicate a person was exposed to a dose of 25 cGy of internal contamination. These values were incorporated into triage procedure sheets which may be used by military personnel to triage those who may have inhaled the isotopes. The methodology for this analysis is shown using the flow chart in Figure 3.1.1.

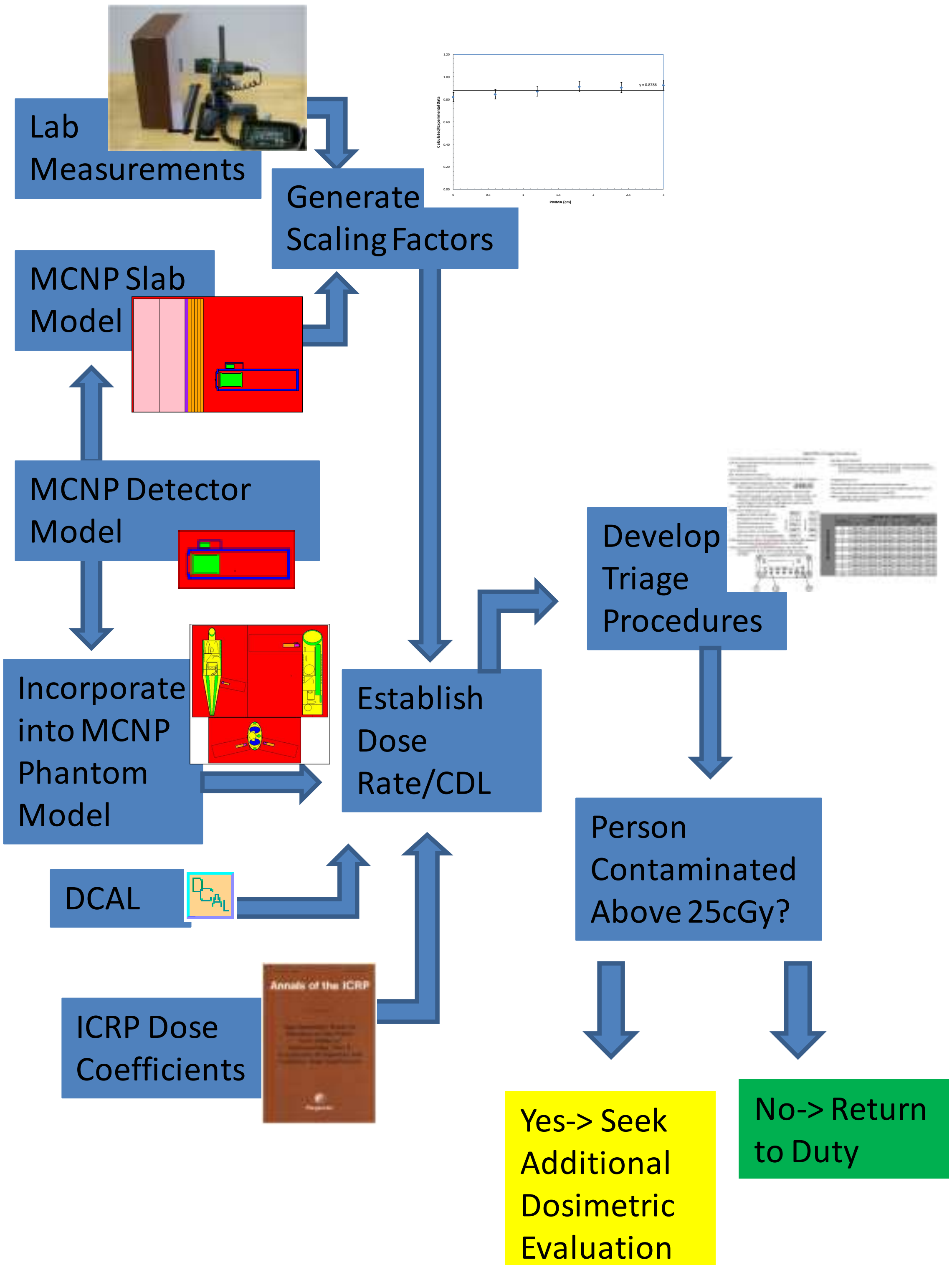


Figure 3.1.1 Procedures for Determining Inhalation Contamination using a DT-616 Probe

3.2 AN/VDR-2 and AN/PDR-77 Military Radiac Detectors

The AN/PDR-77 and the AN/VDR-2 are radiac detectors currently utilized by the Army and Marine Corps. Both detectors have the capability to measure dose and dose rate for beta and gamma radiation. The AN/VDR-2 is a standard piece of equipment common to nearly all deployable units. The AN/PDR-77 is used primarily by EOD, ordnance and CBRNE units for nuclear accident and incident response. In addition, each Army installation is issued two AN/PDR-77s to use to respond to radiological and nuclear incidents [24].

The AN/VDR-2 is one of the primary pieces of radiation detection equipment issued to most deployable units in the Army. In order to determine the quantity of these instruments fielded in the Army, a Modified Table of Organization & Equipment (MTOE) was studied. An MTOE is a document which authorizes units a specific number of personnel and equipment. A typical infantry battalion consisting of over 600 soldiers is authorized from 40 to 60 AN/VDR-2s. A medical company consisting of approximately 80 soldiers, which may be involved in the triaging and treatment of casualties, is authorized between 3 and 13 AN/VDR-2s. Depending on the type of unit and their mission, deployable Army units typically possess one AN/VDR-2 for every 8-25 soldiers [25]. Due to its vast availability, the AN/VDR-2 has the most potential for identifying radiological casualties on the battlefield.

The AN/VDR-2 military radiac detector was originally manufactured by Nuclear Research Corporation which was purchased by Canberra in the mid 1990s [1]. The detector was designed for tactical and non-tactical protection use. It has been engineered for use in extreme temperature conditions and highly elevated levels of radiation resulting from a nuclear accident or incident. The AN/VDR-2 can be mounted on land vehicles and helicopters as well being operated by a foot soldier [26].

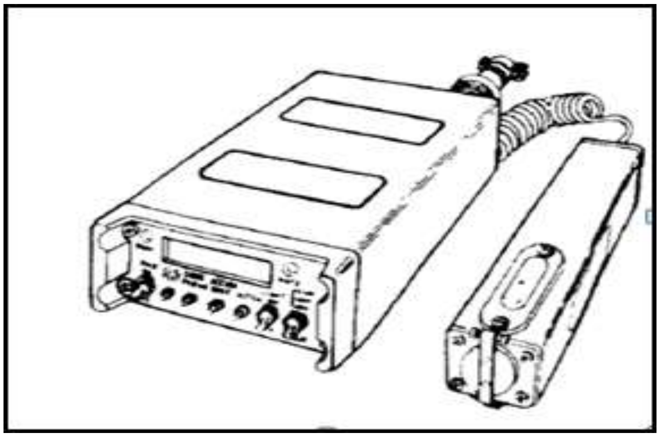


Figure 3.2.1 AN/VDR-2 Radiac Detector

The AN/VDR-2 consists of an IM-243 radiacmeter and a DT-616 probe as shown in Figure 3.2.1. Gamma radiation can be detected and measured at dose rates ranging from 0.01 μGy/hr to 100 Gy/hr. Beta radiation can be detected at dose rates ranging from 0.01 μGy/hr to 5 cGy/hr. The device can also measure an accumulated dose ranging from 0.01 μGy to 9.99 Gy. The LCD display on the radiacmeter shows readings to three digit accuracy and the range is displayed in units of μGy/hr, cGy/hr, and Gy/hr, and μGy, cGy and Gy for total dose. According to the Technical Manual (TM) for the AN/VDR-2, the accuracy of the dose rate is ±20 percent for up to 10.0 Gy/hr and ±25 percent for up to 100 Gy/hr (overall system error) [26].

The DT-616 probe contains two Geiger-Mueller (GM) tubes. The low range detector covers the range from 0.01 μGy/hr to 5 cGy/hr, and the high range detector covers the range from 2cGy/hr to 100 Gy/hr. The low range tube is capable of detecting both gamma and beta radiation, whereas the high range tube is only capable of detecting gamma radiation. The AN/VDR-2 contains a beta shield which covers the low range GM tube, resulting in the measurement of only gamma radiation. Both tubes are energy compensated to provide a tissue dose response, with a roll-off below 100 keV to around 50% at 50 keV and a relatively flat response from 100 keV to above 1 MeV. During development, testing was conducted by the manufacturer using a ^{137}Cs and a ^{60}Co source, and x-rays of various energies produced by a filtered x-ray machine resulting in the relative response in Figure 3.2.2 [2, 24].

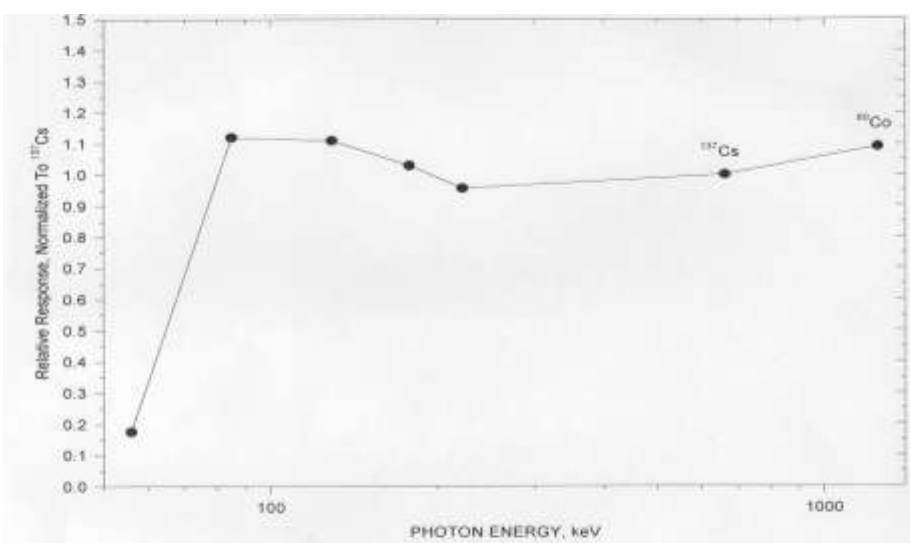


Figure 3.2.2 Relative Energy Response of the AN/VDR-2

Geiger-Mueller counters are common radiation detectors, which have advantages over other detectors due to their simplicity, low cost and ease of operation. Disadvantages of these detectors include their inability to provide energy information and large amount of dead time, particularly in areas with high levels of radiation. A thorough review of GM-based detection can be found in Knoll [27]. Due to the construction and shielding of the GM tubes in the DT-616, the detector attempts to provide a tissue dose response. The DT-616 is able to operate in environments with high levels of radiation without missing events in dead time by using the "time-to-count" method. The DT-616 probe was also designed for operation in extreme temperatures by the selection of fill gases. These three improvements make the detector suitable for military operations and usage [1].

The GM tubes are operated in time-to-count mode. This method was developed and patented by Jack Cooley and Elmo DiIanni [28]. This mode reduces the amount of dead time within the detector where a typical GM tube requires a longer recovery time between events. In the time-to-count mode, the GM tube is operated at 250 volts, which is half the potential operating region. In the count mode, the voltage is increased to 500 volts, and an oscillator clock starts counting in 1 microsecond cycles. The counting continues until a GM tube pulse is obtained, at which time, the time counting is stopped and the time is recorded. At this point, the voltage is returned to half the operating voltage allowing the GM tube time to recover. After two milliseconds, the GM tube is recovered and returns to the operating voltage. During the count time, only one GM pulse can be obtained and the time is inversely proportional to the count rate. This process occurs many times per second in order to obtain a statistically reliable time-to-count. The sensitivity in the low range tube is approximately 30 cps/mR/hr and in the high range tube, the sensitivity is approximately 0.08 cps/mR/hr. For low count rates, counting statistics are not ideal, requiring long count times to obtain accurate results [1].

The modeling was conducted for the DT-616 probe of the AN/VDR-2. This probe is also a component of the AN/PDR-77 radiac set. Due to its limited fielding, the AN/PDR-77 is not as readily available in combat zones compared to the AN/VDR-2. The AN/PDR-77 uses an IM-263 radiacmeter as opposed to the IM-243 radiacmeter used with the AN/VDR-2. In order to reduce development time, the IM-263 was modeled after the IM-243, and operates similar to the IM-243. The IM-263 has improvements over the IM-243 including the ability to subtract background radiation. In addition to the DT-616 probe, the AN/PDR-77 also contains a DT-669 alpha probe, and a DT-674 x-ray probe as shown in Figure 3.2.3. The AN/PDR-77 measures beta and gamma radiation in Rad/hr, as opposed to the AN/VDR-2 measuring in Gray/hr [29]. In addition to being widely used by the Army and Marine Corps, the DT-616 probe is a component of radiac detectors utilized by other NATO nations. Canada, Italy and Great Britain also use radiac detectors containing a DT-616 probe and radiacmeters modeled after the IM-243 [1].

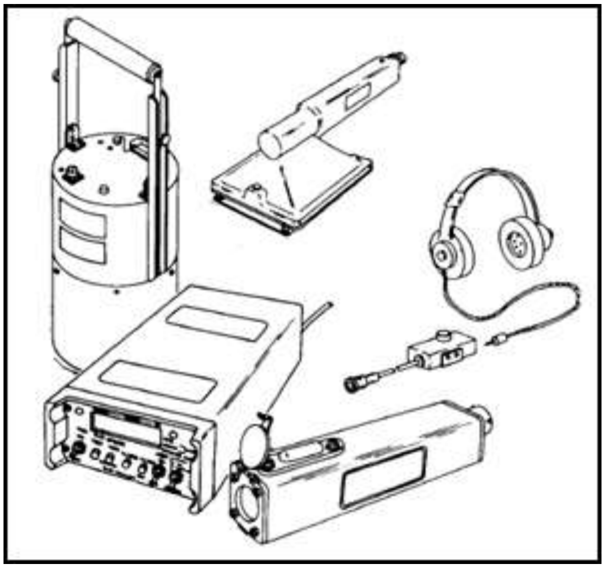


Figure 3.2.3 AN/PDR-77 Radiac Detector

The DT-616 probe from the AN/VDR-2 and AN/PDR-77 radiac detectors was modeled using MCNP and VisEd [30]. Detailed drawings (Figure 3.2.4) and specifications of the probe were obtained directly from Canberra [1]. The internal components of the probe are shown in Figure 3.2.5. The modeling effort focused only on the GM tubes and associated shielding. The electronics were not modeled as their effect was insignificant for this analysis and would be compensated for in the detector scaling factors. Material densities and compositions were obtained from the Standards Compositions Manual [31] and Rad Toolbox [32]. The composition of the aluminum alloy was obtained using North American Die Casting Association product specification standards [33]. The VisEd representation of the probe is in Figure 3.2.6.

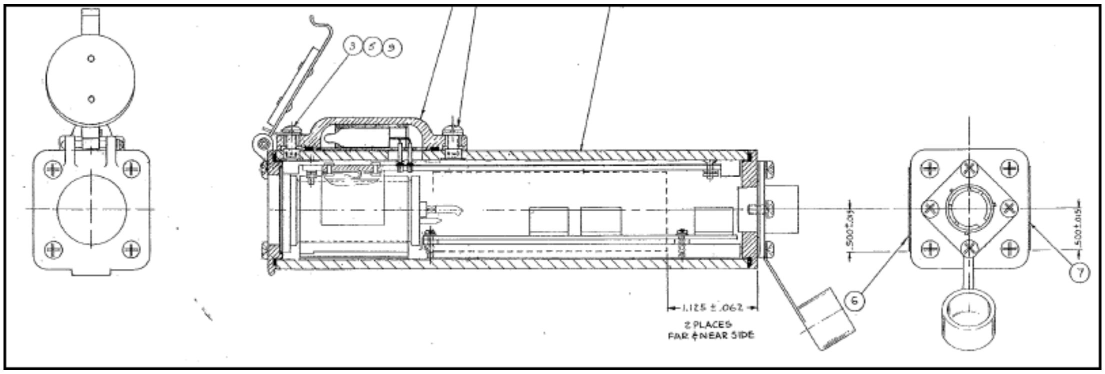


Figure 3.2.4 Technical Drawing of DT-616 Probe

Figure 3.2.5 Internal Components of DT-616 Probe (High-Range Tube is not shown)

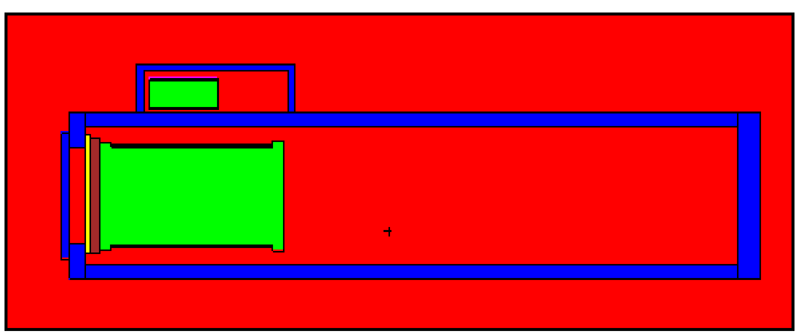


Figure 3.2.6 VisEd Representation of DT-616 Probe

3.3 PMMA Slab Phantom Measurements

In order to validate the computational model of the detector, a PMMA slab phantom was used to conduct benchmark measurements with the DT-616. The slab phantom consisted of varying thicknesses of PMMA ranging from 0 cm to 3 cm in increments of 0.6 cm. A source holder constructed of PMMA was used to secure the source and virtual water was placed behind the source holder as a backscatter medium. Virtual water was obtained from the CNMC Company and is designed to scatter and attenuate photons in the same manner as water. Virtual water is commonly used for quality assurance and validation of medical radiation treatment plans [34]. Four different sources were used with the slab phantom, ^{57}Co, ^{60}Co, ^{137}Cs, and ^{22}Na. Information on the sources used is located in Table 3.3.1. These sources were chosen due to the broad range of gamma radiation energy (Table 3.3.2). Additionally, ^{60}Co and ^{137}Cs are considered military significant candidate RDD isotopes and were also used with the MIRD phantoms.

Table 3.3.1 Source Activity

Isotope	Assay Date	Initial Activity (µCi)	Half-life (days)	Measurement Date	Experimental Activity (µCi)
^{57}Co	27 FEB 07	10,000	2.72E+2	19 FEB 10	580.559
^{60}Co	19 MAR 02	10	1.92E+3	19 FEB 10	3.524
^{137}Cs	28 FEB 92	10	1.10E+4	11 MAR 10	6.608
^{22}Na	17 JUL 09	1	9.51E+02	03 MAR 10	0.818

Table 3.3.2 Gamma Energy Intensity Data

Isotope	Energy (keV)	Intensity
^{57}Co	122, 6.4, 6.39, 136, 14.4, 7.06, 7.06, 0.705, 692	0.856, 0.334, 0.169, 0.106, 0.092, 0.045, 0.029, 0.0026, 0.0016
^{60}Co	1173, 1333	0.9985, 0.9998
^{137}Cs	662	0.898
^{22}Na	511, 1270	1.8, 0.999

For the experimental set-up (Figure 3.3.1), the DT-616 was placed one inch from the PMMA slab in all of the measurements. The dose rates were recorded five times for each thickness of the PMMA slab for each isotope to ensure consistency for each run, and a total of three runs were conducted for each isotope and thickness. The background was obtained by taking the average over 20 readings in the absence of the sources. An average was taken of the dose rates for each thickness of PMMA for each source, and the background radiation was subtracted. Results showing the attenuation of ^{60}Co are shown in Figure 3.3.2.

Figure 3.2.1 Experimental Set-up

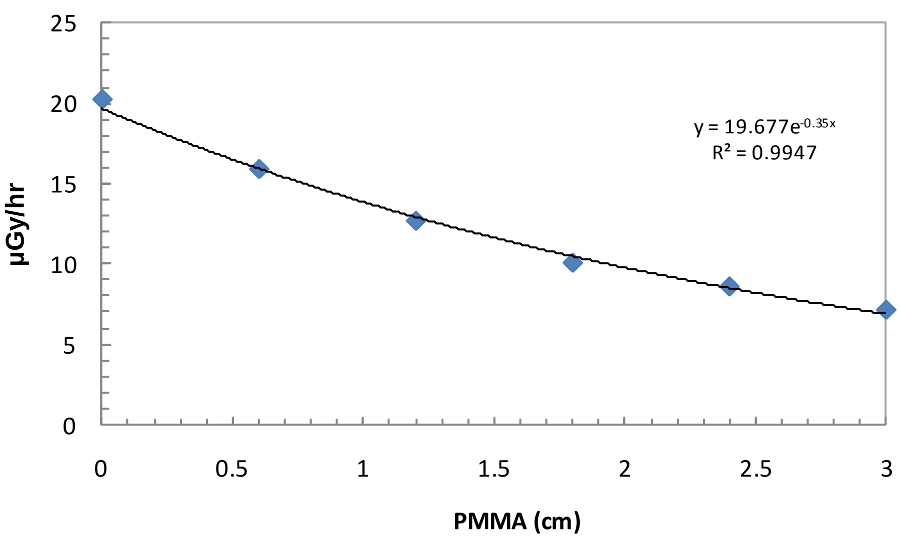


Figure 3.2.2 Experimental Data for ^{60}Co

3.4 MCNP Model Verification

A slab phantom model was created using MCNP. The slab phantom consisted of virtual water, air, a source holder, and PMMA. A separate slab phantom was created for each of the varying thicknesses of PMMA ranging from 0 cm to 3 cm. A representation of the model using VisEd is shown in Figure 3.4.1 for a model consisting of 3 cm of PMMA. The composition for these materials is in Table 3.4.1.

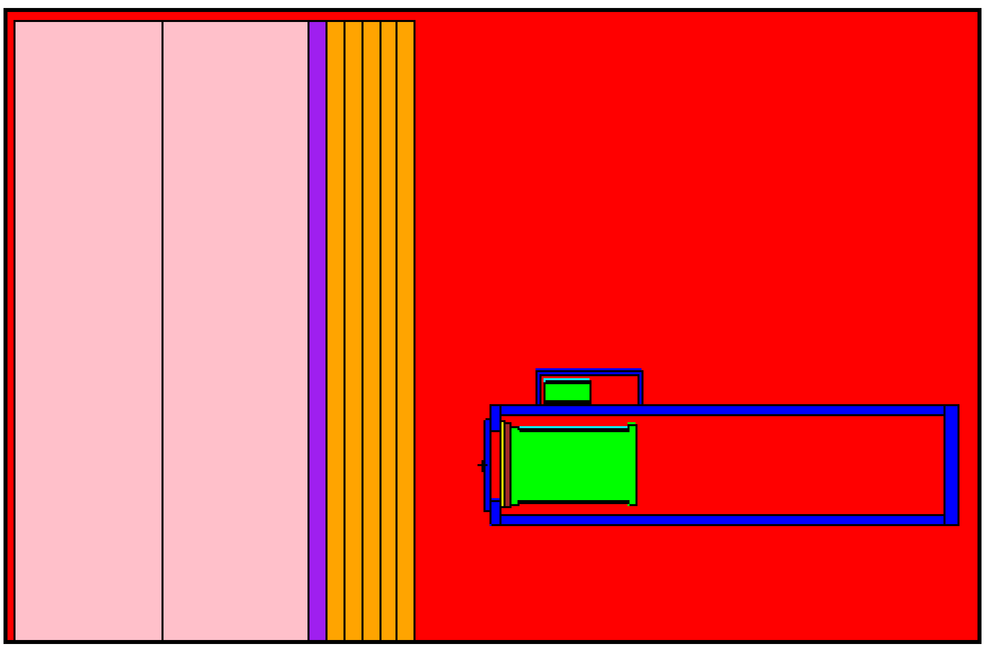


Figure 3.4.1 VisEd Representation of the Slab Phantom Model

Table 3.4.1 Slab Phantom Composition

Component	**Composition (weight percent)**		**Density (g/cm^3)**
PMMA Slabs and Source Holder	H C O	8.06% 59.99% 31.95%	1.19
Virtual Water	H C N O Cl Ca	0.64% 63.99% 2.53% 25.14% 0.39%l 7.31%	1.03
Surrounding Air	N O Ar	76.5058% 23.4793% 0.0126%	1.20479×10^{-3}

A track length estimate of cell flux (F4 tally) was generated using MCNP over the volume of the GM tube in the DT-616 [2]. The tally output was distributed over 19 energy bins. The MCNP computed flux for each energy bin was folded with the ICRP-74 conversion factor (H*(10)/Φ) [35] and the source strength used in the laboratory analysis, to obtain the ambient dose equivalent at each energy bin. The ambient dose equivalents for each bin were summed to obtain the total dose rate. This calculated dose rate was divided by the experimental dose rate to obtain a scaling factor for each of the four isotopes.

3.5 MIRD Computational Phantoms and Biokinetics

Since the military has standards for physical fitness and age, the primary people of concern would be of a greater level of physical fitness than the general population, thus only the reference male and reference female anthropomorphic computational phantoms were studied. Both of these are MIRD phantoms, initially developed at Oak Ridge National Laboratory (ORNL) [3]. Pacific Northwest National Laboratory created MCNP-coded versions of the MIRD phantoms using ICRP 32 recommendations [36, 37]. The phantoms were further modified at Georgia Institute of Technology with the addition of the esophagus and 2 mm of skin tissue [38]. The physical characteristics are listed in Table 3.5.1

Table 3.5.1 MIRD Phantoms

Body Type	**Height (cm)**	**Weight (kg)**	**BMI**
Reference Male	179	73.1	23
Reference Female	168	56.5	20

Four detector locations were selected of the study of the reference male; the anterior right upper torso, the posterior right upper torso, the anterior of the neck, and the lateral left thigh. For the reference female, the anterior right upper torso was not used due to the attenuation from breast tissue. The two upper torso positions were used due to the inhalation initially depositing the isotope within the lungs. As a result, a higher dose rate would be initially acquired by taking measurements over the lungs. Due to the location of the heart on the left side of the body, a higher count rate is obtained by using the right lung. The neck was selected to obtain counts from any isotopes that are thyroid seekers.

Each phantom was independently simulated for the inhalation of ^{60}Co, ^{137}Cs and ^{192}Ir, since all three isotopes can be detected by an AN/VDR-2 and AN/PDR-77 and are also militarily significant candidate isotopes for RDDs. DCAL was used to provide the distribution of each of the three isotopes within the body over a given period of time. The sources were distributed based on organs where the isotopes would migrate to according to DCAL, as seen in Table 3.5.2.

Table 3.5.2 Organs of Interest for Isotopes

Organ	^{60}Co	^{137}Cs	^{192}Ir
Blood	X	X	X
Body Tissue	X	X	X
Kidneys			X
Liver	X		X
Lower Large	X	X	X
Lungs	X	X	X
Small Intestines	X	X	X
Spleen			X
Stomach Contents	X	X	X
Upper Large	X	X	X
Urinary Bladder	X	X	X

The dose rate at four locations was simulated using MCNP to determine the optimum location to obtain a dose during triage. Since the isotopes are inhaled, the dose is initially greatest in the lungs. Detectors were placed on the model one inch away from the surface as shown in Figure 3.5.1. The distance of one inch was selected based on personnel monitoring procedures outlined by the Army [39]. Although this methodology assumes that external contamination was removed, ensuring the probe does not touch the person prevents the probe from getting contaminated.

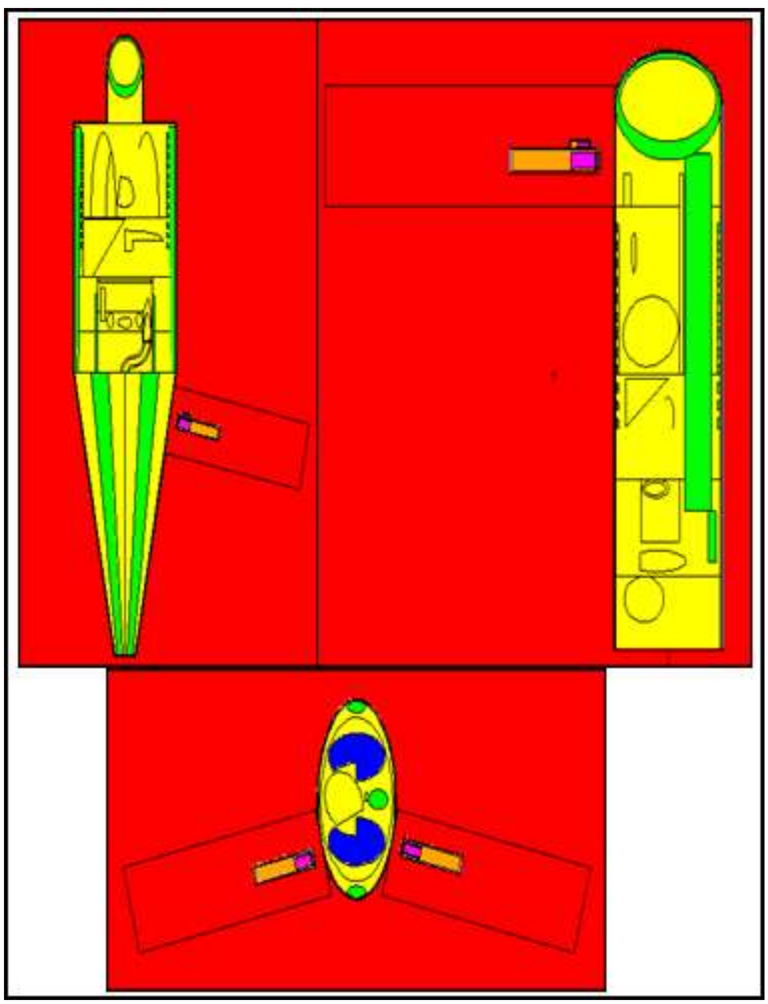


Figure 3.5.1 Detector Placement on the Anthropomorphic Phantoms

A track length estimate of cell flux (F4 tally) was used in conjunction with a source contribution tally modifier (SCX card) to determine the flux in the detector per unit source distributed in each organ [2]. The tally modifier records the source organ of each particle reaching the detector. The flux was then multiplied by the $H^*(10)/\Phi$ coefficient to obtain the ambient dose equivalent contributed by each organ.

3.6 DCAL Biokinetic Modeling

ORNL developed the DCAL code which calculates the tissue dose and subsequent health risks resulting from exposure or intake of isotopes. DCAL can perform biokinetic and dosimetric calculations for the uptake of an isotope, by the pathways of inhalation, ingestion and injection. The dose rates can be computed as a function of time following the intake of the isotope. DCAL contains extensive libraries of biokinetic data, dosimetric data, and models to provide the most accurate estimate of the behavior of the isotopes within the body [5].

DCAL was used to determine the distribution of ^{137}Cs, ^{60}Co and ^{192}Ir over a period of time following the release of radioactive material from an RDD. The inhalation from an environmental source was selected as the pathway on DCAL. In this pathway, the isotopes are initially deposited in the lungs, and are transported to different organs in the body based on their chemical properties. ICRP default inhalation classes were used for each of the isotopes, with ^{60}Co and ^{192}Ir set to moderate absorption and ^{137}Cs set to fast absorption [40]. ^{137}Cs was also analyzed using a moderate inhalation class. The diameter of the particles was set to the default of 1 μm. DCAL was used to estimate the amount of each isotope in the body over a period of 30 days. Figures 3.6.1-3.6.4 illustrate the amount of the isotopes in the major organs where the various isotopes migrate. ^{137}Cs, an alkali metal, tends to become concentrated in body tissue. ^{60}Co and ^{192}Ir are both transition metals with similar chemical properties and tend to migrate from the lungs to the stomach and intestines.

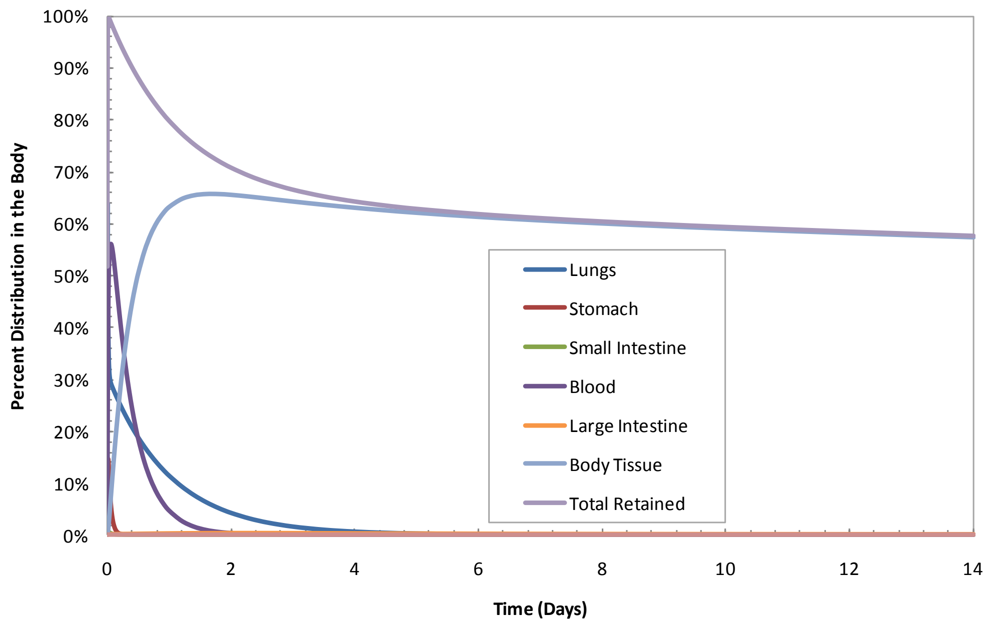


Figure 3.6.1 Distribution of ^{137}Cs (Fast) in Male Phantom

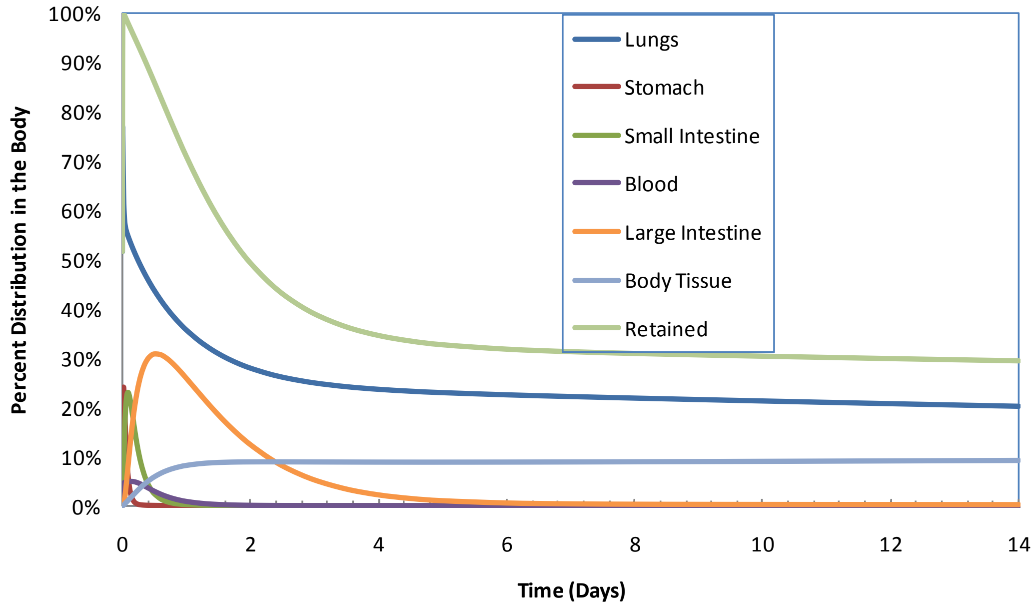


Figure 3.6.2 Distribution of ^{137}Cs (Moderate) in Male Phantom

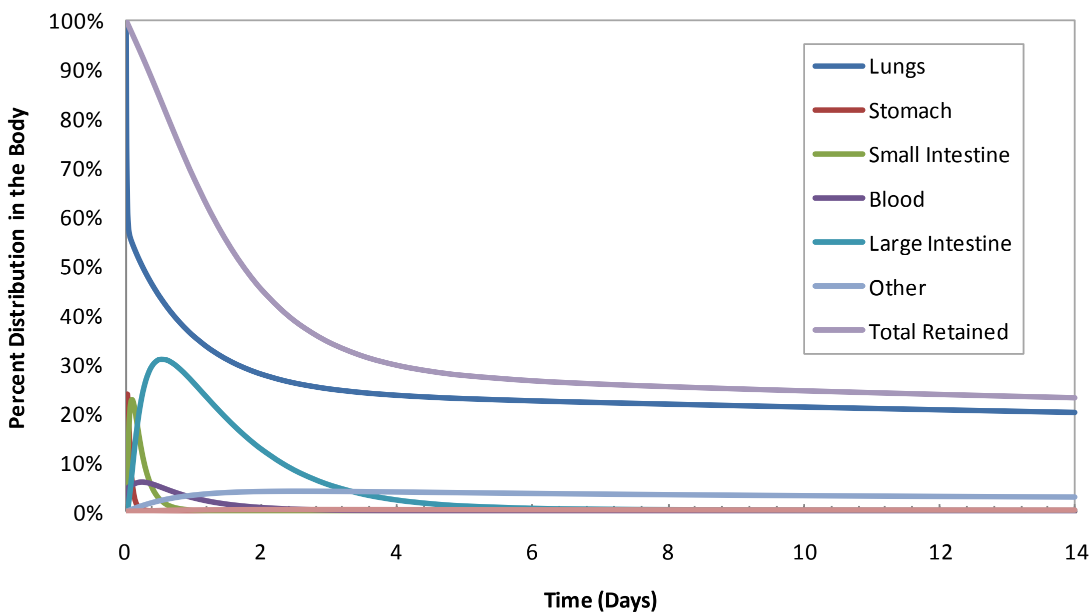


Figure 3.6.3 Distribution of ^{60}Co in Male Phantom

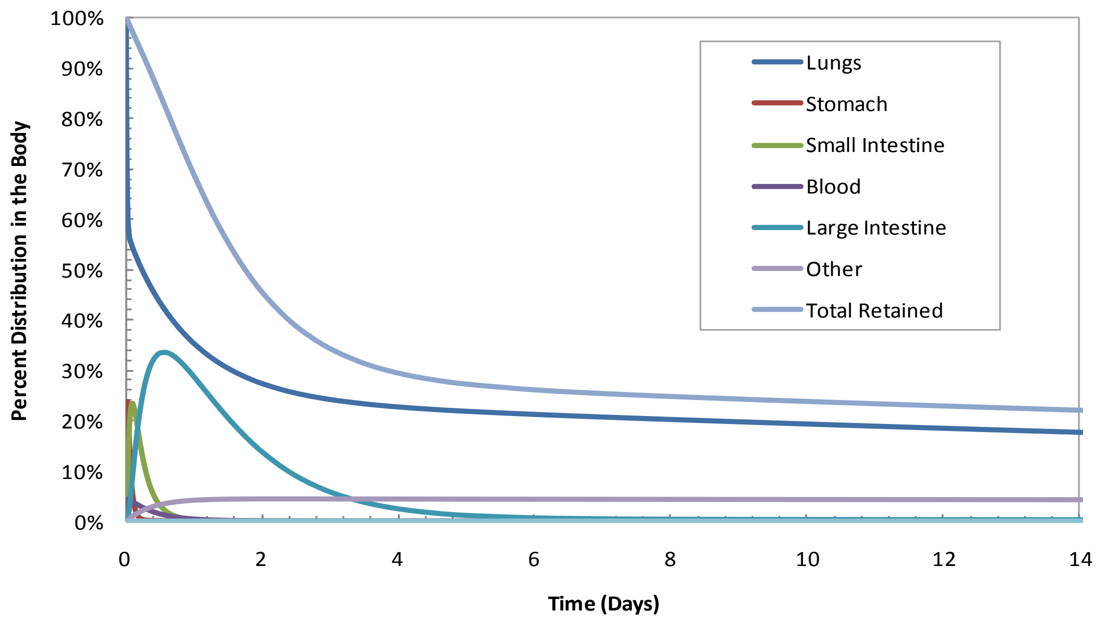


Figure 3.6.4 Distribution of ^{192}Ir in Male Phantom

According to DCAL, more than half of the inhaled initial activity of isotopes with a moderate absorption class, including ^{60}Co and ^{192}Ir, is exhaled in the first breath. Additionally ^{60}Co and ^{192}Ir have nearly the same removal time from the body, whereas the body retains ^{137}Cs at significantly higher concentrations, as shown in Figure 3.5.4. Using a moderate inhalation class for ^{137}Cs also shows a greater retention in the body compared to ^{60}Co and ^{192}Ir.

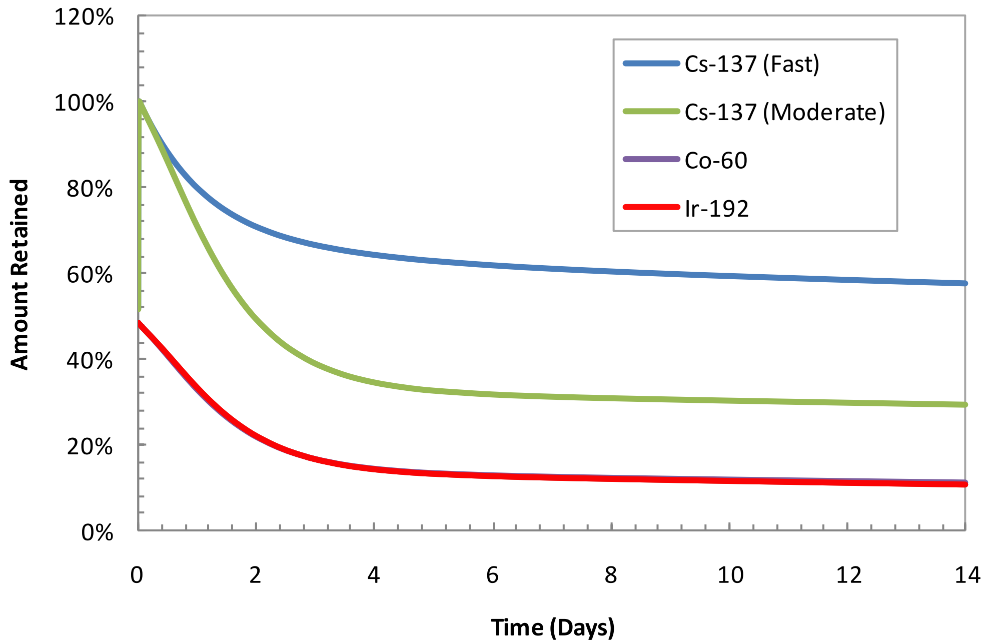


Figure 3.6.5 Retention of Isotopes in the Body

3.7 Command Decision Levels and Triaging Protocol

Upon completion of running the phantom models in MCNP, a dose rate per unit activity was determined. Based on commander's guidance in Medical Management for Radiological Casualties [6], a Command Decision Level (CDL) was established at which personnel would require additional dosimetric evaluation with the possibility for expedited evacuation from theater. The CDL was selected at 25 cGy. Using the DT-616 probe, readings would be taken at locations that produce the highest dose rate from the MIRD phantom model. A triage procedure sheet for military personnel provides information for AN/VDR-2 and AN/PDR-77 equipment operators to properly assess radiological casualties for inhaled contamination.

CHAPTER 4

RESULTS

4.1 Model Validation and Scaling Factors

In order to determine scaling factors and validate the model, the response from the detector in the laboratory was compared to the MCNP detector model. According to Jack Cooley, who was responsible for the engineering and development of the probe, the probe was designed to provide a tissue dose response with a roll-off around 100 keV [1]. Four different isotopes were measured using the DT-616 probe. Isotopes were selected to provide a range of energies for gamma-ray emission. Using the F4 tally on MCNP to compare ambient dose equivalent, a dose rate in units of picoSievert per second was obtained. This value was divided by the experimental response of the detector which was converted to picoSievert per second. The ratios of these values are shown in Figures 4.1.1 through 4.1.4. These ratios remain relatively constant over various PMMA thicknesses for each isotope. These results provide confidence in using the detector model in the MIRD phantoms.

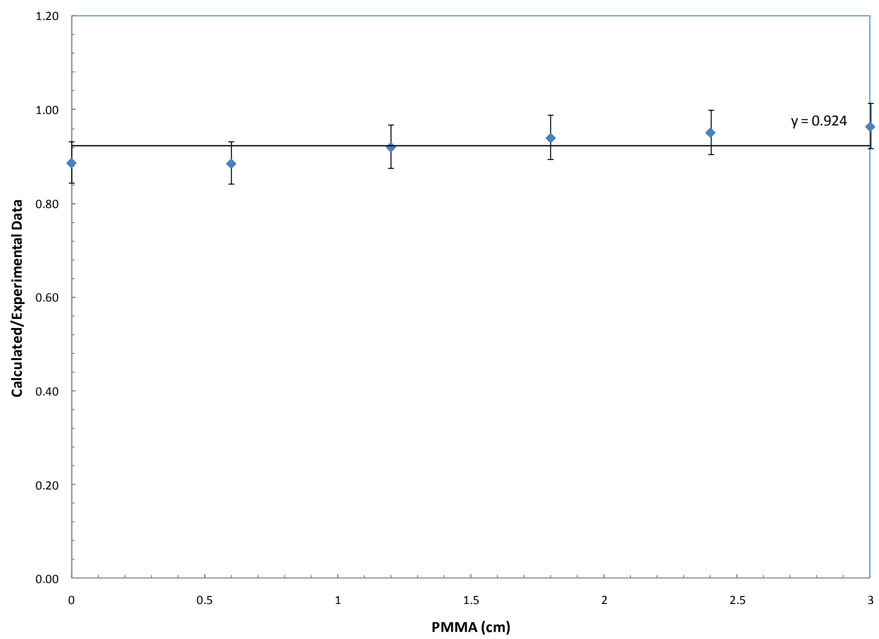


Figure 4.1.1 ^{137}Cs Scaling Factor

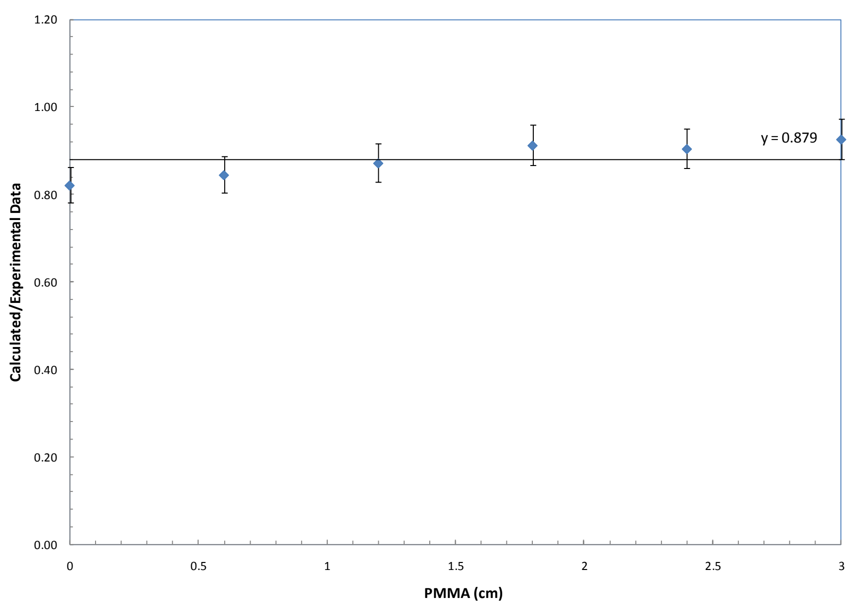


Figure 4.1.2 ^{60}Co Scaling Factor

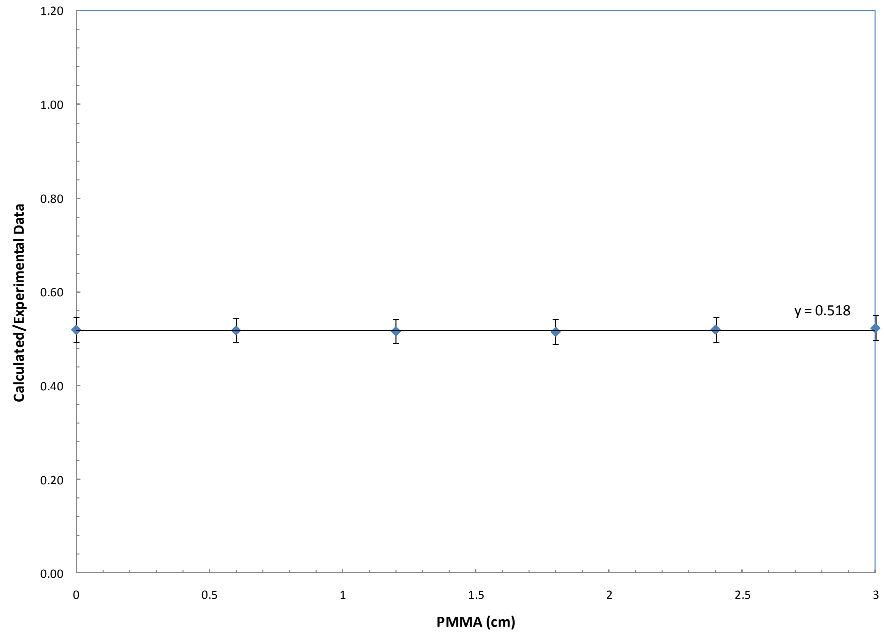


Figure 4.1.3 ^{57}Co Scaling Factor

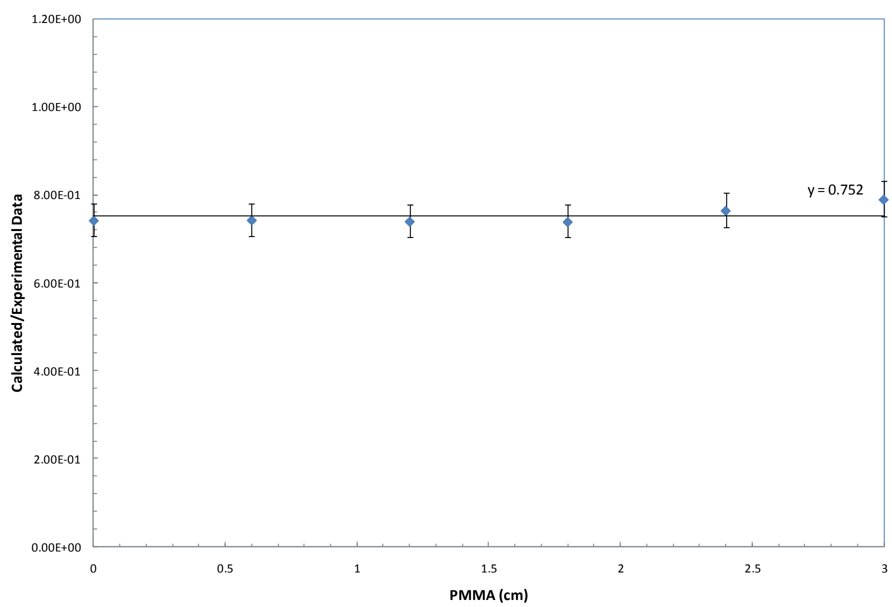


Figure 4.1.4 ^{22}Na Scaling Factor

Errors bar on the graphs represent a five percent fluctuation in both directions based on the readings of the detector. The detector takes an average of the time to count data over a period of two seconds. During the experimental measurements, the readings provided by the detector fluctuated within a ten percent range. Applying this factor of ten percent is reasonable according to Canberra [1]. The scaling factor for each of the isotopes was obtained by taking the average values of the calculated/experimental data. The scaling factor was plotted against the average photon energy of the isotope in Figure 4.1.5. Based on the dose response of the detector, a trend line was added as a log function to show the relationship between the energy and scaling factor.

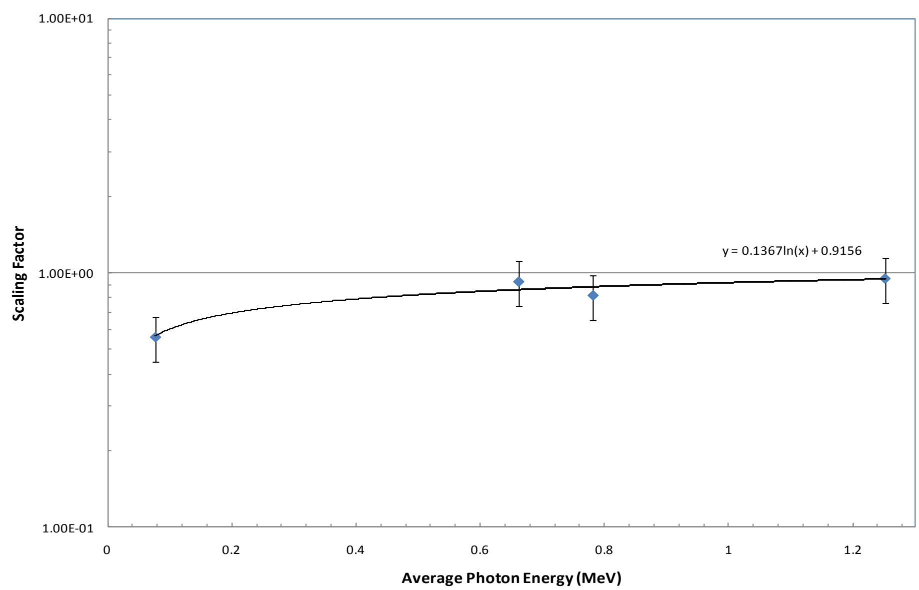


Figure 4.1.5 Scaling Factors vs. Average Photon

^{137}Cs is the isotope most commonly used by the Army to calibrate the radiac meter [24]. Therefore, the response of the detector for each isotope was normalized to provide the relative energy response with respect to ^{137}Cs. These data are shown in Figure 4.1.6.

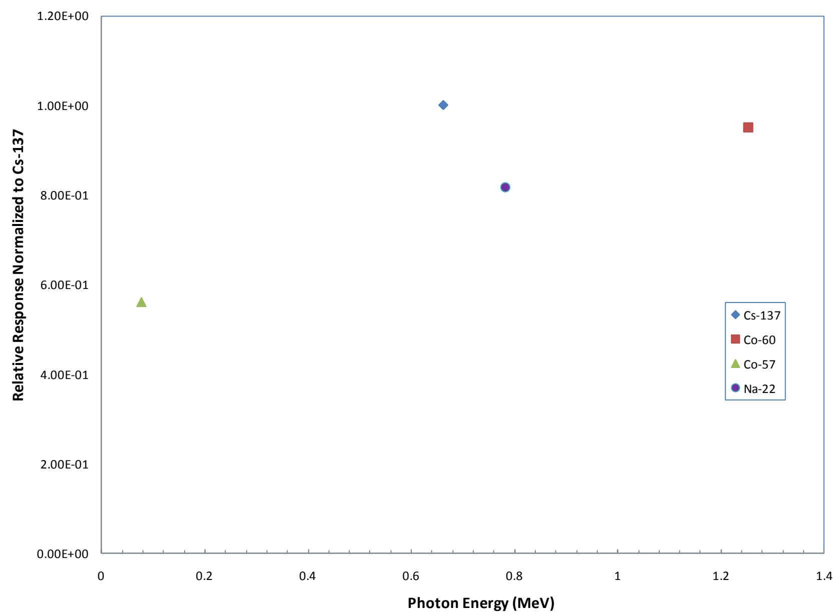


Figure 4.1.6 Relative Energy Response to ^{137}Cs

4.2 MIRD Phantom Results

An SCX tally modifier was used to generate a unit source in each organ and show the contribution of each organ to the detector reading at each location. It does not show the actual distribution of the isotope. Figures 4.2.1-4.2.3 show the contribution from each organ to the readings on the detector after the scaling factors have been applied. Units are displayed in picoSievert/second per becquerel. Initially, all of the activity detected using the DT-616 would be due to the isotope residing in the lungs. The results are shown for 12 hours after exposure, at which time the isotopes are able to migrate within the body. This is also a reasonable time for deployed military forces to detect the radiation, identify the isotope, and begin triage procedures.

Figure 4.2.1 illustrates that after 12 hours, nearly all of the ^{137}Cs has migrated from the lungs to the body tissue when classified in the fast inhalation class. The activity in the body tissue was distributed uniformly to all regions that were not compartments in the DCAL model, which includes the legs and areas in the torso not occupied by organs. This contribution from the body tissue results in nearly all of the activity detected by the DT-616 probe. When classified in the moderate inhalation class, the majority of activity read by the detector from ^{137}Cs still originates in the lungs, but with a large amount coming from body tissue as shown in Figure 4.2.2

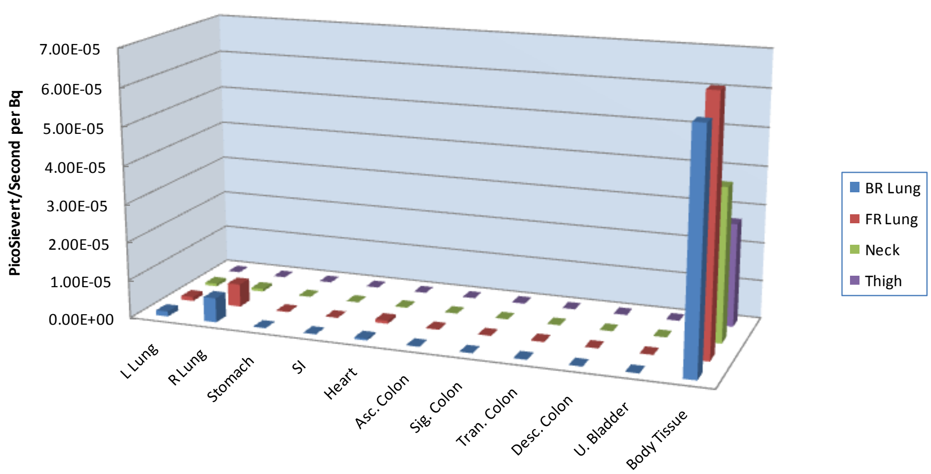


Figure 4.2.1 SCX Tally Results at 12 hours for Male with ^{137}Cs (Fast)

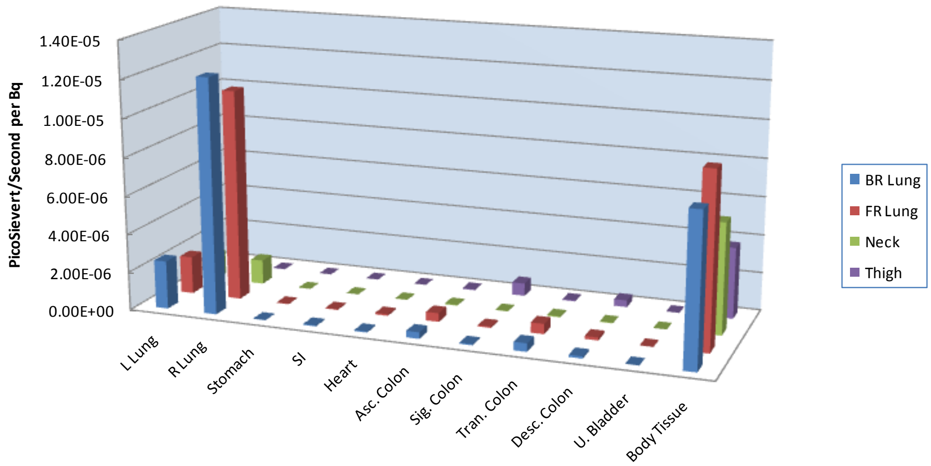


Figure 4.2.2 SCX Tally Results at 12 hours for Male with ^{137}Cs (Moderate)

Figures 4.2.3 and 4.2.4 illustrate the organs contributing to the detector readings at 12 hours for ^{60}Co and ^{192}Ir. For both of these isotopes, the majority of the reading is due to the isotope being absorbed in the lung.

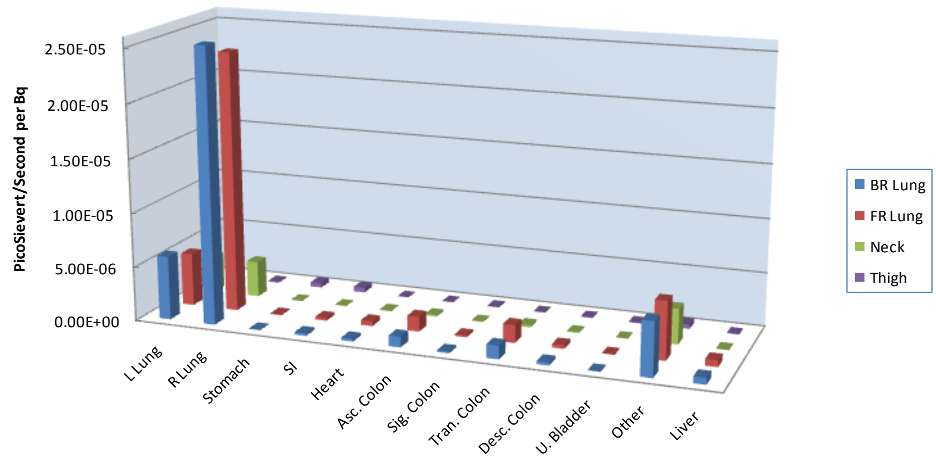


Figure 4.2.3 SCX Tally Results at 12 hours for Male with ^{60}Co

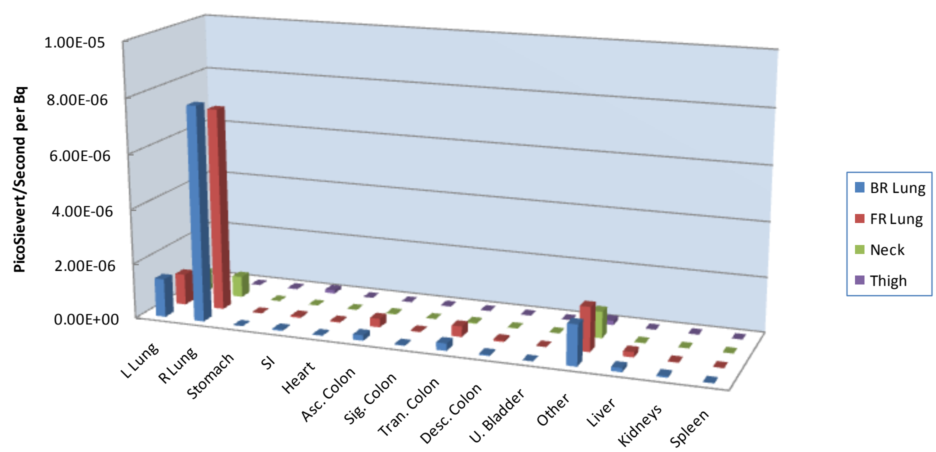


Figure 4.2.4 SCX Tally Results at 12 hours for Male with ^{192}Ir

The estimated radiac dose rate reading using an AN/VDR-2 or AN/PDR-77 was calculated with the output of the MCNP file. Using the SCX tally, the ambient dose equivalent was calculated for significant organs for each detector location. This data was folded with the biokinetic information provided using DCAL to obtain the contribution of each organ to the reading of the detector. The result was summed to determine the expected detector reading from one becquerel of activity from the isotope. The results for the male phantom using an AN/VDR-2 for ^{137}Cs, ^{60}Co and Ir-92 are in Tables 4.2.1-4.2.4. The estimated radiac dose rate reading per becquerel for the female phantoms is located in Appendix A.

Table 4.2.1 Radiac Dose Rate Reading per Bq for Male Phantom with ^{137}Cs (Fast)

	Time (Days)	Back Right Lung µGy/hr per Bq	Front Right Lung µGy/hr per Bq	Neck µGy/hr per Bq	Thigh µGy/hr per Bq
Days following exposure	0	7.05E-08	6.49E-08	1.33E-08	1.86E-10
	0.5	2.72E-07	2.90E-07	1.61E-07	1.06E-07
	1	3.09E-07	3.31E-07	1.93E-07	1.28E-07
	2	3.06E-07	3.29E-07	1.96E-07	1.32E-07
	3	2.97E-07	3.20E-07	1.91E-07	1.29E-07
	4	2.90E-07	3.12E-07	1.88E-07	1.27E-07
	5	2.85E-07	3.07E-07	1.85E-07	1.25E-07
	6	2.81E-07	3.03E-07	1.82E-07	1.23E-07
	7	2.78E-07	3.00E-07	1.80E-07	1.22E-07
	8	2.75E-07	2.97E-07	1.78E-07	1.21E-07
	9	2.73E-07	2.94E-07	1.77E-07	1.20E-07
	10	2.71E-07	2.92E-07	1.76E-07	1.19E-07
	12	2.67E-07	2.87E-07	1.73E-07	1.17E-07
	14	2.63E-07	2.83E-07	1.71E-07	1.15E-07
	20	2.53E-07	2.73E-07	1.64E-07	1.11E-07
	30	2.37E-07	2.56E-07	1.54E-07	1.04E-07

Table 4.2.2 Radiac Dose Rate Reading per Bq for Male Phantom with ^{137}Cs (Moderate)

	Time (Days)	Back Right Lung µGy/hr per Bq	Front Right Lung µGy/hr per Bq	Neck µGy/hr per Bq	Thigh µGy/hr per Bq
Days following exposure	0	7.05E-08	6.49E-08	1.33E-08	1.86E-10
	0.5	9.28E-08	9.21E-08	3.01E-08	1.58E-08
	1	8.87E-08	8.87E-08	3.38E-08	2.05E-08
	2	7.91E-08	7.94E-08	3.33E-08	2.01E-08
	3	7.44E-08	7.48E-08	3.24E-08	1.87E-08
	4	7.23E-08	7.28E-08	3.20E-08	1.80E-08
	5	7.13E-08	7.19E-08	3.18E-08	1.78E-08
	6	7.07E-08	7.13E-08	3.17E-08	1.77E-08
	7	7.03E-08	7.10E-08	3.17E-08	1.77E-08
	8	7.00E-08	7.08E-08	3.17E-08	1.77E-08
	9	6.98E-08	7.06E-08	3.17E-08	1.78E-08
	10	6.96E-08	7.05E-08	3.18E-08	1.79E-08
	12	6.93E-08	7.02E-08	3.19E-08	1.81E-08
	14	6.90E-08	7.00E-08	3.20E-08	1.82E-08
	20	6.81E-08	6.94E-08	3.24E-08	1.87E-08
	30	6.66E-08	6.83E-08	3.28E-08	1.93E-08

Table 4.2.3 Radiac Dose Rate Reading per Bq for Male Phantom with ^{60}Co

	Time (Days)	Back Right Lung µGy/hr per Bq	Front Right Lung µGy/hr per Bq	Neck µGy/hr per Bq	Thigh µGy/hr per Bq
Days following exposure	0	2.91E-07	2.69E-07	2.69E-07	6.20E-08
	0.5	1.65E-07	1.43E-07	1.61E-07	3.16E-08
	1	1.44E-07	1.15E-07	1.41E-07	2.62E-08
	2	1.21E-07	8.78E-08	1.18E-07	2.08E-08
	3	1.10E-07	7.78E-08	1.08E-07	1.86E-08
	4	1.05E-07	7.37E-08	1.02E-07	1.77E-08
	5	1.01E-07	7.18E-08	9.86E-08	1.72E-08
	6	9.84E-08	7.06E-08	9.58E-08	1.70E-08
	7	9.62E-08	6.98E-08	9.36E-08	1.67E-08
	8	9.42E-08	6.90E-08	9.15E-08	1.65E-08
	9	9.23E-08	6.84E-08	8.97E-08	1.64E-08
	10	9.06E-08	6.77E-08	8.80E-08	1.62E-08
	12	8.76E-08	6.65E-08	8.50E-08	1.59E-08
	14	8.49E-08	6.53E-08	8.23E-08	1.56E-08
	20	7.85E-08	6.22E-08	7.61E-08	1.48E-08
	30	7.11E-08	5.80E-08	6.91E-08	1.38E-08

Table 4.2.4 Radiac Dose Rate Reading per Bq for Male Phantom with ^{192}Ir

	Time (Days)	Back Right Lung µGy/hr per Bq	Front Right Lung µGy/hr per Bq	Neck µGy/hr per Bq	Thigh µGy/hr per Bq
Days following exposure	0	9.88E-08	9.12E-08	1.63E-08	1.41E-10
	0.5	5.36E-08	5.23E-08	1.20E-08	4.98E-09
	1	4.59E-08	4.46E-08	1.16E-08	6.16E-09
	2	3.74E-08	3.63E-08	1.05E-08	5.38E-09
	3	3.39E-08	3.30E-08	9.90E-09	4.52E-09
	4	3.23E-08	3.15E-08	9.62E-09	4.10E-09
	5	3.14E-08	3.06E-08	9.45E-09	3.92E-09
	6	3.07E-08	3.00E-08	9.32E-09	3.84E-09
	7	3.02E-08	2.95E-08	9.21E-09	3.80E-09
	8	2.97E-08	2.90E-08	9.11E-09	3.78E-09
	9	2.92E-08	2.85E-08	9.02E-09	3.77E-09
	10	2.87E-08	2.81E-08	8.93E-09	3.75E-09
	12	2.78E-08	2.73E-08	8.76E-09	3.73E-09
	14	2.70E-08	2.65E-08	8.60E-09	3.71E-09
	20	2.47E-08	2.43E-08	8.16E-09	3.64E-09
	30	2.15E-08	2.14E-08	7.52E-09	3.53E-09

The percentage error for the analysis conducted using MNCP was calculated for each organ using the SCX tally modifier card. The error was averaged over all organs for each detector location and isotope. The overall error for all detectors and isotopes was approximately 1.7%. The error was the lowest for detectors placed over the anterior right lung and posterior right lung, which averaged below 1%. The error was highest for the detector placed on the left thigh, which averaged around 3%.

4.3 Phantom Isotope Decision Levels

The estimated reading above the background of each detector location for a given isotope at the CDL was calculated. If the detector reading is above this level, it is recommended for the person to receive additional dosimetric evaluation. In order to calculate the radiac dose rate reading which corresponds to one CDL, the radiac dose rate reading per becquerel is multiplied by the number of becquerel per CDL. The CDL, previously established at 25 cGy, was divided by the ICRP dose coefficient for each isotope to determine the number of becquerel per CDL. For ^{137}Cs, which was classified as a fast inhalation class, the dose coefficient used was 4.6 x 10^{-07} rem per becquerel. As moderate inhalation class, the dose coefficient used was 9.7 x 10^{-07} rem per becquerel. ^{60}Co and ^{192}Ir were both considered as moderate inhalation class and dose coefficients used were 1 x 10^{-06} and 4.81 x 10^{-07} rem per becquerel, respectively. Table 4.3.1 shows the expected readings for one CDL for a male with internal ^{137}Cs contamination at a fast inhalation class using the AN/VDR-2. The highest readings were obtained with detector placements at the lungs. Table 4.3.2 shows the expected readings for ^{137}Cs at a moderate inhalation class.

Table 4.3.1 Radiac Dose Rate Reading per CDL for Male with ^{137}Cs (Fast) using AN/VDR-2

	Time (Days)	Back Right Lung µGy/hr per CDL	Front Right Lung µGy/hr per CDL	Neck µGy/hr per CDL	Thigh µGy/hr per BCDL
Days following exposure	Class →	F	F	F	F
	0	3.83E+00	3.76E+00	7.72E-01	2.56E-02
	0.5	1.58E+01	1.68E+01	9.36E+00	1.46E+01
	1	1.79E+01	1.92E+01	1.12E+01	1.77E+01
	2	1.78E+01	1.91E+01	1.14E+01	1.82E+01
	3	1.72E+01	1.85E+01	1.11E+01	1.79E+01
	4	1.68E+01	1.81E+01	1.09E+01	1.75E+01
	5	1.65E+01	1.78E+01	1.07E+01	1.72E+01
	6	1.63E+01	1.76E+01	1.06E+01	1.70E+01
	7	1.61E+01	1.74E+01	1.05E+01	1.68E+01
	8	1.60E+01	1.72E+01	1.04E+01	1.67E+01
	9	1.58E+01	1.71E+01	1.03E+01	1.65E+01
	10	1.57E+01	1.69E+01	1.02E+01	1.64E+01
	12	1.55E+01	1.67E+01	1.00E+01	1.61E+01
	14	1.53E+01	1.64E+01	9.89E+00	1.59E+01
	20	1.47E+01	1.58E+01	9.51E+00	1.53E+01
	30	1.38E+01	1.48E+01	8.93E+00	1.44E+01

Table 4.3.2 Radiac Dose Rate Reading per CDL for Male with ^{137}Cs (Moderate) using AN/VDR-2

	Time (Days)	Back Right Lung µGy/hr per CDL	Front Right Lung µGy/hr per CDL	Neck µGy/hr per CDL	Thigh µGy/hr per BCDL
	Class →	M	M	M	M
Days following exposure	0	1.82E+00	1.14E+00	1.03E-02	6.78E-04
	0.5	2.65E+00	9.09E-01	2.43E-01	2.39E-02
	1	2.29E+00	8.96E-01	2.99E-01	2.96E-02
	2	1.89E+00	8.23E-01	2.56E-01	2.59E-02
	3	1.73E+00	7.83E-01	2.11E-01	2.17E-02
	4	1.65E+00	7.63E-01	1.89E-01	1.97E-02
	5	1.61E+00	7.51E-01	1.80E-01	1.88E-02
	6	1.57E+00	7.42E-01	1.76E-01	1.85E-02
	7	1.55E+00	7.34E-01	1.74E-01	1.83E-02
	8	1.52E+00	7.27E-01	1.73E-01	1.82E-02
	9	1.50E+00	7.20E-01	1.72E-01	1.81E-02
	10	1.47E+00	7.13E-01	1.71E-01	1.80E-02
	12	1.43E+00	7.01E-01	1.70E-01	1.79E-02
	14	1.39E+00	6.89E-01	1.69E-01	1.78E-02
	20	1.27E+00	6.57E-01	1.66E-01	1.75E-02
	30	1.12E+00	6.10E-01	1.61E-01	1.70E-02

Tables 4.3.3 and 4.3.4 show the radiac dose rate readings obtained for one CDL of deposition for the ^{60}Co and ^{192}Ir using the AN/VDR-2. For both of these isotopes, the highest readings are obtained with the detector placement at the posterior right lung. Similar results were obtained using the female phantoms. The detector readings for the AN/PDR-77 for the male phantom and the detector readings for the AN/VDR-2 and AN/PDR-77 for the female phantom are located in Appendix A.

Table 4.3.3 Radiac Dose Rate Reading per CDL for Male with ^{60}Co using AN/VDR-2

Days following exposure	Time (Days)	Back Right Lung µGy/hr per CDL	Front Right Lung µGy/hr per CDL	Neck µGy/hr per CDL	Thigh µGy/hr per CDL
	Class →	M	M	M	M
	0	7.27E+00	6.72E+00	1.55E+00	4.67E-02
	0.5	4.12E+00	4.03E+00	1.09E+00	5.14E-01
	1	3.60E+00	3.52E+00	1.09E+00	6.50E-01
	2	3.03E+00	2.95E+00	1.04E+00	6.02E-01
	3	2.76E+00	2.69E+00	9.86E-01	5.12E-01
	4	2.62E+00	2.55E+00	9.44E-01	4.55E-01
	5	2.53E+00	2.46E+00	9.09E-01	4.21E-01
	6	2.46E+00	2.40E+00	8.80E-01	3.99E-01
	7	2.40E+00	2.34E+00	8.55E-01	3.83E-01
	8	2.35E+00	2.29E+00	8.33E-01	3.69E-01
	9	2.31E+00	2.24E+00	8.13E-01	3.58E-01
	10	2.27E+00	2.20E+00	7.95E-01	3.47E-01
	12	2.19E+00	2.12E+00	7.64E-01	3.31E-01
	14	2.12E+00	2.06E+00	7.38E-01	3.18E-01
	20	1.96E+00	1.90E+00	6.81E-01	2.93E-01
	30	1.78E+00	1.73E+00	6.28E-01	2.76E-01

Table 4.3.4 Radiac Dose Rate Reading per CDL for Male with ^{192}Ir using AN/VDR-2

Days following exposure	Time (Days)	Back Right Lung µGy/hr per CDL	Front Right Lung µGy/hr per CDL	Neck µGy/hr per CDL	Thigh µGy/hr per CDL
	Class →	M	M	M	M
	0	4.75E+00	4.39E+00	7.84E-01	6.78E-03
	0.5	2.58E+00	4.25E+00	5.77E-01	2.39E-01
	1	2.20E+00	2.15E+00	5.57E-01	2.96E-01
	2	1.80E+00	1.75E+00	5.03E-01	2.59E-01
	3	1.63E+00	1.59E+00	4.76E-01	2.17E-01
	4	1.55E+00	1.51E+00	4.62E-01	1.97E-01
	5	1.51E+00	1.47E+00	4.54E-01	1.88E-01
	6	1.48E+00	1.44E+00	4.48E-01	1.85E-01
	7	1.45E+00	1.42E+00	4.43E-01	1.83E-01
	8	1.43E+00	1.39E+00	4.38E-01	1.82E-01
	9	1.40E+00	1.37E+00	4.34E-01	1.81E-01
	10	1.38E+00	1.35E+00	4.29E-01	1.80E-01
	12	1.34E+00	1.31E+00	4.21E-01	1.79E-01
	14	1.30E+00	1.27E+00	4.14E-01	1.78E-01
	20	1.19E+00	1.17E+00	3.93E-01	1.75E-01
	30	1.04E+00	1.03E+00	3.62E-01	1.70E-01

A graphical comparison of the external dose rate readings as indicated by the detector in the male phantoms for the three isotopes is shown in Figures 4.3.1 through 4.3.4

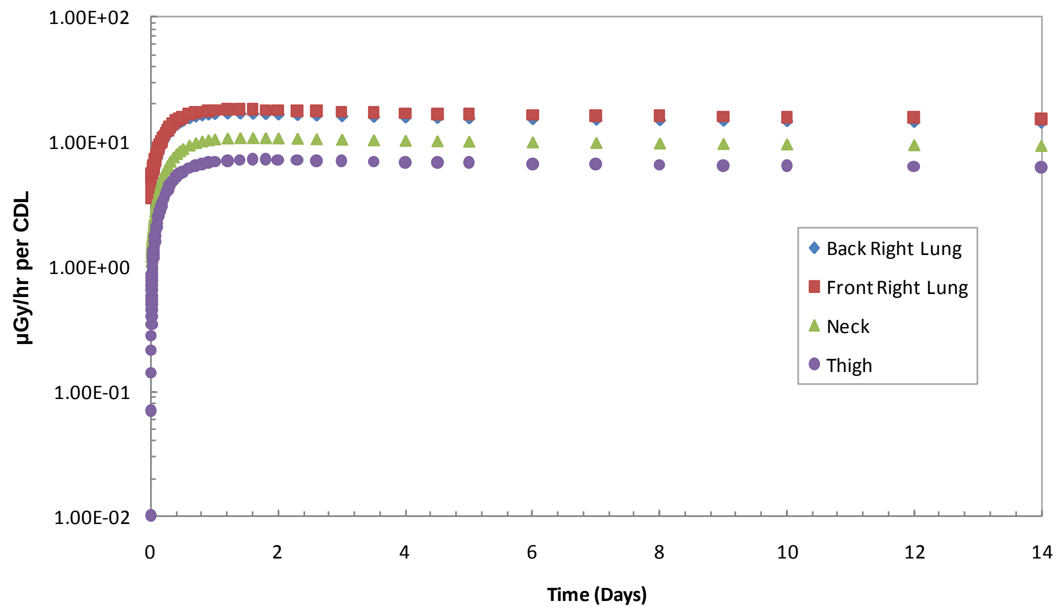


Figure 4.3.1 Radiac Dose Rate Reading per CDL for Male with ^{137}Cs (Fast)

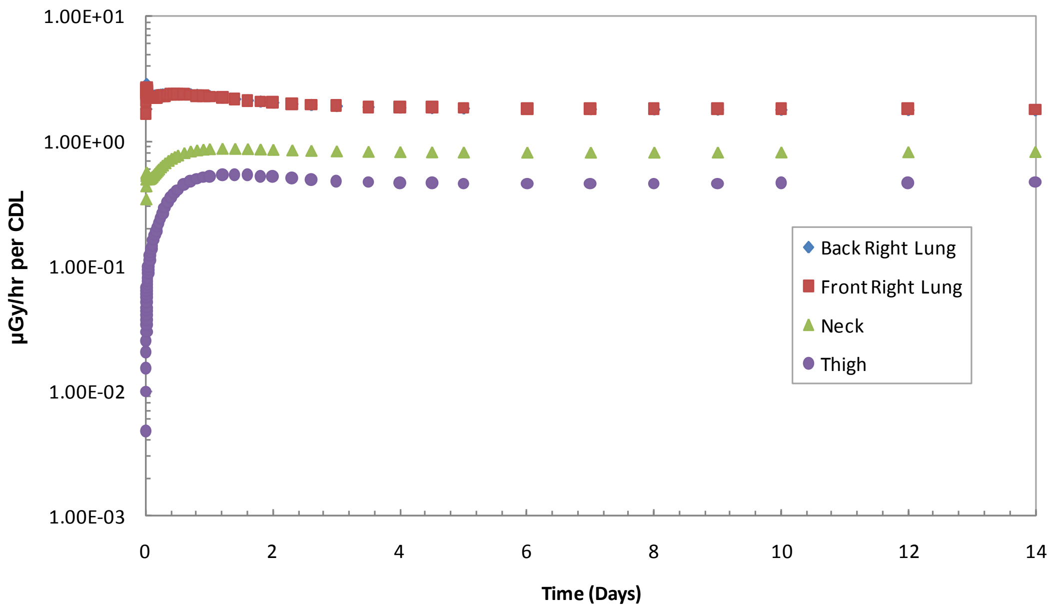


Figure 4.3.2 Radiac Dose Rate Reading per CDL for Male with ^{137}Cs (Moderate)

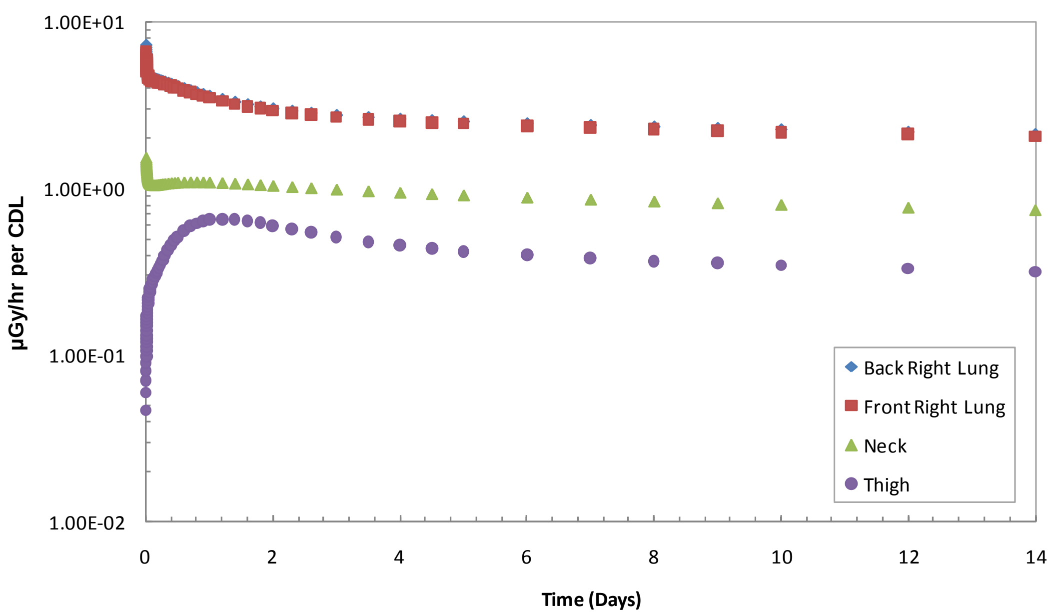


Figure 4.3.3 Radiac Dose Rate Reading per CDL for Male with ^{60}Co

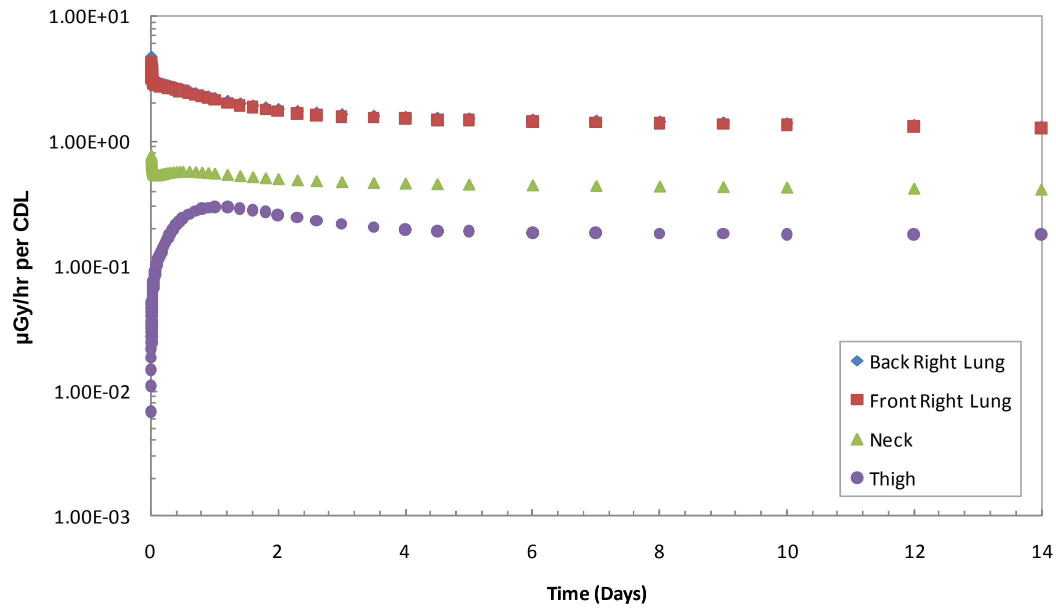


Figure 4.3.4 Radiac Dose Rate Reading per CDL for Male with ^{192}Ir

For the three isotopes, the highest dose rate readings came from the posterior right lung. Similar results were also found using the female phantoms. For triage procedures, all readings should be taken using the posterior right lung.

The changes in radiac dose rate reading per CDL are comparable for ^{60}Co and ^{192}Ir, as the graphs have similar curves. This can be attributed to the isotopes having similar chemical properties due to the number of valence electrons, and the same inhalation class. The retention rate of ^{192}Ir is slightly lower than that of ^{60}Co which may be partially due to ^{192}Ir having an effective half-life of 74 days compared to that of ^{60}Co which is at 5.27 years [32]. When factoring in the biological removal from the body, the effective half-life of ^{192}Ir is slightly less than ^{60}Co. The external dose rate reading per CDL using the DT-616 for ^{60}Co is approximately 60 percent greater than the dose rate per CDL for ^{192}Ir. This can be attributed to ^{60}Co emitting higher energy gamma rays which are more likely to be detected by the DT-616 probe.

The radiac dose rate reading per CDL for ^{137}Cs is significantly higher than that of ^{60}Co and ^{192}Ir. This can be attributed to several reasons. ^{137}Cs is classified as "fast" inhalation class, and ^{60}Co and ^{192}Ir are both considered as "moderate" inhalation class. These classes are based on the International Commission of Radiological Protection (ICRP) defaults [40]. The dose coefficient for ^{137}Cs is less than half of that for ^{60}Co. As a "fast" inhalation class, ^{137}Cs tends to migrate away from the lungs at a faster rate than isotopes with a moderate class. Since the ^{137}Cs is deposited in body tissue as opposed to the lungs, it is closer to the surface of the body. As a result, there is less attenuation of the gamma rays, resulting in a larger reading by the DT-616. When ^{137}Cs was treated as a moderate inhalation class, the radiac dose rate reading per CDL is approximately 12% of the radiac dose rate reading per CDL when treated as a fast inhalation class. Additionally, the dose rate per CDL is comparable to that of ^{60}Co and ^{192}Ir.

In determining the decision levels, one also needs to evaluate the "detection limit" of the counting system. The minimum radiac dose rate reading above the background reading resulting in real activity must be determined. The average background dose rate in the laboratory was 0.198 μGy/hr. Since the detector uses GM tubes, the dose rate is actually a count rate. Using the count rate per unit activity data obtained from Canberra (Figure 4.3.5), the background count rate was determined to be 35.8 cpm. When the number of counts is over 30, the Central Limit Theorem applies, and both the mean of the net counts and sample counts should both follow a Normal distribution.

False positives are the result of an increased reading on the detector when there is no real activity present. Fluctuations could be due to counting statistics, and positive indications could actually be false positives. In order to limit the false positives, the critical level, L_c should be set high enough to ensure a measure of statistical certainty. To ensure false positives are no greater than 5%, the following equation should be used [27]

$$L_C = 1.645\ \sigma_{N_S} = 1.645\sqrt{2}\ \sigma_{N_B} = 2.326\ \sigma_B \qquad \text{[Equation 4.3.1]}$$

Using equation 4.3.1, L_c is equal to 13.921 cpm. Therefore any activity that is 13.92 cpm or 0.077 μGy/hr above the background may be considered to be real activity. This value is significantly below the activity per CDL, making the detector readings following one week of exposure statistically significant.

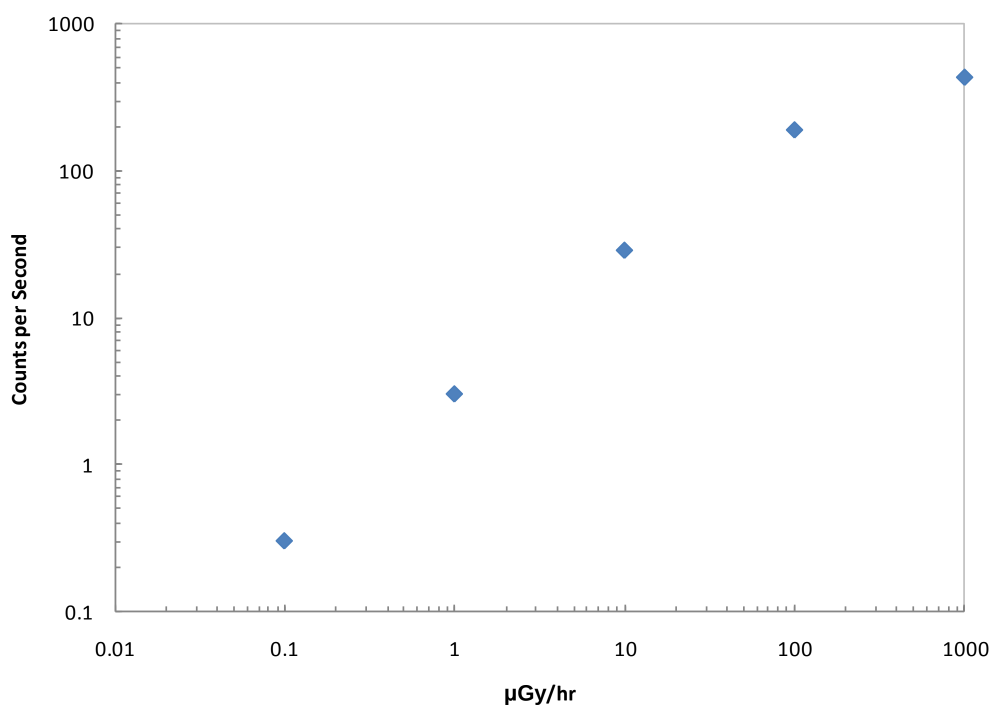


Figure 4.3.5 AN/VDR-2 Counts per Dose Rate

4.4 Triage Procedure Sheets

In order for these results to be utilized by military personnel in the event of an RDD, triaging procedure sheets were developed. The procedure sheets are for equipment operators to evaluate personnel and determine if further dosimetric evaluation is required. Separate procedure sheets were developed for the AN/VDR-2 and AN/PDR-77. Although there should be several trained operators to use each piece of equipment, the procedure sheets also include basic operation of the detectors. In MCNP, the detector was placed one inch away from the surface of the phantom. Additional files were also run using MCNP with the detector on the surface of the phantom. The resulting dose rate per CDL was approximately 30% greater than when the detector was placed one inch away. By using the lower number at one inch away, it provides a more conservative estimate. Tables 4.4.1 and 4.4.2 indicate the expected dose rate reading for individuals who have inhaled one CDL of isotope. ^{137}Cs was treated as a moderate inhalation class in order to obtain a more conservative reading. These values reported are the same as those used in the triage sheets in Appendix B.

Table 4.4.1 Radiac Dose Rate Reading per CDL using the AN/VDR-2

Days following exposure	Gender	Readings are in µGy/hr per CDL					
		Male			Female		
	Isotope	^{137}Cs	^{60}Co	^{192}Ir	^{137}Cs	^{60}Co	^{192}Ir
	0	1.82	7.27	4.75	1.83	7.37	4.85
	0.5	2.39	4.12	2.58	2.52	3.84	2.65
	1	2.29	3.60	2.20	2.47	3.23	2.29
	2	2.04	3.03	1.80	2.24	2.60	1.89
	3	1.92	2.76	1.63	2.12	2.34	1.73
	4	1.86	2.62	1.55	2.07	2.22	1.65
	5	1.84	2.53	1.51	2.04	2.14	1.61
	6	1.82	2.46	1.48	2.03	2.09	1.57
	7	1.81	2.40	1.45	2.02	2.05	1.55
	8	1.80	2.35	1.43	2.01	2.01	1.52
	9	1.80	2.31	1.40	2.01	1.97	1.50
	10	1.79	2.27	1.38	2.01	1.94	1.47

Table 4.4.2 Radiac Dose Rate Reading per CDL using the AN/PDR-77

Days following exposure	Gender	Readings are in mR/hr per CDL					
		Male			Female		
	Isotope	^{137}Cs	^{60}Co	^{192}Ir	^{137}Cs	^{60}Co	^{192}Ir
	0	0.18	0.73	0.48	0.18	0.74	0.48
	0.5	0.24	0.41	0.26	0.25	0.38	0.26
	1	0.23	0.36	0.22	0.25	0.32	0.23
	2	0.20	0.30	0.18	0.22	0.26	0.19
	3	0.19	0.28	0.16	0.21	0.23	0.17
	4	0.19	0.26	0.16	0.21	0.22	0.17
	5	0.18	0.25	0.15	0.20	0.21	0.16
	6	0.18	0.25	0.15	0.20	0.21	0.16
	7	0.18	0.24	0.15	0.20	0.20	0.15
	8	0.18	0.24	0.14	0.20	0.20	0.15
	9	0.18	0.23	0.14	0.20	0.20	0.15
	10	0.18	0.23	0.14	0.20	0.19	0.15

CHAPTER 5

CONCLUSIONS

In the event of an RDD attack in a combat area, the AN/VDR-2 and AN/PDR-77 radiac detectors can be used to triage personnel who have received internal contamination from ^{137}Cs, ^{60}Co or ^{192}Ir. The minimum detectable activity (MDA) was determined to be 0.077 μGy/hr above the background dose rate, which is insignificant compared to the radiac dose rate reading per CDL for each of the isotopes. Inhalation classes and detector placement were selected to provide a conservative estimate of triage level, thus minimizing false negatives.

The AN/VDR-2 is widely available to combat units currently deployed to Iraq and Afghanistan, and will likely remain in the military inventory for the next decade. Although there is better technology available to detect internal contamination, including gamma cameras and the Whole Body Counter, these devices are not available to deployed units, and will not likely become available in the theater of operations until the use of RDDs becomes a common occurrence.

Both radiac sets are not able to detect isotopes with low energy gamma photons including Am-241 and Sr-90. As a result, traditional methods to assess casualties, including the use of bioassays and determining the level of contamination based on clinical symptoms, will continue to be the only methods available to assess these casualties.

CHAPTER 6

FUTURE WORK

This study focused on the specific scenario of an RDD detonation in a combat environment evaluating three isotopes of interest to the military. As a result it focused on one probe being used to evaluate an average male and female, which would be typical of the population of the military.

This research could be expanded by increasing the size of the population evaluated. In order to triage civilians on the battlefield, including contractors working for US and allied forces and local nationals, additional phantoms would be needed to account for various body types. Additionally, the AN/VDR-2 could also be used by military personnel to triage casualties in a domestic event involving an RDD.

Although there were only three isotopes considered in this research, there are several other isotopes identified by the Army, the Centers for Disease Control and Prevention, the DOE and Nuclear Regulatory Commission which are also of interest and could be studied further [6]. The DT-616 probe has a limited ability to detect low energy gamma radiation. The IM-263 radiacmeter in the AN/PDR-77 kit can be used with eight different probes. The DT-674 x-ray probe contains a 5” diameter x 0.25” thick NaI scintillation crystal and a 2” diameter PMT. This probe is able to detect low energy photons at 17 keV with upper and lower discriminators set for 12.5 and 21.5 keV, as well photons at 60 keV with upper and lower discriminators set at 52 and 68 keV. Although the AN/PDR-77 is not as widely available in forward deployed and combat areas as the AN/VDR-2, there is the potential to use this probe in the future to detect isotopes that produce photons of low energy. There is a Radiation Protection Officer (RPO) accessory kit which can also be used with the IM-263 from the AN/PDR-77. This kit includes a pancake beta probe and micro-R probe. The micro-R probe contains a 1” x 1.5” NaI scintillation crystal and 1” diameter PMT. The x-ray probe and the micro-R probe can be modified for use with several portable multi-channel analyzers that are available commercially [24].

There is potential to model these additional probes in order to expand the capability to triage casualties who inhale isotopes of lower gamma ray energy compared those assessed in this research.

APPENDIX A

MIRD PHANTOM RESULTS

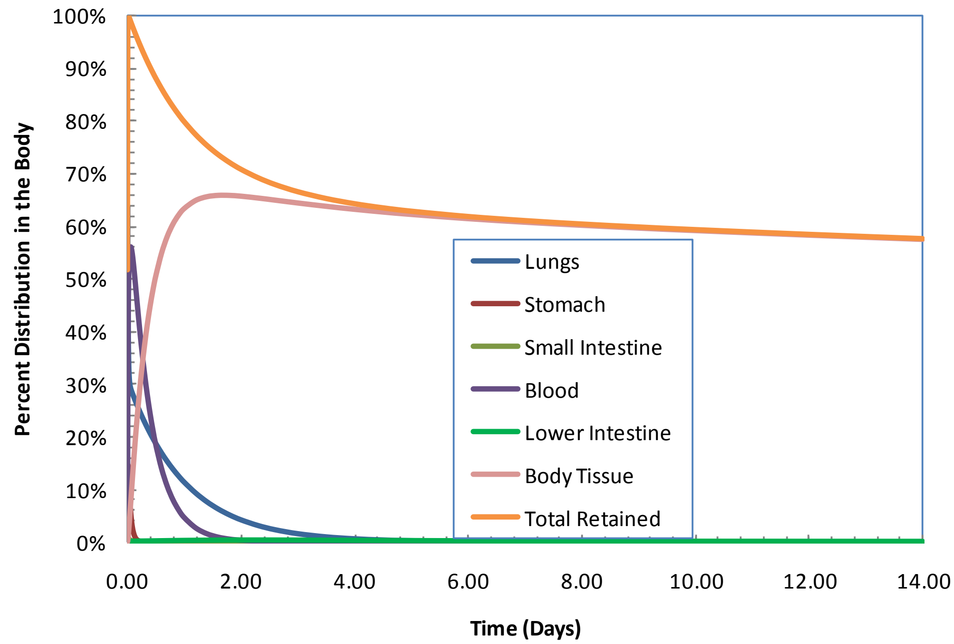


Figure A.1 Distribution of ^{137}Cs (Fast) in Female Phantom

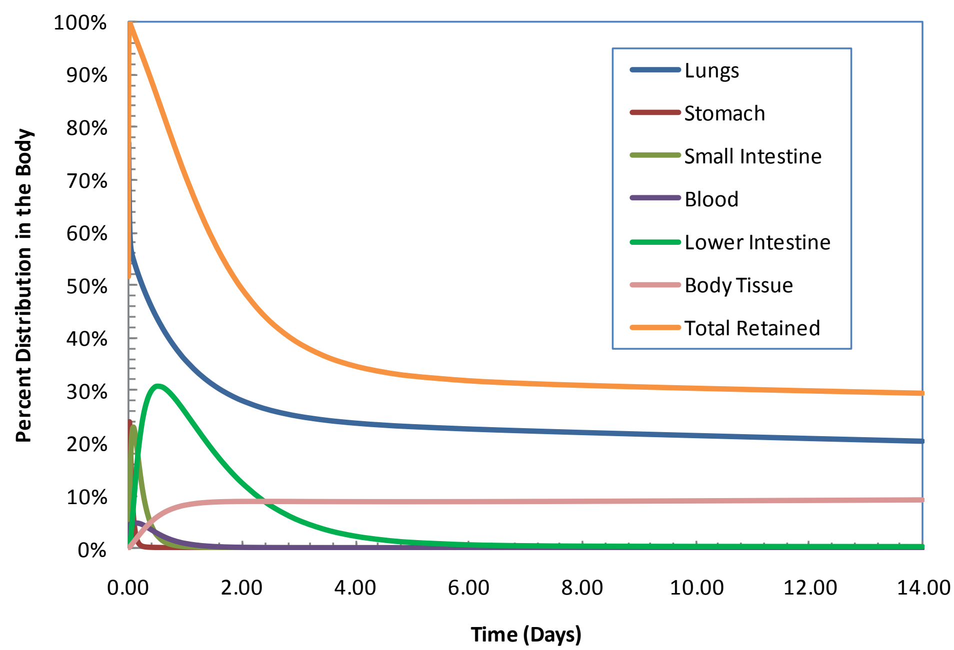


Figure A.2 Distribution of ^{137}Cs (Moderate) in Female Phantom

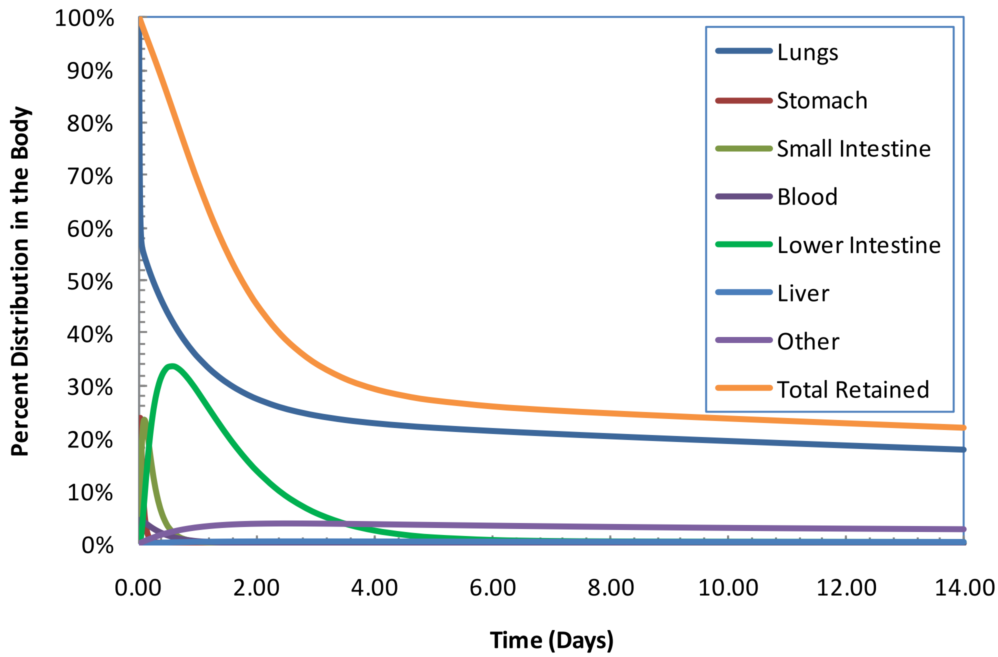


Figure A.3 Distribution of ^{60}Co in Female Phantom

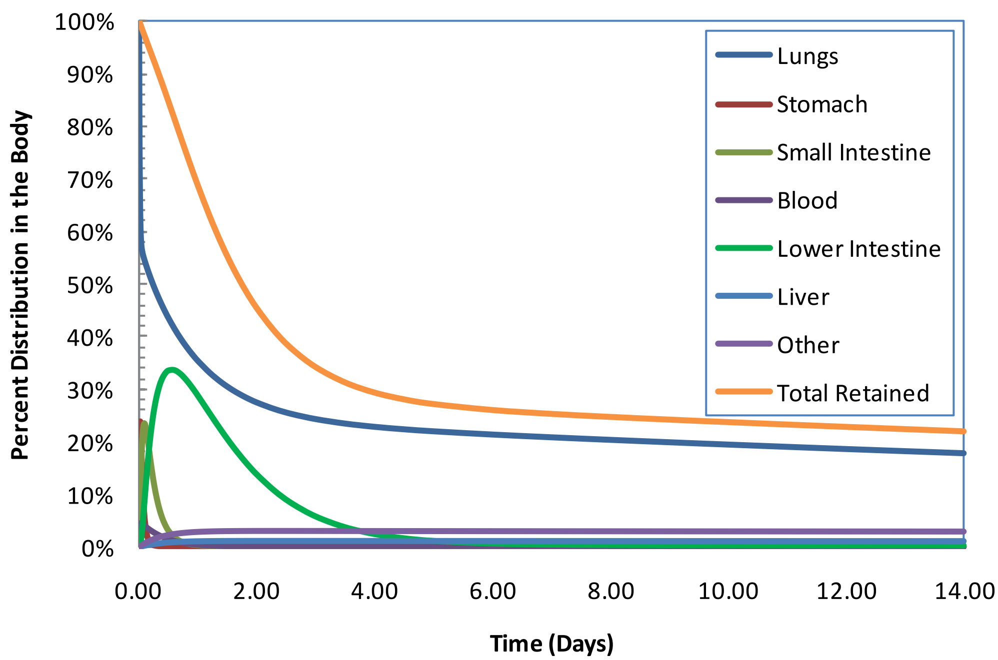


Figure A.4 Distribution of ^{192}Ir in Female Phantom

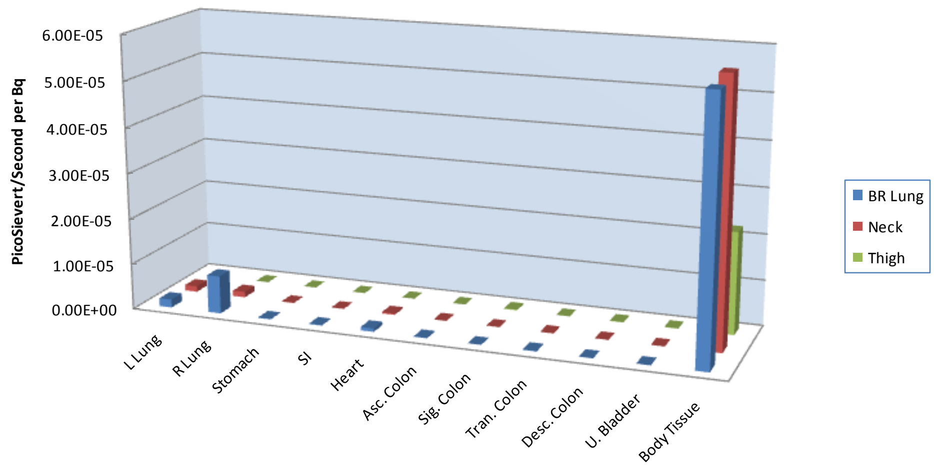


Figure A.5 SCX Tally Results at 12 hours for Female with ^{137}Cs (Fast)

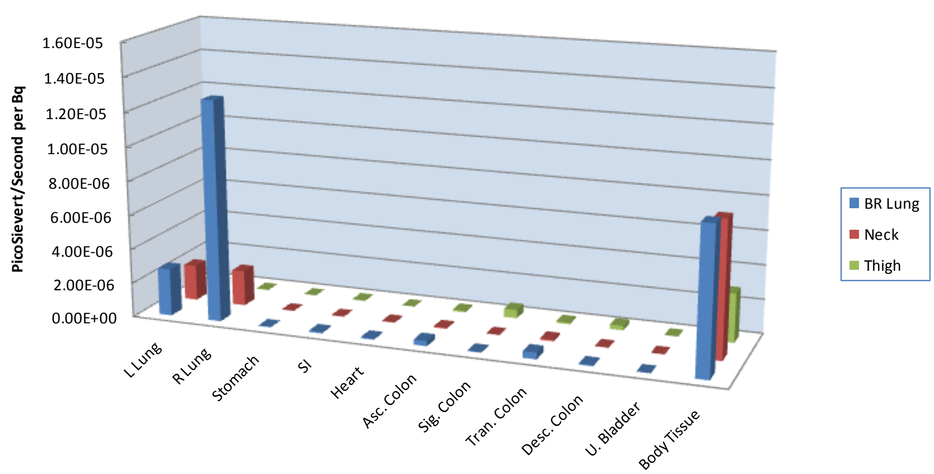


Figure A.6 SCX Tally Results at 12 hours for Female with ^{137}Cs (Moderate)

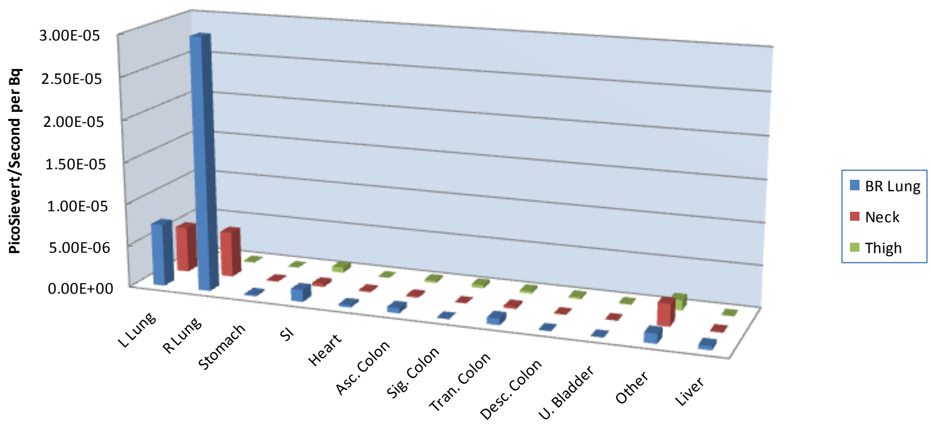


Figure A.7 SCX Tally Results at 12 hours for Female with ^{60}Co

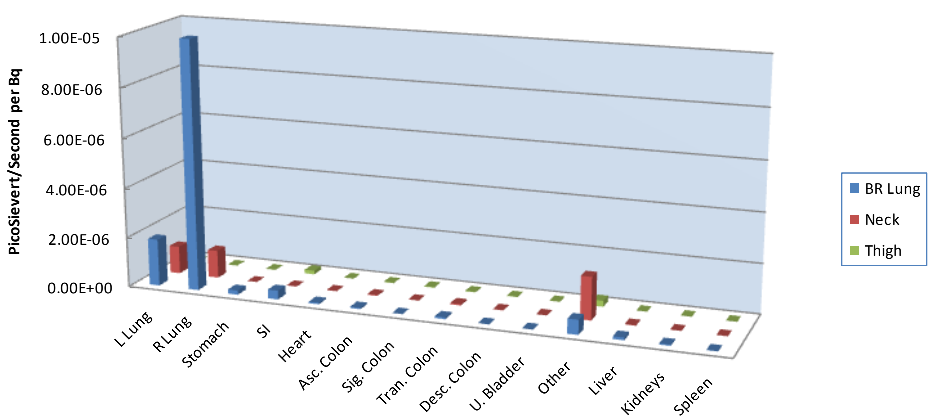


Figure A.8 SCX Tally Results at 12 hours for Female with ^{192}Ir

Table A.1 Radiac Dose Rate Reading per Bq for Female Phantom with ^{137}Cs (Fast)

	Time (Days)	Back Right Lung µGy/hr per Bq	Neck µGy/hr per Bq	Thigh µGy/hr per Bq
Days following exposure	0	7.10E-08	1.88E-08	2.62E-10
	0.5	3.19E-07	2.76E-07	9.74E-08
	1	3.67E-07	3.30E-07	1.18E-07
	2	3.66E-07	3.37E-07	1.21E-07
	3	3.55E-07	3.29E-07	1.19E-07
	4	3.47E-07	3.23E-07	1.16E-07
	5	3.41E-07	3.18E-07	1.14E-07
	6	3.36E-07	3.14E-07	1.13E-07
	7	3.33E-07	3.10E-07	1.12E-07
	8	3.29E-07	3.07E-07	1.11E-07
	9	3.27E-07	3.04E-07	1.10E-07
	10	3.24E-07	3.02E-07	1.09E-07
	12	3.19E-07	2.98E-07	1.07E-07
	14	3.15E-07	2.93E-07	1.06E-07
	20	3.03E-07	2.82E-07	1.02E-07
	30	2.84E-07	2.65E-07	9.54E-08

Table A.2 Radiac Dose Rate Reading per Bq for Female Phantom with ^{137}Cs (Moderate)

	Time (Days)	Back Right Lung µGy/hr per Bq	Neck µGy/hr per Bq	Thigh µGy/hr per Bq
Days following exposure	0	7.10E-08	1.88E-08	2.62E-10
	0.5	9.77E-08	4.80E-08	1.52E-08
	1	9.59E-08	5.51E-08	1.95E-08
	2	8.71E-08	5.51E-08	1.89E-08
	3	8.24E-08	5.38E-08	1.74E-08
	4	8.03E-08	5.31E-08	1.66E-08
	5	7.93E-08	5.28E-08	1.64E-08
	6	7.88E-08	5.27E-08	1.63E-08
	7	7.84E-08	5.27E-08	1.63E-08
	8	7.82E-08	5.28E-08	1.63E-08
	9	7.80E-08	5.29E-08	1.64E-08
	10	7.78E-08	5.30E-08	1.65E-08
	12	7.75E-08	5.32E-08	1.66E-08
	14	7.73E-08	5.35E-08	1.68E-08
	20	7.67E-08	5.43E-08	1.72E-08
	30	7.55E-08	5.50E-08	1.78E-08

Table A.3 Radiac Dose Rate Reading per Bq for Female Phantom with ^{60}Co

Days following exposure	Time (Days)	Back Right Lung µGy/hr per Bq	Neck µGy/hr per Bq	Thigh µGy/hr per Bq
	0	2.95E-07	8.49E-08	2.30E-09
	0.5	1.54E-07	6.37E-08	2.17E-08
	1	1.29E-07	6.56E-08	2.72E-08
	2	1.04E-07	6.40E-08	2.48E-08
	3	9.36E-08	6.11E-08	2.09E-08
	4	8.86E-08	5.85E-08	1.84E-08
	5	8.57E-08	5.64E-08	1.70E-08
	6	8.36E-08	5.46E-08	1.61E-08
	7	8.19E-08	5.30E-08	1.55E-08
	8	8.03E-08	5.15E-08	1.49E-08
	9	7.89E-08	5.03E-08	1.44E-08
	10	7.76E-08	4.91E-08	1.40E-08
	12	7.52E-08	4.71E-08	1.34E-08
	14	7.31E-08	4.55E-08	1.28E-08
	20	6.76E-08	4.20E-08	1.18E-08
	30	6.07E-08	3.88E-08	1.11E-08

Table A.4 Radiac Dose Rate Reading per Bq for Female Phantom with ^{192}Ir

Days following exposure	Time (Days)	Back Right Lung µGy/hr per Bq	Neck µGy/hr per Bq	Thigh µGy/hr per Bq
	0	1.01E-07	2.38E-08	2.14E-10
	0.5	5.50E-08	1.89E-08	5.06E-09
	1	4.77E-08	1.86E-08	6.22E-09
	2	3.94E-08	1.71E-08	5.33E-09
	3	3.59E-08	1.63E-08	4.39E-09
	4	3.43E-08	1.59E-08	3.93E-09
	5	3.34E-08	1.56E-08	3.74E-09
	6	3.27E-08	1.54E-08	3.65E-09
	7	3.21E-08	1.53E-08	3.61E-09
	8	3.16E-08	1.51E-08	3.59E-09
	9	3.11E-08	1.50E-08	3.57E-09
	10	3.06E-08	1.48E-08	3.56E-09
	12	2.97E-08	1.46E-08	3.54E-09
	14	2.89E-08	1.43E-08	3.52E-09
	20	2.65E-08	1.37E-08	3.45E-09
	30	2.32E-08	1.27E-08	3.34E-09

Table A.5 Radiac Dose Rate Reading per CDL for Male with ^{137}Cs (Fast) using AN/PDR-77

	Time (Days)	Back Right Lung mR/hr per CDL	Front Right Lung mR/hr per CDL	Neck mR/hr per CDL	Thigh mR/hr per CDL
Days following exposure	Class →	F	F	F	F
	0	3.83E-01	3.53E-01	7.23E-02	1.01E-03
	0.5	1.48E+00	1.58E+00	8.77E-01	5.76E-01
	1	1.68E+00	1.80E+00	1.05E+00	6.97E-01
	2	1.67E+00	1.79E+00	1.07E+00	7.17E-01
	3	1.61E+00	1.74E+00	1.04E+00	7.02E-01
	4	1.58E+00	1.70E+00	1.02E+00	6.89E-01
	5	1.55E+00	1.67E+00	1.00E+00	6.78E-01
	6	1.53E+00	1.65E+00	9.91E-01	6.69E-01
	7	1.51E+00	1.63E+00	9.80E-01	6.62E-01
	8	1.50E+00	1.61E+00	9.70E-01	6.56E-01
	9	1.48E+00	1.60E+00	9.62E-01	6.50E-01
	10	1.47E+00	1.59E+00	9.54E-01	6.45E-01
	12	1.45E+00	1.56E+00	9.40E-01	6.35E-01
	14	1.43E+00	1.54E+00	9.27E-01	6.26E-01
	20	1.37E+00	1.48E+00	8.91E-01	6.02E-01
	30	1.29E+00	1.39E+00	8.36E-01	5.65E-01

Table A.6 Radiac Dose Rate Reading per CDL for Male with ^{137}Cs (Moderate) using AN/PDR-77

	Time (Days)	Back Right Lung mR/hr per CDL	Front Right Lung mR/hr per CDL	Neck mR/hr per CDL	Thigh mR/hr per CDL
Days following exposure	Class →	M	M	M	M
	0	1.82E-01	1.67E-01	3.43E-02	4.78E-04
	0.5	2.39E-01	2.37E-01	7.75E-02	4.07E-02
	1	2.29E-01	2.29E-01	8.70E-02	5.28E-02
	2	2.04E-01	2.05E-01	8.59E-02	5.18E-02
	3	1.92E-01	1.93E-01	8.36E-02	4.82E-02
	4	1.86E-01	1.88E-01	8.24E-02	4.64E-02
	5	1.84E-01	1.85E-01	8.19E-02	4.57E-02
	6	1.82E-01	1.84E-01	8.17E-02	4.56E-02
	7	1.81E-01	1.83E-01	8.16E-02	4.56E-02
	8	1.80E-01	1.82E-01	8.17E-02	4.57E-02
	9	1.80E-01	1.82E-01	8.18E-02	4.59E-02
	10	1.79E-01	1.82E-01	8.19E-02	4.61E-02
	12	1.79E-01	1.81E-01	8.22E-02	4.66E-02
	14	1.78E-01	1.80E-01	8.26E-02	4.70E-02
	20	1.76E-01	1.79E-01	8.35E-02	4.83E-02
	30	1.72E-01	1.76E-01	8.44E-02	4.98E-02

Table A.7 Radiac Dose Rate Reading per CDL for Male with ^{60}Co using AN/PDR-77

Days following exposure	Time (Days)	Back Right Lung mR/hr per CDL	Front Right Lung mR/hr per CDL	Neck mR/hr per CDL	Thigh mR/hr per CDL
	Class →	M	M	M	M
	0	7.27E-01	6.72E-01	1.55E-01	4.67E-03
	0.5	4.12E-01	4.03E-01	1.09E-01	5.14E-02
	1	3.60E-01	3.52E-01	1.09E-01	6.50E-02
	2	3.03E-01	2.95E-01	1.04E-01	6.02E-02
	3	2.76E-01	2.69E-01	9.86E-02	5.12E-02
	4	2.62E-01	2.55E-01	9.44E-02	4.55E-02
	5	2.53E-01	2.46E-01	9.09E-02	4.21E-02
	6	2.46E-01	2.40E-01	8.80E-02	3.99E-02
	7	2.40E-01	2.34E-01	8.55E-02	3.83E-02
	8	2.35E-01	2.29E-01	8.33E-02	3.69E-02
	9	2.31E-01	2.24E-01	8.13E-02	3.58E-02
	10	2.27E-01	2.20E-01	7.95E-02	3.47E-02
	12	2.19E-01	2.12E-01	7.64E-02	3.31E-02
	14	2.12E-01	2.06E-01	7.38E-02	3.18E-02
	20	1.96E-01	1.90E-01	6.81E-02	2.93E-02
	30	1.78E-01	1.73E-01	6.28E-02	2.76E-02

Table A.8 Radiac Dose Rate Reading per CDL for Male with ^{192}Ir using AN/PDR-77

Days following exposure	Time (Days)	Back Right Lung mR/hr per CDL	Front Right Lung mR/hr per CDL	Neck mR/hr per CDL	Thigh mR/hr per CDL
	Class →	M	M	M	M
	0	4.75E-01	4.39E-01	7.84E-02	6.78E-04
	0.5	2.58E-01	4.25E-01	5.77E-02	2.39E-02
	1	2.20E-01	2.15E-01	5.57E-02	2.96E-02
	2	1.80E-01	1.75E-01	5.03E-02	2.59E-02
	3	1.63E-01	1.59E-01	4.76E-02	2.17E-02
	4	1.55E-01	1.51E-01	4.62E-02	1.97E-02
	5	1.51E-01	1.47E-01	4.54E-02	1.88E-02
	6	1.48E-01	1.44E-01	4.48E-02	1.85E-02
	7	1.45E-01	1.42E-01	4.43E-02	1.83E-02
	8	1.43E-01	1.39E-01	4.38E-02	1.82E-02
	9	1.40E-01	1.37E-01	4.34E-02	1.81E-02
	10	1.38E-01	1.35E-01	4.29E-02	1.80E-02
	12	1.34E-01	1.31E-01	4.21E-02	1.79E-02
	14	1.30E-01	1.27E-01	4.14E-02	1.78E-02
	20	1.19E-01	1.17E-01	3.93E-02	1.75E-02
	30	1.04E-01	1.03E-01	3.62E-02	1.70E-02

Table A.9 Radiac Dose Rate Reading per CDL for Female with ^{137}Cs (Fast) using AN/VDR-2

	Time (Days)	Back Right Lung µGy/hr per CDL	Neck µGy/hr per CDL	Thigh µGy/hr per CDL
	Class →	F	F	F
Days following exposure	0	3.86E+00	1.02E+00	1.42E-02
	0.5	1.73E+01	1.50E+01	5.29E+00
	1	1.99E+01	1.79E+01	6.40E+00
	2	1.99E+01	1.83E+01	6.57E+00
	3	1.93E+01	1.79E+01	6.44E+00
	4	1.89E+01	1.75E+01	6.32E+00
	5	1.85E+01	1.73E+01	6.22E+00
	6	1.83E+01	1.70E+01	6.14E+00
	7	1.81E+01	1.69E+01	6.07E+00
	8	1.79E+01	1.67E+01	6.01E+00
	9	1.77E+01	1.65E+01	5.96E+00
	10	1.76E+01	1.64E+01	5.91E+00
	12	1.73E+01	1.62E+01	5.83E+00
	14	1.71E+01	1.59E+01	5.75E+00
	20	1.65E+01	1.53E+01	5.52E+00
	30	1.54E+01	1.44E+01	5.18E+00

Table A.10 Radiac Dose Rate Reading per CDL for Female with ^{137}Cs (Moderate) using AN/VDR-2

	Time (Days)	Back Right Lung µGy/hr per CDL	Neck µGy/hr per CDL	Thigh µGy/hr per CDL
	Class →	M	M	M
Days following exposure	0	1.83E+00	1.08E+00	1.50E-02
	0.5	2.52E+00	1.24E+00	3.91E-01
	1	2.47E+00	1.42E+00	5.03E-01
	2	2.24E+00	1.42E+00	4.86E-01
	3	2.12E+00	1.39E+00	4.48E-01
	4	2.07E+00	1.37E+00	4.29E-01
	5	2.04E+00	1.36E+00	4.22E-01
	6	2.03E+00	1.36E+00	4.19E-01
	7	2.02E+00	1.36E+00	4.19E-01
	8	2.01E+00	1.36E+00	4.21E-01
	9	2.01E+00	1.36E+00	4.22E-01
	10	2.01E+00	1.37E+00	4.24E-01
	12	2.00E+00	1.37E+00	4.28E-01
	14	1.99E+00	1.38E+00	4.32E-01
	20	1.98E+00	1.40E+00	4.44E-01
	30	1.94E+00	1.42E+00	4.58E-01

Table A.11 Radiac Dose Rate Reading per CDL for Female with ^{60}Co using AN/VDR-2

Days following exposure	Time (Days)	Back Right Lung µGy/hr per CDL	Neck µGy/hr per CDL	Thigh µGy/hr per CDL
	Class →	M	M	M
	0	7.37E+00	2.12E+00	5.74E-02
	0.5	3.86E+01	3.33E+01	1.18E+01
	1	4.43E+01	3.99E+01	1.42E+01
	2	4.42E+01	4.08E+01	1.46E+01
	3	4.29E+01	3.98E+01	1.43E+01
	4	4.20E+01	3.90E+01	1.41E+01
	5	4.13E+01	3.84E+01	1.38E+01
	6	4.07E+01	3.79E+01	1.37E+01
	7	4.02E+01	3.75E+01	1.35E+01
	8	3.99E+01	3.71E+01	1.34E+01
	9	3.95E+01	3.68E+01	1.33E+01
	10	3.92E+01	3.65E+01	1.32E+01
	12	3.86E+01	3.60E+01	1.30E+01
	14	3.81E+01	3.55E+01	1.28E+01
	20	3.66E+01	3.41E+01	1.23E+01
	30	3.44E+01	3.20E+01	1.15E+01

Table A.12 Radiac Dose Rate Reading per CDL for Female with ^{192}Ir using AN/VDR-2

Days following exposure	Time (Days)	Back Right Lung µGy/hr per CDL	Neck µGy/hr per CDL	Thigh µGy/hr per CDL
	Class →	M	M	M
	0	4.85E+00	1.14E+00	1.03E-02
	0.5	2.65E+00	9.09E-01	2.43E-01
	1	2.29E+00	8.96E-01	2.99E-01
	2	1.89E+00	8.23E-01	2.56E-01
	3	1.73E+00	7.83E-01	2.11E-01
	4	1.65E+00	7.63E-01	1.89E-01
	5	1.61E+00	7.51E-01	1.80E-01
	6	1.57E+00	7.42E-01	1.76E-01
	7	1.55E+00	7.34E-01	1.74E-01
	8	1.52E+00	7.27E-01	1.73E-01
	9	1.50E+00	7.20E-01	1.72E-01
	10	1.47E+00	7.13E-01	1.71E-01
	12	1.43E+00	7.01E-01	1.70E-01
	14	1.39E+00	6.89E-01	1.69E-01
	20	1.27E+00	6.57E-01	1.66E-01
	30	1.12E+00	6.10E-01	1.61E-01

Table A.13 Radiac Dose Rate Reading per CDL for Female with ^{137}Cs (Fast) using AN/PDR-77

	Time (Days)	Back Right Lung mR/hr per CDL	Neck mR/hr per CDL	Thigh mR/hr per CDL
Days following exposure	Class →	F	F	F
	0	3.86E-01	1.02E-01	1.42E-03
	0.5	1.73E+00	1.50E+00	5.29E-01
	1	1.99E+00	1.79E+00	6.40E-01
	2	1.99E+00	1.83E+00	6.57E-01
	3	1.93E+00	1.79E+00	6.44E-01
	4	1.89E+00	1.75E+00	6.32E-01
	5	1.85E+00	1.73E+00	6.22E-01
	6	1.83E+00	1.70E+00	6.14E-01
	7	1.81E+00	1.69E+00	6.07E-01
	8	1.79E+00	1.67E+00	6.01E-01
	9	1.77E+00	1.65E+00	5.96E-01
	10	1.76E+00	1.64E+00	5.91E-01
	12	1.73E+00	1.62E+00	5.83E-01
	14	1.71E+00	1.59E+00	5.75E-01
	20	1.65E+00	1.53E+00	5.52E-01
	30	1.54E+00	1.44E+00	5.18E-01

Table A.14 Radiac Dose Rate Reading per CDL for Female with ^{137}Cs (Moderate) using AN/PDR-77

	Time (Days)	Back Right Lung mR/hr per CDL	Neck mR/hr per CDL	Thigh mR/hr per CDL
Days following exposure	Class →	M	M	M
	0	1.83E-01	1.08E+00	1.50E-02
	0.5	2.52E-01	1.24E+00	3.91E-01
	1	2.47E+00	1.42E+00	5.03E-01
	2	2.24E+00	1.42E+00	4.86E-01
	3	2.12E+00	1.39E+00	4.48E-01
	4	2.07E+00	1.37E+00	4.29E-01
	5	2.04E+00	1.36E+00	4.22E-01
	6	2.03E+00	1.36E+00	4.19E-01
	7	2.02E+00	1.36E+00	4.19E-01
	8	2.01E+00	1.36E+00	4.21E-01
	9	2.01E+00	1.36E+00	4.22E-01
	10	2.01E+00	1.37E+00	4.24E-01
	12	2.00E+00	1.37E+00	4.28E-01
	14	1.99E+00	1.38E+00	4.32E-01
	20	1.98E+00	1.40E+00	4.44E-01
	30	1.94E+00	1.42E+00	4.58E-01

Table A.15 Radiac Dose Rate Reading per CDL for Female with ^{60}Co using AN/PDR-77

Days following exposure	Time (Days)	Back Right Lung mR/hr per CDL	Neck mR/hr per CDL	Thigh mR/hr per CDL
	Class →	M	M	M
	0	7.37E-01	2.12E-01	5.74E-03
	0.5	3.84E-01	1.59E-01	5.42E-02
	1	3.23E-01	1.64E-01	6.79E-02
	2	2.60E-01	1.60E-01	6.20E-02
	3	2.34E-01	1.53E-01	5.22E-02
	4	2.22E-01	1.46E-01	4.61E-02
	5	2.14E-01	1.41E-01	4.26E-02
	6	2.09E-01	1.36E-01	4.03E-02
	7	2.05E-01	1.32E-01	3.86E-02
	8	2.01E-01	1.29E-01	3.73E-02
	9	1.97E-01	1.26E-01	3.61E-02
	10	1.94E-01	1.23E-01	3.51E-02
	12	1.88E-01	1.18E-01	3.34E-02
	14	1.83E-01	1.14E-01	3.21E-02
	20	1.69E-01	1.05E-01	2.96E-02
	30	1.52E-01	9.71E-02	2.79E-02

Table A.16 Radiac Dose Rate Reading per CDL for Female with ^{192}Ir using AN/PDR-77

Days following exposure	Time (Days)	Back Right Lung mR/hr per CDL	Neck mR/hr per CDL	Thigh mR/hr per CDL
	Class →	M	M	M
	0	4.85E-01	1.14E-01	1.03E-03
	0.5	2.65E-01	9.09E-02	2.43E-02
	1	2.29E-01	8.96E-02	2.99E-02
	2	1.89E-01	8.23E-02	2.56E-02
	3	1.73E-01	7.83E-02	2.11E-02
	4	1.65E-01	7.63E-02	1.89E-02
	5	1.61E-01	7.51E-02	1.80E-02
	6	1.57E-01	7.42E-02	1.76E-02
	7	1.55E-01	7.34E-02	1.74E-02
	8	1.52E-01	7.27E-02	1.73E-02
	9	1.50E-01	7.20E-02	1.72E-02
	10	1.47E-01	7.13E-02	1.71E-02
	12	1.43E-01	7.01E-02	1.70E-02
	14	1.39E-01	6.89E-02	1.69E-02
	20	1.27E-01	6.57E-02	1.66E-02
	30	1.12E-01	6.10E-02	1.61E-02

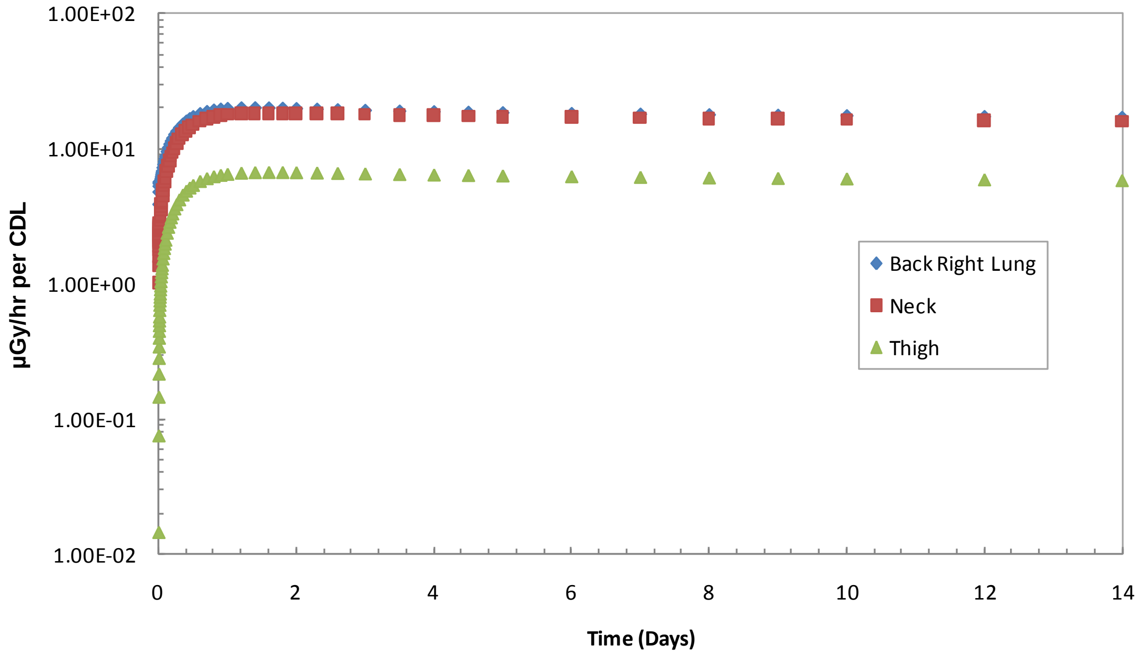


Figure A.9 Radiac Dose Rate Reading per CDL for Female with ^{137}Cs (Fast)

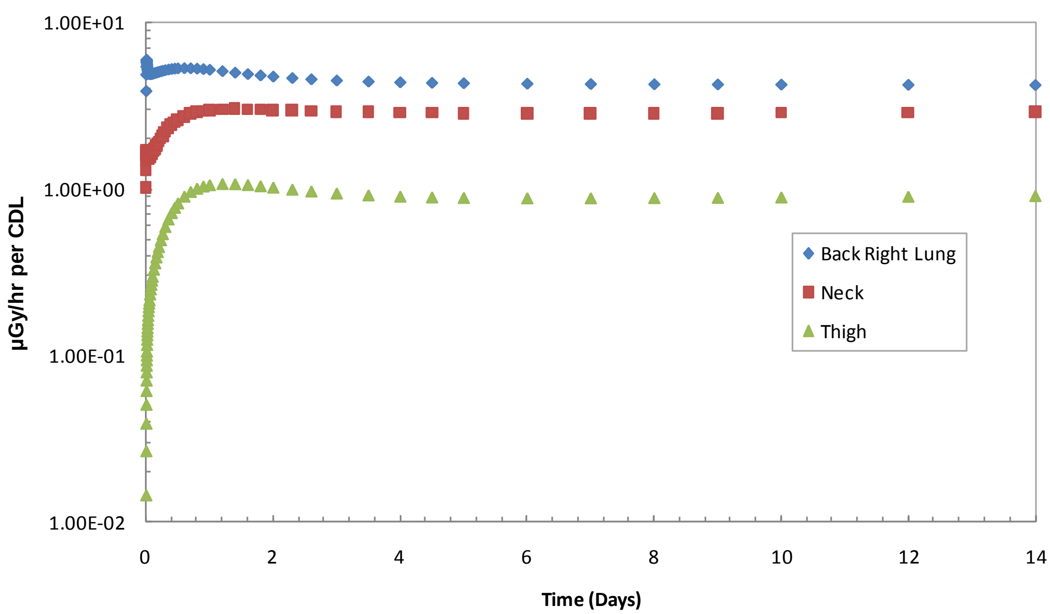


Figure A.10 Radiac Dose Rate Reading per CDL for Female with ^{137}Cs (Moderate)

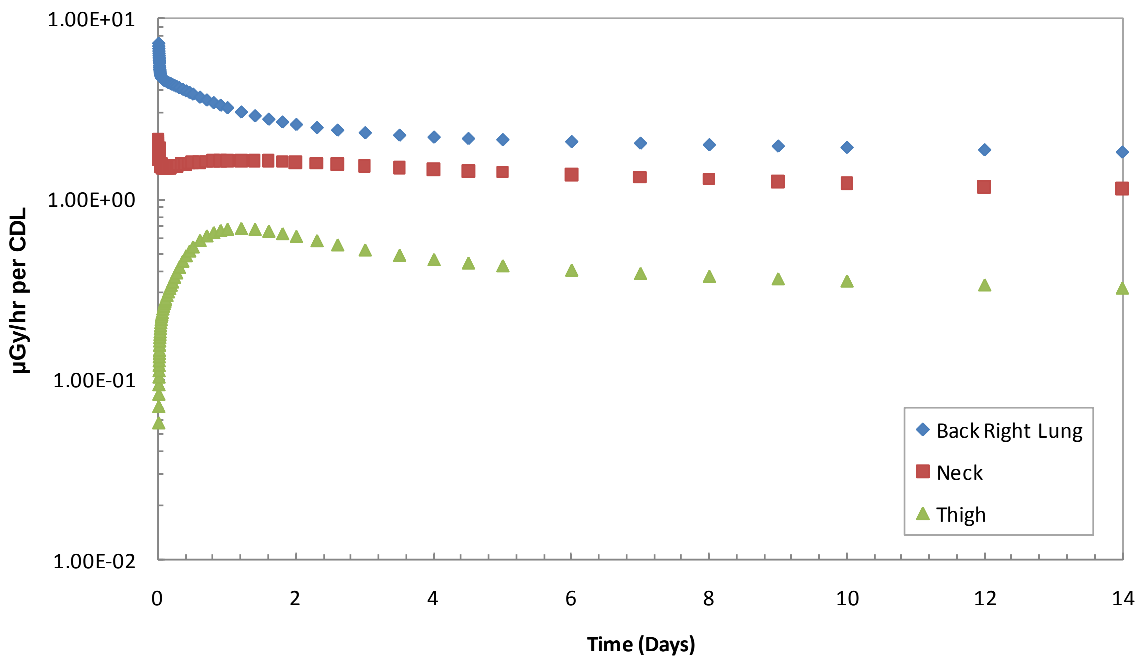


Figure A.11 Radiac Dose Rate Reading per CDL for Female with ^{60}Co

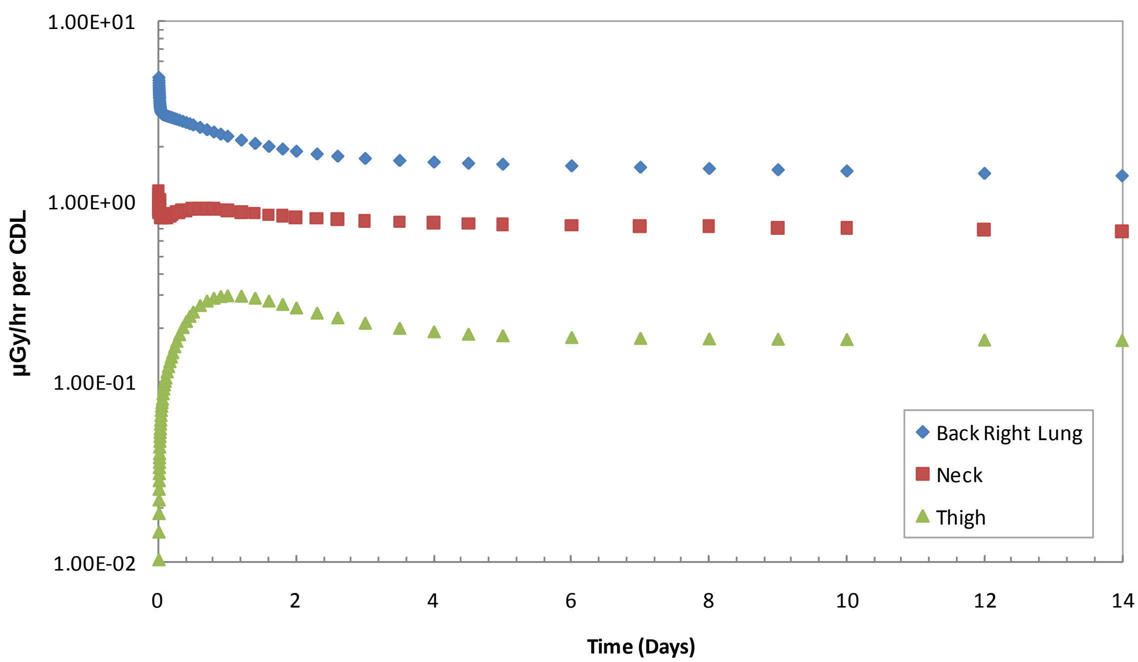


Figure A.12 Radiac Dose Rate Reading per CDL for Female with ^{192}Ir

APPENDIX B

TRIAGE PROCEDURES FOR MILITARY PERSONNEL

AN/PDR-77 Triage Procedures

Preoperational Test Procedures

Prior to turning on IM-263, ensure DT-616 probe is attached

Set PWR to ON (up) and wait for arrow display

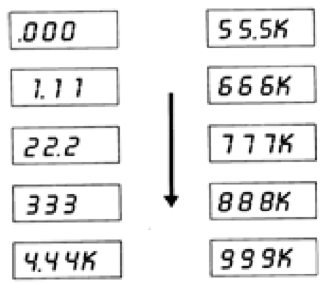
Set ALARM switch to CHIRP (up)

Press and hold CLR/TEST button until alarm sets, then release

When segment display appears, check that the display is exactly as shown here then perform all of the next step within 10 seconds

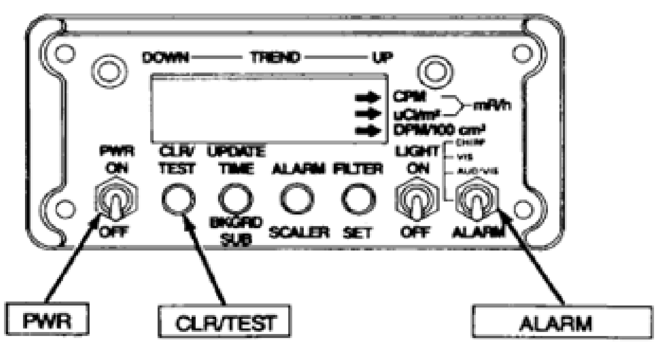
Set ALARM to VIS (center). Alarm sound stops. Set ALARM to AUD/VIS (down). TREND lights come on. Set ALARM switch back to CHIRP (up). Lights go out, alarm sounds. Set ALARM switch to VIS (center)

At the end of the 10-second segment test, the digit/unit test begins with three zeros and the sequence shown. Check each display in the sequence for correctness of all characters including decimals



If all tests are OK, after 10 to 60 seconds , a flashing 9 appears indicating preoperational tests are complete.

Press and release the CLR/TEST button , the IM-263 will display three zeros, then indicate a rate which is variable.



Background Subtract

While depressing the UPDATE TIME button, turn power switch ON. Then release the UPDATE TIME button.

Unit will warm up/stabilize for 120 seconds, the it will accumulate background data until an adequate number of counts are acquired. Trend light flashing indicates completion of this process.

Depress and release CLR/TEST button to resume normal operation with background subtracted

Background subtraction may also be done by average the dose rate over a period of 10 cycles (20 seconds), and subtracting this value from the reading.

Triaging Personnel

Ensure all external contamination has been removed.

Place the detector within one inch of the back right lung of the subject.

Allow the reading on the detector to stabilize.

If the reading is at or exceeds the radiac dose rate reading per Command Decision Level (CDL) below, seek additional dosimetric evaluation

		Readings are in mR/hr per CDL					
	Gender	Male			Female		
	Isotope	^{137}Cs	^{60}Co	^{192}Ir	^{137}Cs	^{60}Co	^{192}Ir
Days following exposure	0	0.18	0.73	0.48	0.18	0.74	0.48
	0.5	0.24	0.41	0.26	0.25	0.38	0.26
	1	0.23	0.36	0.22	0.25	0.32	0.23
	2	0.20	0.30	0.18	0.22	0.26	0.19
	3	0.19	0.28	0.16	0.21	0.23	0.17
	4	0.19	0.26	0.16	0.21	0.22	0.17
	5	0.18	0.25	0.15	0.20	0.21	0.16
	6	0.18	0.25	0.15	0.20	0.21	0.16
	7	0.18	0.24	0.15	0.20	0.20	0.15
	8	0.18	0.24	0.14	0.20	0.20	0.15
	9	0.18	0.23	0.14	0.20	0.20	0.15
	10	0.18	0.23	0.14	0.20	0.19	0.15

AN/VDR-2 Triage Procedures

Preoperational Test Procedures

Prior to turning on IM-243, ensure DT-616 probe is attached

Set PWR to ON (up)

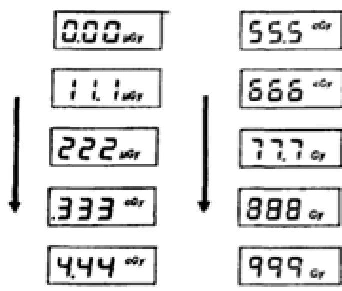
Set ALM switch to AUD (up)

Press and hold CLR/TEST button until alarm sets, then release

When segment display appears, check that the display is exactly as shown here then perform all of the next step within 10 seconds

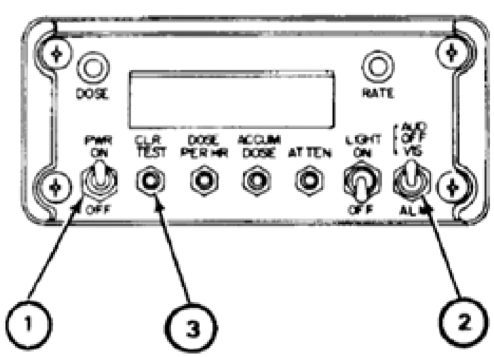
Set ALM to OFF (center). Alarm sound stops. Set ALM to VIS (down). RATE and DOSE lights come on. Set ALARM switch back to AUD (up). Lights go out, alarm sounds. Set ALARM switch to OFF (center)

At the end of the 10-second segment test, the digit/unit test begins with three zeros and the sequence shown. Check each display in the sequence for correctness of all characters including decimals



If all tests are OK, after 10 to 60 seconds , a flashing 9 appears indicating preoperational tests are complete.

Press and release the CLR/TEST button , the IM-243 will display three zeros, then indicate a rate which is variable.



Background Subtract

Average the dose rate over a period of at least 10 cycles (20 seconds), and subtracting this value from the reading. This should be done in an area away from any radiological sources

Triaging Personnel

Ensure all external contamination has been removed.

Place the detector within one inch of the back right lung of the subject.

Allow the reading on the detector to stabilize.

If the reading is at or exceeds the radiac dose rate reading per Command Decision Level (CDL) below, seek additional dosimetric evaluation

		Readings are in µGy/hr per CDL					
	Gender	Male			Female		
	Isotope	^{137}Cs	^{60}Co	^{192}Ir	^{137}Cs	^{60}Co	^{192}Ir
Days following exposure	0	1.82	7.27	4.75	1.83	7.37	4.85
	0.5	2.39	4.12	2.58	2.52	3.84	2.65
	1	2.29	3.60	2.20	2.47	3.23	2.29
	2	2.04	3.03	1.80	2.24	2.60	1.89
	3	1.92	2.76	1.63	2.12	2.34	1.73
	4	1.86	2.62	1.55	2.07	2.22	1.65
	5	1.84	2.53	1.51	2.04	2.14	1.61
	6	1.82	2.46	1.48	2.03	2.09	1.57
	7	1.81	2.40	1.45	2.02	2.05	1.55
	8	1.80	2.35	1.43	2.01	2.01	1.52
	9	1.80	2.31	1.40	2.01	1.97	1.50
	10	1.79	2.27	1.38	2.01	1.94	1.47

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