TRAINING MANUAL

RADIATION SAFETY INFORMATION
FOR PET LABORATORY PERSONNEL

Washington University in St. Louis, and
Washington University Medical Center

RADIATION SAFETY OFFICE
Washington University School of Medicine
St. Louis, Missouri

Version 2006

TABLE OF CONTENTS

PREFACE

This manual is intended to provide individuals planning to work in our positron emission tomography (PET) facilities a convenient compilation of the basic essentials of radioactivity and radiation safety practices appropriate for the use of positron emitting radionuclides for PET imaging.

HISTORICAL NOTE

You may find it of interest that Washington University is a pioneer in the use of cyclotrons for biomedical research and in the development of PET. Dr. Sherwood Moore, a past Director of the Mallinckrodt Institute of Radiology, anticipated the medical use of radioactive materials in the late 1930s and collaborated with the WU Physics Department to build a cyclotron on the Hilltop Campus. Soon after being put into service it was taken over by the US War Department and used to prepare trace amounts of ^{239}Pu for the Manhattan Project in order to learn about the chemistry of plutonium. After World War II ended, the supply of relatively inexpensive radioactive materials from the US Atomic Energy Commission eliminated much of the medical interest in the cyclotron and Radiology withdrew from the joint effort. Then, in 1964, Dr. Michel Ter-Pogossian, an early MIR physicist, installed the first cyclotron in a hospital in the United States in the basement of the Barnard Hospital building. Later, in the early 1970s, a research team organized by Dr. Ter-Pogossian built and successfully tested the first PET device in the world.

RADIATION SAFETY INFORMATION
FOR PET LABORATORY PERSONNEL

I. FUNDAMENTAL CONCEPTS AND NOMENCLATURE

1 NATURE OF RADIOACTIVITY AND POSITRON RADIATIONS

Atoms of radioactive materials exhibit their nuclear instability by undergoing transformations referred to as *disintegrations*. The disintegrations of a particular radionuclide generally result in the emission of one or more distinctive types of radiation that are classified as ionizing radiation, i.e., the radiation possesses sufficient energy to directly ionize matter. Only a few types of disintegration or transformation have been observed in the "decay" of radionuclides. The four most common types are (1) alpha decay, (2) beta decay, (3) electron capture and (4) isomeric transition. One form of beta decay results in the emission of a positively charged electron, a *positron*, from each nucleus undergoing decay. Prior to discussing positron emission, it is helpful to introduce the unit of energy commonly used to denote particle and photon energies in atomic physics -- the electron volt (eV). Typical forms of this unit are:

- kiloelectron volt = 1 keV = 1,000 eV, and
- megaelectron volt = 1 MeV = 1,000,000 eV.

Positron Emission

Positron emission is the name of the beta decay transformation that results in the emission of an energetic positron from the nucleus of an unstable or "radioactive" atom. There are positron emitters that exhibit "simple positron decay" in which the *daughter nucleus* (the nucleus after transformation) is at the *ground state* of the nucleus after the decay. In such cases, the only ionizing emission from the nucleus is the positron, one from each decaying atom. Important examples of such positron emitters used in the PET laboratories are carbon-11 (^{11}C), oxygen-15 (^{15}O) and fluorine-18 (^{18}F).

However, some positron emitters result in the daughter nucleus being in an *excited state* after the decay. There is a subsequent emission (usually promptly) of a *photon* of electromagnetic radiation from the excited nucleus, a *gamma ray*. (A photon is the smallest entity of energy emitted in the form of electromagnetic radiation and is sometimes referred to as a *quantum* of energy). In such cases, at least two ionizing radiations are emitted from the nucleus, the positron and the gamma ray. Examples of this type include copper-60 (^{60}Cu), gallium-66 (^{66}Ga) and iodine-124 (^{124}I).

The positrons emitted by a particular radionuclide have a continuum of kinetic energies, from essentially zero kinetic energy to a maximum energy that is uniquely characteristic for the radionuclide. As examples, the maximum positron energy for ^{15}O is 1.74 MeV, that of ^{11}C is 0.97 MeV. The average positron energy for a particular positron-emitting radionuclide is about 40% of its maximum energy.

After emission, each positron immediately interacts with the matter that it encounters by a variety of processes:

- dislodging electrons from atoms to form ions (ionization)
- exciting atomic electrons to higher energy levels (excitation)
- causing vibrations of molecules (excitation)
- breaking molecular bonds (excitation), and
- producing electromagnetic radiation subsequent to a sudden change of direction in the positron's path (bremstrahlung).

These energy-dissipating processes are generally categorized as (1) ionization, (2) excitation and (3) bremstrahlung.

The distance that the most energetic positrons travel in a particular material from the point of their origin to the place where they no longer act as destructive particles is called their *range* in that material. For example, the range of the 1.74 MeV positrons emitted by ^{15}O is 8 mm of unit density material, like water. However, remember that very few of the positrons from a given radionuclide have the characteristic "maximum energy"; rather, the positrons have a continuum of energies from zero to the "maximum energy". It turns out that less than 10% of the emitted positrons from a given radionuclide will travel as far as one-half of the range before dissipating their kinetic energies.

The fate of the emitted positrons is very important to PET imaging. After an emitted positron has dissipated its kinetic energy, it very quickly combines with an ordinary electron and the two particles undergo mutual *annihilation*. In the usual annihilation process the rest mass of each particle is converted to electromagnetic energy in the form of a 511 keV (0.511 MeV) annihilation photon. The two 511 keV photons are emitted in opposite directions (180° apart), to conserve momentum. The simultaneous emission of the two 511 keV photons in opposite directions serves as the foundation of positron emission tomography (PET) detection.

2 ACTIVITY

The rate of radioactive decay, i.e., the disintegration rate, is used to indicate the "radioactivity" of a sample and it is termed the *activity*. The traditional unit of activity is the curie (Ci), defined as the amount of radioactive material having a disintegration rate of 3.70×10^{10} (37 billion) disintegrations per second. It is common to express activities in

- curie (Ci),
- millicurie = mCi = 0.001 Ci,
- microcurie = uCi = 0.000001 Ci, and so on.

It is important to note that activity indicates only the rate of disintegration or decay; it provides no information concerning the kind of radiation emitted during the radioactive decay.

3 HALF-LIFE

An important characteristic of any specific radionuclide is its half-life. The half-life corresponds to the time necessary for one-half of the radioactive atoms of a sample to decay. The remaining activity as a function of time is given by the equation:

$$A(t) = A_o e^{-0.693\, t/T_{1/2}}$$

where A(t) is the activity at time t, A_o is the original activity (at t = 0) and $T_{1/2}$ is the half-life. As an example, the ^{18}F activity in a sample that was assayed to be 15 mCi that remains 2 hours later (half-life of ^{18}F = 110 min = 1.83 hr) is

$$A(2\text{ hrs}) = 15e^{-0.693(2)/1.83} \text{ mCi}$$

$$= 15(0.469) \text{ mCi}$$

$$= 7.04 \text{ mCi}$$

You should notice that the exponential $e^{-.693(2)/l.83}$, easily computed with a scientific calculator, represents the fraction of ^{18}F that remains after 2 hours.

4 HALF-VALUE LAYER

It is frequently convenient to express the attenuation or "absorption" properties of a material for photons in terms of its half-value-layer, HVL. The HVL is defined as the amount of material (often expressed as the thickness) required to reduce the transmitted photon radiation to one-half of the incident value. The transmitted intensity as a function of absorber thickness is given by the equation:

$$I(x) = I_o e^{-0.693x/HVL}$$

where I(x) is the intensity of the photon radiation transmitted through a barrier of thickness x and HVL is the half-value-layer. Again, an example may be helpful. The HVL in lead for the 511 keV annihilation radiation produced by positron emitters is about 4.1 mm (0.41 cm). The fraction of the 511 keV radiation that is transmitted through a one inch (2.54 cm) thick lead shield is given by

$$I(2.54\text{ cm}) = 1\, e^{-0.693(2.54)/0.41}$$

$$= 0.0137 \text{ (or 1.37\%)}$$

5 RADIATION DOSES

A measure of the biological damage caused by "ionizing" radiation, e.g., gamma rays, x-rays, beta particles, etc., is expressed by the dose equivalent (often referred to by just "dose"), the unit of which is the rem. To provide some perspective regarding this unit, the naturally occurring "background" radiation level, due to a) radiation reaching earth from outer space, b) the radioactive content of all matter, including human tissues and c) exposure to the radioactive gas radon, is considered to be 0.3 rem per year (or 300 millirem per year), on the average, in the US.

6 BIOLOGICAL EFFECTS OF IONIZING RADIATION

It is known that large doses of radiation (either "acute" doses of greater than 10 rem received over a short period of time, or "chronic" doses incurred over a prolonged period, e.g., years, of greater than one hundred rem) may cause harm to humans, including an elevated risk of cancer, cataracts, genetic effects, etc. Normal occupational doses are at much lower levels where harmful effects, if they occur, are not measureable. In this sense, no one knows whether your work-related radiation doses are harmful or not. Today, there are three distinctly different opinions concerning the harm of relatively low radiation dose, e.g., doses that radiation workers are allowed to receive.

One group of scientists chooses a conservative approach by assuming a linear, no threshold model to describe the relationship between most risk and dose. This concept yields unit dose risk factors, e.g., % chance of harm per rem that are numerically the same as those that apply to much higher doses, like those received by the Japanese A-bomb survivors. State and federal regulatory agencies use this approach. For example the US Nuclear Regulatory Commission recommends the use of a lifetime risk factor for radiation-induced fatal cancer of four chances in 10,000 per rem for a population of radiation workers exposed to low doses imparted at low dose rates.

Another group of scientists believe that thresholds exist for most harmful effects and that the thresholds are greater than the doses received by occupational radiation workers.

Finally, a third group proposes that low doses of ionizing radiation are actually beneficial. This concept is called "hormesis". The beneficial or hormetic effect is attributed to various adaptive processes that are thought to be initiated by exposure to low doses of ionizing radiation.

This dilemma may never be answered. Regardless, the view of the regulatory agencies is the one that we must adopt and it is based on the assumption that any amount of radiation exposure is potentially harmful. The Nuclear Regulatory Commission (NRC) has developed guidance for workers concerning the risk associated with occupational radiation exposure. If you would like to read the NRC document, ask Radiological Sciences (362-8426) or Radiation Safety (362-2988) for a copy of Regulatory Guide 8.29.

7 RADIATION DOSE RECOMMENDATIONS AND REGULATIONS

Historically, the State of Missouri (Department of Health and Senior Services) has had authority over the use of the cyclotron-produced radioactive materials employed in the PET laboratories. Effective with the signing of the Energy Policy Act in 2005, this authority has been transferred to the NRC. In addition, a federally-funded advisory group, the National Council on Radiation Protection and Measurements (NCRP), provides recommendations concerning dose limits for radiation workers. The dose limits of the NRC and the recommendations of the NCRP are shown in the following table.

Occupational Radiation Dose Limits

	Dose Limit	
Category	**NRC (regulations)**	**NCRP (recommendation)**
Whole body	5 rem/year	5 rem in any one year; an average of about 1 rem per year over several years or more
Lens of the eyes	15 rem/year	15 rem/year
Any other organ or tissue	50 rem/year	50 rem/year
Extremity	50 rem/year	50 rem/year

For perspective, technologists with the NM Clinical PET currently receive average whole body doses of about 0.1 rem per year (14% of the NRC limit) and extremity doses of about 5 rem per year (10% of the NRC limit). These annual doses are substantially higher than those for a technologist in conventional nuclear medicine at our institution, where the average annual doses are 0.03 rem and 0.18 rem for whole body and extremities, respectively.

II. OPERATIONAL RADIATION SAFETY

1 CONTROL OF RADIATION EXPOSURE

Good radiation hygiene can be achieved by (a) recognizing sources of potential external exposure and practicing proper precautions and (b) controlling internal contamination.

External Exposure

As you have learned, all of the radionuclides used in the PET laboratories emit positrons with the resultant annihilation radiation, and some emit gamma rays, in addition. The three classic methods for controlling external radiation exposure are:

(a) minimize *time* spent in a radiation field

(b) maximize *distance* from the source of radiation

(c) utilize *shielding* between you and the source

The relatively large annual radiation doses incurred by PET personnel occur because (a) the emitted radiations are abundant and generally penetrating and (b) large activities are often handled to compensate for the rapid decay occurring during the studies in which they are used. Certain characteristics of selected positron-emitters are listed in Appendix 1. You should be aware of the characteristics for the radionuclides that you handle.

As an example, let's consider a study involving ^{18}F. The dose rate constant for ^{18}F is 0.60 mrem/hr per mCi @ 1 meter (refer to Appendix 1). This constant allows you to estimate the dose rate due to the photon radiation.

Consider an unshielded syringe containing 15 mCi of ^{18}F. The dose rate at a distance of one meter from the source is 9.0 mrem/hr (15 mCi x 0.60 mrem-m2/mCi-hr = 9.0 mrem/hr @ 1 meter). If you are only one foot (0.30 m) from the syringe the dose rate is about 100 mrem/hr or 1.7 mrem per minute ($9.0/0.30^2 = 100$)! The dose rate to a hand holding the unshielded syringe can be of the order of several hundred mrem per minute, due to both annihilation radiation and positrons that penetrate the wall of the syringe.

Soon after the material has been administered to an adult patient and distributed throughout the body, the dose rate will be about 6.5 mrem/hour at a distance of 1 meter (the dose rate at 1 meter from an adult subject is almost half that due to a point source because of self absorption by the patient and the more linear distribution of the activity). The cumulative dose at a point one meter from the subject for the complete decay of the ^{18}F is about 16 mrem (2.8 in the first 30 min, 5.0 in the first hour, etc.). With this situation the following steps could be considered when trying to minimize your dose:

The time factor, which is often overlooked in efforts to minimize personnel exposure, can often be of practical importance. Procedures involving multiple steps, e.g., the transfer of a syringe of activity from the pneumatic line to a dose calibrator followed by the administration to the intended subject can be planned so that the various steps are accomplished in a small area in order to minimize "travelling time" between the steps.

Distance from a source of radiation can be a valuable ally. The exposure level varies inversely with the square of the distance from the source (the relationship applies for distances large compared to the physical dimensions of the source). Thus, doubling the distance, for example the distance of your body from a syringe used for patient injections, will result in a 4-fold reduction of the dose rate. Holding a syringe with fingers behind the plunger, i.e., away from the active solution, can reduce the contact dose rate by as much as 10 to 40-fold compared to holding the syringe at mid-barrel.

Shielding should be utilized in most PET situations. For example, pigs or lead containers used to transport cyclotron-produced materials should be sufficiently thick to reduce external levels to an acceptable value. The half-value-layer (HVL) in lead for the 511 keV annihilation radiation is about 4.1 mm. Thus, the use of a pig with a wall thickness of about an inch (25.4 mm) will result in external exposure levels that are about 1.4% of those that would have resulted without the presence of the shield for most of the positron emitters. In addition, it is helpful to use a Lucite sleeve over a syringe, a so-called "beta shield", to absorb energetic positrons. The dose rate to the hand can be substantially reduced if the positrons are absorbed by the beta shield whose thickness needs to be about equal to the range of the positrons in plastic. However, keep in mind that the plastic beta shield has little effect on the emitted 511 keV annihilation radiation.

A special concern is skin contamination. Because you often handle liquids containing high concentrations of cyclotron-produced materials, a small droplet on the skin, if left unattended, can result in alarmingly high radiation doses and serious harm to the affected skin. Appendix 2 lists the dose rate factors for skin contamination for several positron emitters. As an example, assume 10 lambda (0.01 ml) of a preparation of 15 mCi of ^{18}F in 5 ml (3 mCi/ml) is splashed on the skin. If the droplet containing 30 μCi of ^{18}F spreads over a circular area of a 1/4" diameter (0.32 cm^2 – approximately the size of a pea), the resultant dose rate to the radiosensitive tissue beneath the average epidermal thickness is of the order of 12 rem per minute!

If the activity remained in place for 2 hours, the skin dose would be about 1,000 rem (this value considers the decay of the ^{18}F during the 2-hour period). As part II of Appendix 2 shows, serious skin damage can result from doses of this magnitude. Any incident that results in direct radionuclide contamination of skin should be promptly addressed. The standard procedure is to rinse the affected area with copious amounts of water, taking care to avoid irritation of the skin and to not spread the contamination. Gentle scrubbing with a soft brush and the use of a mild detergent, e.g., a dishwashing detergent, may be helpful. Do not use abrasives, highly alkaline soaps or organic solvents. More complete instructions are specified on the "Emergency Procedures Involving Radioactive Material Contamination" chart that is posted in each PET facility.

Internal Contamination

Doses due to internal contamination are not a primary concern in your work because of the short half-lives of the radionuclides that you use. To provide some perspective regarding tolerable internal contamination levels, the federal government specifies maximum annual limits of intake (ALI). The concept of ALI is that it represents the activity of a given radionuclide that, if ingested or inhaled by a person will result in the more limiting of (a) 5 rem of effective whole body dose or (b) 50 rem to the "critical" organ. The following table lists the ALI for some of the radionuclides you may use:

Radionuclide	ALI (via ingestion)
^{11}C	400 mCi
^{15}O	1,500 mCi
^{18}F	50 mCi
^{60}Cu	30 mCi

Fortunately, most of the materials you use are considered only slightly "radiotoxic", primarily because of their short half-lives.

Additional practices that help to minimize radiation exposure in the PET laboratories include the following:

- wear buttoned laboratory coats and disposable gloves while handling unsealed activities,
- wear protective goggles, in addition to lab coat and gloves, while administering patient dosages,
- use a portable survey instrument to monitor clothing, hands and work area for contamination after handling dosages and after removing gloves,
- do not eat or drink in areas where unsealed activities are used,
- avoid contaminating objects such as telephones, light switches, calculators, etc. Be aware of what you touch while wearing potentially contaminated gloves,
- wear your whole body dosimeter while working in the PET laboratory and your ring dosimeter (beneath the glove), if handling sources,
- have a portable survey instrument conveniently nearby during PET procedures and understand how to use it,
- be familiar with posted instructions concerning the actions to take in the case of a spill of radioactive material, and
- be aware of the nearest eyewash station in case activity is splashed in an eye.

2 EMERGENCIES INVOLVING RADIOACTIVE MATERIALS SPILLS

The most common radiation emergency involves handling a spill of radioactive material. An "Emergency Procedures Involving Radioactive Material Contamination" notice is posted in each PET laboratory. The instructions address the clean up of a spill and personnel decontamination. Also, each notice explains how to contact Radiation Safety for assistance and who to notify. You should be familiar with the posted instructions.

Pneumatic line blockages

Pneumatic lines are used to transport very short-lived radiopharmaceuticals. Occasionally, the carrier encounters an obstruction along the delivery route and fails to arrive at its destination. The cyclotron personnel should be immediately informed (362-2261 or 362-8393) if an anticipated delivery fails to arrive.

Wrong radiopharmaceutical

On rare occasions, the wrong radiopharmaceutical is sent from the cyclotron. If the label specifies a radiopharmaceutical different than the one that is expected, you should promptly notify the cyclotron (362-2261, 362-8393) and Sally Schwarz (362-8426, pager # 490-3081). If the label is ignored and the wrong material is administered to the subject, you should promptly notify the cyclotron, Sally Schwarz and the physician responsible for the PET procedure.

3 RESTRAINING CERTAIN PATIENTS

Occasionally a patient will not remain motionless during PET imaging. In that situation a family member or other accompanying individual should be asked to restrain the patient; it should not be done by PET personnel. This practice is recommended by the NCRP. The radiation dose to the assisting individual will be low - of the order of 10 to 20 mrem for an ^{18}F patient restrained for an hour. The individual will receive this dose only once versus multiple times that a nurse or technologist would incur the added dose in a year if the practice were different.

4 PERSONNEL RADIATION MONITORING

The body dosimeters used at our institution utilize a technology referred to as "optically stimulated luminescence" (OSL) while the ring dosimeters are "thermoluminescent" dosimeters (TLD). The OSL body dosimeters, referred to by the supplier as "Luxel" dosimeters, are very sensitive to ionizing radiation. The minimum reported dose is one millirem (mrem). A measured dose less than one mrem is reported as "minimal " and denoted on the report with a capital M. The reported doses for each body dosimeter are (1) the deep dose (the calculated dose at a tissue depth of 1.0 cm), (2) the shallow (or skin) dose and (3) the lens dose.

The doses for ring dosimeters are reported as shallow doses down to a minimum of 30 mrem. Ring doses less than 30 mrem are reported as "minimal " (M).

Certain practices are essential if the radiation monitoring program is to be successful. The dosimeters should be faithfully worn while involved with the PET procedures and they should be promptly turned in for processing at the end of each wear period.

A copy of each report of radiation doses assessed with the personnel dosimeters is forwarded to the appropriate group for posting.

Our institution adopted a program in 1980 that attempts to maintain personnel radiation doses as low as reasonably achievable (ALARA). As a component of the ALARA program, all reported external doses are reviewed for unusually high levels. A member of the Radiation Safety staff investigates reported doses that exceed established levels, makes recommendations of how to reduce future doses and reports the investigations to a special subcommittee of our institutional Radiation Safety Committee.

5 HOW TO USE A PORTABLE SURVEY INSTRUMENT

A portable radiation survey instrument should be available in each PET laboratory. There are several different types of survey instruments; however, the ones currently used in the PET laboratories are Geiger-Muller (GM) instruments. The instruments are compact, lightweight, reliable and relatively inexpensive. The GM units use a gas detector that is capable of detecting individual ionizing events occurring within the detector. The ionizing events can be due to gamma rays, annihilation radiation, positrons or other ionizing radiation. Usually the GM detector is enclosed in a metal shield that precludes positron (or other beta radiation) detection except through a thin portion of the shield that is called the "window". When the window is open, the probe can detect particle radiation, e.g., positrons, that are incident on the window. With the window closed the survey instrument primarily detects ionizing photons, like gamma rays and annihilation radiation. The exposure rate scale of a calibrated GM instrument, typically in milliroentgen per hour (mR/hr), will yield a fairly accurate indication of the exposure rate when the detected events are due to photons, i.e., when the window is closed to eliminate particle detection. Incidentally, an exposure rate of 5 mR/hr will result in an entrance dose rate of about 5 mrem/hr to an exposed individual. Thus, the measured exposure rate in mR per hour is often interpreted or recorded as the radiation dose rate in mrem/hr, i.e., the two radiation quantities are used interchangeably. This is approximately true only for photon radiation. If the window is "open" and the instrument is detecting particles like positrons in addition to photons, the mR/hr scale no longer applies and should not be used. When the device is used to detect particle radiation (window open), only the counts per minute (cpm) scale is appropriate. If the count rate increases substantially when the window is utilized (either "opened" on some instruments or pointed toward the radiation source with "end-window" GMs), then you know that particle radiation is present.

Remember that a GM survey instrument can indicate the dose rate only when particles are not being detected; in that situation, the scale calibrated in mR/hr is properly used. However, when particles are detected, only the count rate scale in cpm is appropriate.

With these characteristics of a GM-based survey instrument in mind, the proper operating procedures can be explained as follows:

- Before use, check the calibration sticker to ensure the unit has been calibrated within the past twelve months. If not, don't use it and submit it to Radiation Safety Staff for calibration.
- Before use, set the RANGE switch to BATT (battery) and observe the reading. The needle should be in the acceptable section of the scale. If not, replace the batteries or refer to the user manual.
- With the beta window closed, set the RANGE switch to a high multiplier, e.g., X 10, and allow 30 seconds for stabilization.
- Verify proper function of the unit at the beginning of each day-of-use by observing the response of the survey unit to a radioactive check source. The check source must be placed in the pre-established position that was determined at the time of the most recent calibration of the unit. Change the RANGE switch progressively until the needle is not at the very low-end of the scale or off-scale. Compare the reading (in mR/hr or cpm) to the acceptable range that is denoted on a sticker affixed to the unit (or in a logbook). If the response is acceptable, it means the survey unit is operating similar to the way it responded when last calibrated. If no standard check source is available, any "source" of radiation may be used, i.e. stock vials, waste, etc., to verify the instrument is operating.
- Use the unit to measure exposure rates as needed, (window closed or an end-window device not pointed toward the radiation source) using the mR/hr scales.

- Use the unit to detect the presence of (or lack of) particle radiation by observing the indicated count rates in cpm with the window open vs. closed or an end-window pointed toward the source vs. not toward the source. A substantial increase in the cpm when particle radiation detection is enhanced demonstrates the presence of particle radiation (Placing your hand over the "window" will confirm particle radiation if the count rate drastically decreases).
- Turn off the instrument when finished. The battery life of modern GM instruments is typically about one hundred hours.

APPENDIX 1.

Characteristics of Selected Positron Emitter

Radionuclide	Mode of Decay	Half-Life	Max β Energy (MeV)	Exposure Rate Constant (mR/hr per mCi @ 1 meter in air)*	Range of Major Particle (mm of unit density material)
^{11}C	β^+	20.4 min	0.96	0.60	3.9
^{13}N	β^+	10.0 min	1.19	0.60	5.1
^{15}O	β^+	2.04 min	1.72	0.60	8.0
^{18}F	β^+	110 min	0.64	0.60	2.2
^{60}Cu	β^+	23.4 min	3.0	1.9	16
^{61}Cu	β^+; EC	3.3 hr	1.21	0.42	4.0
^{62}Cu	β^+	9.74 min	2.93	0.60	14
^{64}Cu	β^+; β^-; EC	12.7 hr	0.65; 0.58	0.21	2.3
^{67}Cu	β^-	61.9 hr	0.58	0.059	2.0
^{77}Br	EC; β^+	57.0 hr	0.34	0.17	0.9

*Health Physics and Radiological Health Handbook, 1992

APPENDIX 2.

I. Dose-rate Conversion Factors For Skin Contamination

Radionuclide	Dose-rate Factor (rem/min per μCi/cm^2
^{11}C	0.14
^{18}F	0.13
^{68}Ga	0.13

II. Radiation-induced Skin Injuries

Effect	Typical Threshold (rem)	Time to Onset Of Effect
Early transient erythema	200	Hours
Temporary epilation	300	3 weeks
Permanent epilation	700	3 weeks
Dermal atrophy	1100	>14 weeks
Dermal necrosis	1800	>10 weeks
Secondary ulceration	2000	>6 weeks