

BETA CONSIDERATIONS IN INTERNAL DOSE ESTIMATION
USING A MONTE CARLO CODE

A Dissertation

BY

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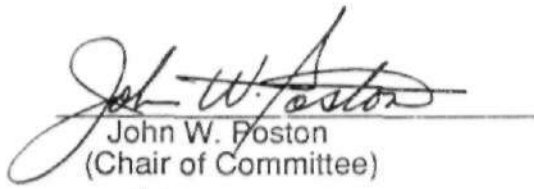
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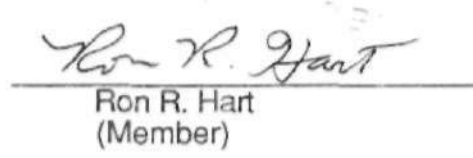
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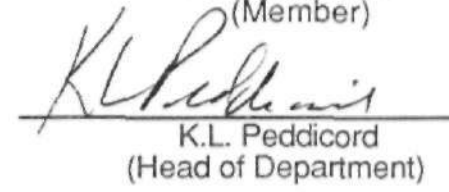
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DEDICATION

To my children, Morayo and Olugbenga.
I hope you will always have a desire to learn.

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CHAPTER I

INTRODUCTION

1.1 Subject

Radiation is broadly used in modern science and medicine. This use often requires the calculation of energy deposited in the irradiated media. The subject of this dissertation is an analytical study of energy deposition from gamma-ray and electron transport in a mathematical, anthropomorphic phantom. This study also considers in detail the transport and energy deposition from secondary particles produced in gamma-ray and electron interactions.

Energy deposition from radioactive sources in the human body and the effects of such depositions are considered in the field of internal dosimetry. Internal dose calculations are a two step process. The first step is to make a model of the kinetics of the radionuclide in the body. Movement of the radionuclide from one organ to another until the nuclide is eliminated from the body or until its residence time in the body exceeds the mean life of the nuclide is of interest. When the mean life of the radionuclide exceeds 50 years, the movement of the nuclide for 50 years will be used in the model. The body organs are considered as compartments into which nuclides move in and out. The net input and output of the nuclide (including radioactive decay) from a compartment is described by a system of first order differential equations. The solutions to these equations include constants that depend on biochemical properties of the organs.

This Dissertation follows the style of *Health Physics*

The second part of the internal dose calculation considers the movement of radiation from a nucleus undergoing a radioactive decay to the surrounding tissue. The radiation emitted in the transformation could be alpha, beta, or gamma radiation. These radiations travel varying distances from the site of their creation before an interaction takes place. The result of an interaction can be a total or partial deposition of the radiation energy. The organ in which the transformation occurs is called the 'source' organ while the organ into which the energy is deposited is called the 'target'. The absorbed fraction of energy (AF), is a the number between 0 and 1 which quantifies the amount of energy released in the source eventually deposited in the target. Estimation of the absorbed fractions is done by the Monte Carlo calculations. This research concerns the calculation of absorbed fractions.

1.2 Background

In 1968 the first publications of the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine appeared in the open literature. Pamphlet No. 1 (Lo68) presented a schema for absorbed dose calculations for biologically-distributed radionuclides. Pamphlet No. 2 (Be68) presented data on photon energy deposition in a water medium. Photon sources were assumed to be point isotropic, and nineteen monoenergies were considered over the range 15 keV to 3 MeV. In these calculations, it was assumed that energy lost by photons in scattering or absorption events was deposited in the medium at the spot of interaction. The author justified this assumption by showing that the distance traveled by secondary electrons was small compared to the mean free path of the photons. This assumption was valid for the framework in which the calculations were performed. But, this assumption may not be valid for more realistic situations.

Generally, factors considered in dose estimation include;

- a) Initial activity of the radionuclides
- b) Entry pathways into the medium (body)
- c) Decay schemes
- d) Compartment models and biological removal rates, i.e., effective half lives.

The MIRD Committee recommended a basic framework for absorbed dose calculations. In considering a radionuclide decay scheme, the framework for dose calculations involved estimation of an "absorbed fraction of energy" (AF). MIRD Pamphlet No. 3 (Br68) presented the data on photon absorbed fractions for three organ models. These calculations assumed that monoenergetic photon sources, in the range 0.02 to 2.75 MeV, were uniformly distributed in the organ volumes, and results were presented as a function of mass of the model. Pamphlets No. 2 and 3 have been used widely for dose calculations related to the practice of nuclear medicine.

One of the most significant of the early MIRD publications was Pamphlet No. 5 which presented estimates of absorbed fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom (Sn69). This pamphlet presented the first estimates of absorbed fractions which were obtained in a realistic representation of the adult human body. These estimates were much needed in nuclear medicine and were quickly accepted and used in the profession. Pamphlet No. 5 was issued in revised form in 1978 (Sn78). The revised version of Pamphlet No. 5 presented data on specific absorbed fractions (SAF) for monoenergetic photon sources distributed in the organs of an improved mathematical model of the adult human. The SAF is defined as the quotient of the absorbed fraction and

the mass of the region of interest (called the "target").

In both sets of data (i.e., MIRD-5 and MIRD-5, revised) no consideration was given to the finite range of electrons and positrons produced by photon interactions in the tissue. As with previous calculations, it was assumed that the electron ranges were small compared with the diameters of most organs. Hence, for beta radiation the absorbed fraction is assumed to be unity when the source and target organs are identical and zero otherwise. It is clear that this assumption tends to over-estimate the absorbed dose to the source organ (or to the organ in which the photon interaction occurred) and under-estimates the absorbed dose to organs which may lie in the near vicinity (or in some cases, in contact with the organ in question). Examples of these situations are numerous in the human body and include the uterus-bladder, sections of the gastrointestinal tract, and the bone marrow-skeleton. It is desirable to correct the inadequacies of neglecting electron transport in dosimetric calculations. Previous treatments of energy deposition from beta sources have used empirical or semi-empirical methods (Ra82, Cr67). A more accurate treatment of electron transport and energy deposition is the continuous slowing down approximation (CSDA) (Be63).

A number of coupled electron/photon transport codes using Monte Carlo techniques and CSDA have been developed for a broad range of applications. Most of these codes can be divided into four groups, the SANDYL code (Co74) with its enhancements, the TIGER series of codes (Ha79), the BETA code (Jo68), and the EGS code system (Fo78). In consideration of electron transport all of these codes use the random walk technique. The random walk model separates electron transport into particle

advancement (which includes energy loss) and an angular deviation model (incorporating multiple scattering theory). The random walk model theoretically considers a group of single interactions in one particle transport step. Each code can be used to calculate the flux of electrons/photons transmitted and reflected by an absorber. Although the codes also provide information on energy deposited in zones of the absorber, these zones generally are too large for dosimetric purposes.

There is, therefore, a need to incorporate a more realistic treatment of beta-emitting radionuclides and of charged particle interactions into existing internal dosimetry computer codes. The final electron transport code should allow the study of energy deposition in materials such as those present in the human body and in regions small enough to be of interest from the standpoint of biological effects. Also, since most dosimetry applications do not involve monenergetic electron sources, the code should accommodate beta spectra as well as combinations of beta spectra from a variety of potential sources. Ideally, the dosimetry transport code should allow combinations of geometries that simulate the human body. These geometries would be similar to those used in photon transport codes, e.g., those used to produce the data published by the Medical Internal Radiation Dose (MIRD) Committee (Sn69, Sn75, Sn78).

1.3 Objective

It has been the purpose of this research to formally incorporate existing knowledge to model the transport and energy deposition of electrons and photons in internal dose estimation. A Monte Carlo code which can simulate the coupled transport of photons and electrons, using either as primary source of radiation, has been developed to meet the research

objective. The physics of all relevant interactions and the mathematical description of relevant organs of an adult have been incorporated in the final code used to generate the results of this research.

Both electrons and photons are dealt with because their transport in material is strongly coupled. Incident photons set electrons in motion upon interaction, at sufficient energies electrons cause further ionization, excitation or undergo radiative energy loss. Conversely, incident electrons, with sufficient energy, produce bremsstrahlung photons on interacting with the coulomb force of a nearby nucleus. These interactions constitute particle energy degradation and, hence, contribute to the absorbed energy.

The objective of this research is to develop a code that corrects for the inadequacies of neglecting beta transport in previous calculations in internal dosimetry. Results from this code will answer the questions ;

- a) What contribution does the consideration of beta radiation make to the estimation of the absorbed fraction of energy in photon transport?
- b) How much does the absorbed fraction of energy for electrons differ from unity as a function of electron energy and medium (i.e., body organs)?

Answers to these questions would provide a better estimate of radiation absorbed dose for use in radiation protection, radiation damage studies, and nuclear medicine procedures.

1.4 Monte Carlo Method

Due to the stochastic nature of photon interactions, analytical treatment of energy deposition in a phantom is not easily achieved. The Monte Carlo method is now the method of choice for solving problems in

photon and electron transport. The method is essentially a theoretical experiment which tracks each of a large number of photons through the many interactions they undergo. This technique provides a way of including all the fundamental interaction processes in a random nature according to the laws of probability.

The problem of interest in this work is estimating the fraction of energy emitted from a source organ which will be deposited in other organs of the phantom. In solving this problem using the Monte Carlo method, each photon is completely characterized by a set of parameters which include position, energy and direction of travel (called a "history"). Changes in these parameters, due to interactions, are recorded. A lower limit is set for particle energy and position, where the interaction process is stopped. Interaction types are determined by the selection of a set of random numbers.

CHAPTER II

THEORY OF PHOTON AND ELECTRON INTERACTIONS

Interactions of photons and electrons with matter are strongly coupled with one particle producing the other with varying probability that depends on initial particle energy and the microscopic structure of the material through which the radiation is passing. Interactions of interest are those which change the direction of travel and/or the energy of the particle. Each of the interaction events depend on a probability distribution which may be experimentally or/and theoretically determined. The derivation of cross sections used to provide probability distribution functions for these interactions will be discussed in this section.

2.1 Photon Interactions

Usually, gamma-rays with energy in the range of 1 keV to less than 10 MeV are of interest in radiation protection. Interaction mechanisms in this energy range have been discussed in numerous publications (e.g., Ev55). A number of photon interaction mechanisms are known and include the following:

- a) Major processes
 - i) Compton scattering
 - ii) Photoelectric effect
 - iii) Pair production

- b) Minor processes
 - i) Coherent (or Rayleigh) scattering
 - ii) Fluorescence radiation
 - iii) Bremsstrahlung
 - iv) Annihilation radiation
- c) Negligible processes
 - i) Coherent molecular scattering
 - ii) Elastic nuclear potential scattering
 - iii) Nuclear resonance inelastic scattering
 - iv) Photodisintegration of nucleus

Interactions which result in significant changes of particle energy and direction of travel, are photoelectric absorption, pair production, and Compton scattering. The relative importance of the three primary photon interactions as a function of photon energy for water is shown in Figure 2.1. It is expected the the behaviour of photons in a water medium will not be very different from photon behaviour in tissue. From Figure 2.1, photoelectric absorption is seen to dominate at very low photon energies while Compton scattering is more pronounced at intermediate energies and above a threshold energy, pair production dominates. It should be noted that the total mass absorption coefficient (ratio of probability of photon absorption per incident particle per unit path length, to medium density) decreases to a minimum at a photon energy of about 0.01 MeV and levels off at energies

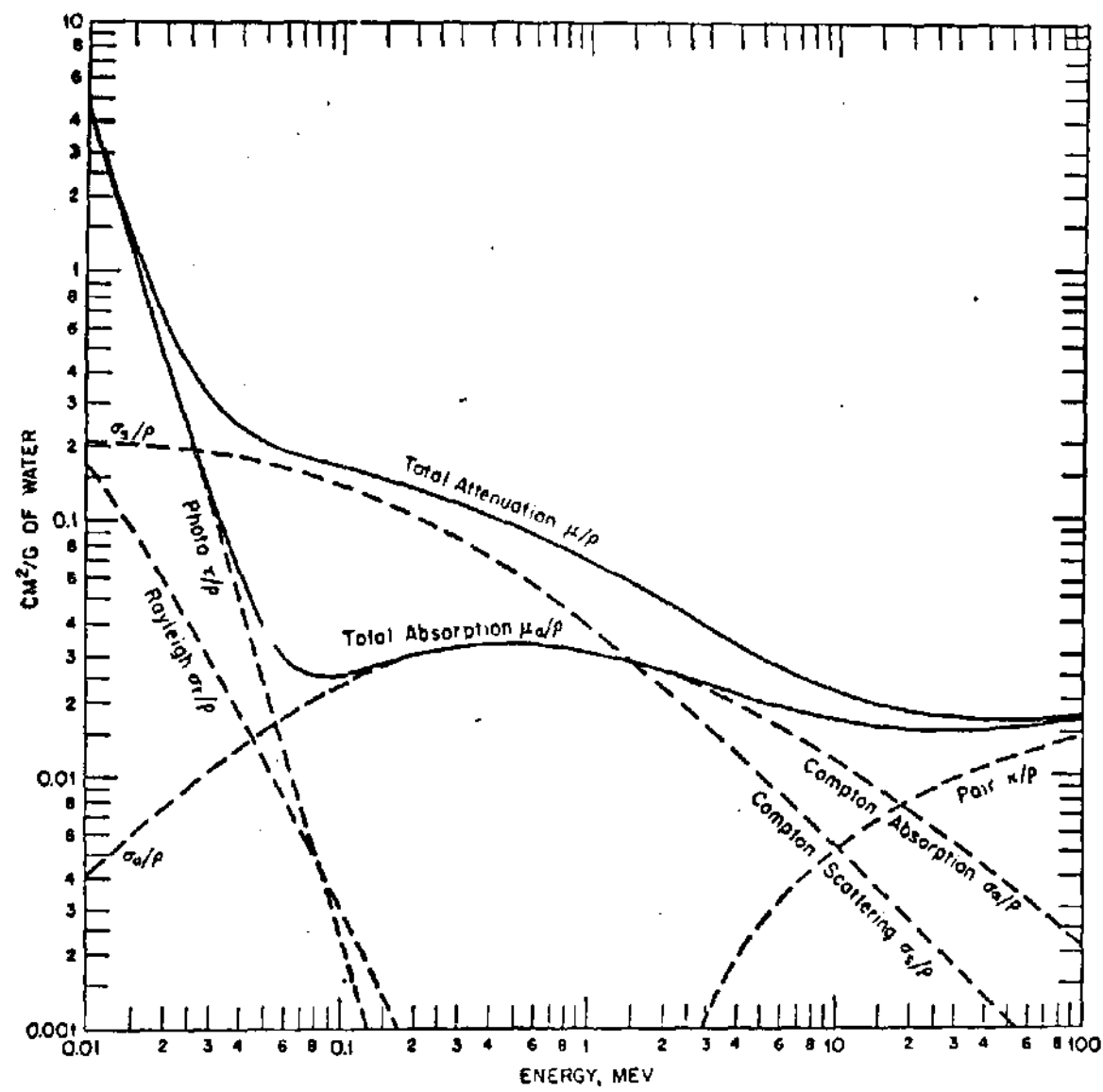


Figure 2.1. Mass attenuation coefficients for photon in water (Ev55)

beyond 0.01 Mev. This trend plays an important role in the nature of results obtained in photon transport problems.

The total cross section for an atom is the sum of the partial cross section for each of the interaction processes involving the atom and the photon. The cross section for a material composed of a mixture of atoms is assumed to depend only on the sum of the cross sections of the atoms present in the mixture. The total cross section for a particular type of interaction is ;

$$\Sigma = (N_a \sigma \rho) / M \quad \text{per cm}$$

where N_a = Avogadro's number

σ = microscopic cross section of medium (cm^2 per atom)

M = molecular weight of medium (gm per mole)

ρ = material density (gm per cm^3)

2.1.1 Photoelectric Effect

Electrons in the various atomic shells are bound with different energies to the nucleus. When an incident photon energy is greater than the electron binding energy, the photon may eject the electron from the atomic shell. The electron is ejected with kinetic energy, T , equal to the difference between the photon energy and the binding energy of the electron. Photoelectric absorption obeys the laws of conservation of energy and momentum. In a photoelectric interaction, a photon is completely absorbed to produce a photoelectron.

When a photoelectric absorption occurs, the atom with which the photon interacts is left in an excited state. When the atom de-excites, fluorescence photons or Auger electrons are produced. The extent to which these particles are produced depends on the effective atomic number of the medium in which the photon is travelling. Tissue has an effective atomic number of about 7.4 . Fluorescence photons and Auger electrons produced when the atoms in tissue de-excite have little energies and travel only short distances from an interaction site. Hence, these particles are considered to be locally deposited.

Methods of evaluating differential photoelectric interaction cross sections involve the use of quantum mechanical theory with approximate wave functions for the bound electron, e.g., the Born approximation. In general, determination of photoelectric cross sections involve the use of both empirical and theoretical methods. From experimental data on photoelectric cross sections for atoms, three photon energy regions can be defined for theoretical description of cross sections. These regions are :

- a) photon energies below 0.35 MeV
- b) photon energies from 0.35 to 2.0 MeV
- c) photon energies greater than 2.0 MeV

A comprehensive review of photoelectric effect has been given by Hall (Ha36). Data for total photoelectric cross-sections have been compiled and made available for use to the general public (St70). These data banks have

been correlated with experiment and were used in our computations involving photoelectric cross sections. Photoelectrons produced in photoelectric interactions deviate from the incident photon path i.e., these electrons are seen to exit the material at angles significantly different from that of the incident photon. However, these angles are a function of the photon energy. The determination of angular deflections of these photoelectrons will complete the description of the photoelectric interaction.

Generally, photoelectric absorption cross sections are given for electrons in the K-shell of an atom. The differential cross section per unit solid angle for the first region, for photon energies less than electron rest mass energy, is given by (He54) ;

$$d\sigma(h\nu, T, \theta) = 2^{1/2} 4r_o^2 (Z^5 / 137^4) (m_o c^2 / h\nu)^{7/2} \sin^2\theta / [1 - (pc/m_o c^2) \cos \theta]^4 d\Omega \quad (2.1)$$

$$\text{where : } pc = (T^2 + 2m_o c^2 T)^{1/2}$$

T = electron kinetic energy (MeV)

θ = scattering angle of the photoelectron with respect to the incident photon direction.

r_o = classical electron radius

m_o = electron mass (gms)

p = electron momentum

c = velocity of light (in vacuum)

Z = effective atomic number of the medium

$h\nu$ = incident photon energy (MeV)

When the incident photon energy is near the K-shell absorption edge, the electron binding energy is considered and a binding energy correction factor is introduced into the cross section. The photoelectron is preferentially emitted at 90° to the incident photon direction for low energy photons. This is shown from the plot of eqn. 2.1 (see Figure 2.2). The total cross section, obtained from integrating the differential cross section (eqn. 2.1) over all scattering angles, is given by;

$$\begin{aligned}\sigma(h\nu) &= 2^{1/2} \frac{32}{3} \pi r_0^2 (Z^5 / 137^4) (m_0 c^2 / h\nu)^{7/2} \\ &= 2^{1/2} \frac{4}{3} (8\pi r_0^2) (Z^5 / 137^4) (m_0 c^2 / h\nu)^{7/2}\end{aligned}\quad (2.2)$$

In the first region, if the ejected electron is relativistic, Sauter showed the total cross section is (Sa31):

$$\begin{aligned}\sigma(h\nu) &= \frac{3}{2} (8\pi r_0^2 / 3) Z^5 / 137^4 (m_0 c^2 / h\nu)^{7/2} (\gamma^2 - 1)^{3/2} \\ &\quad \{4/3 + \gamma(\gamma - 2) / (\gamma + 1) [1 - 1/2 \gamma(\gamma^2 - 1)^{1/2} \ln \gamma + (\gamma^2 - 1)^{1/2} / \gamma - (\gamma^2 - 1)^{1/2}]\}\end{aligned}\quad (2.3)$$

where : $\gamma = 1/(1 - \beta^2)^{1/2} = (h\nu - Be + m_0 c^2) / m_0 c^2$

Be = the electron binding energy.

β = ratio of electron velocity to velocity of light, v/c

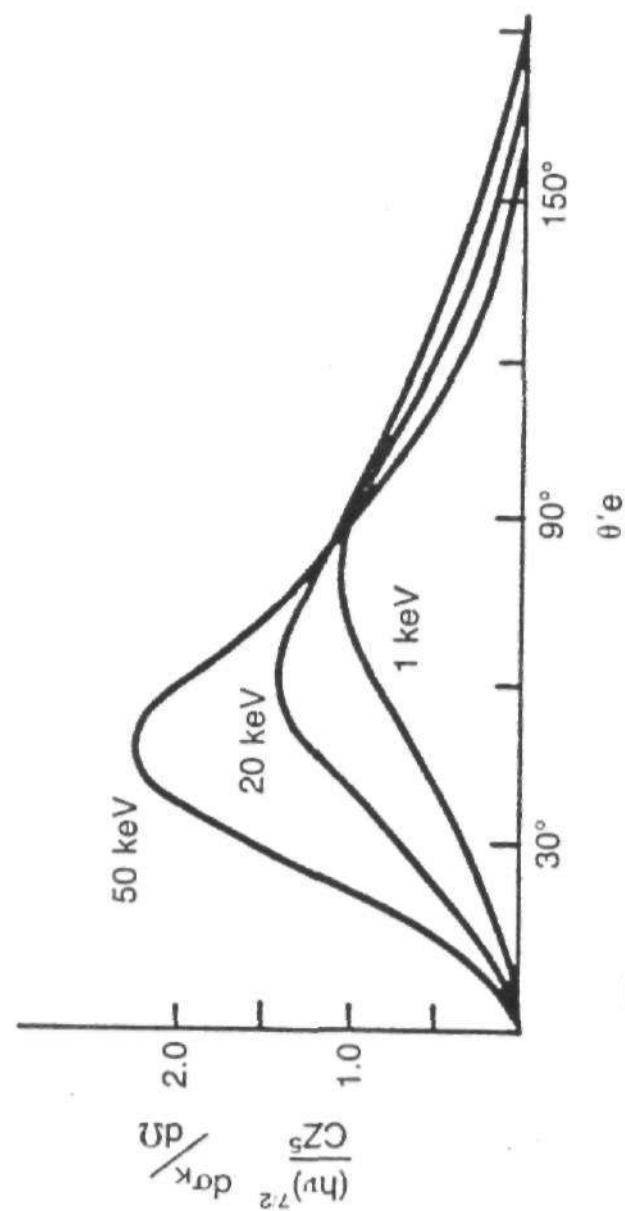


Figure 2.2. Angular distribution of photoelectrons for low Z materials illustrates forward emission angles with increasing electron energy. C is a constant which normalizes the curves to unity at 90° (An84).

For a value of γ approaching 1, Sauter's equation approaches the value for the non-relativistic case. The condition of Sauter's equation is that the value of $Z/137$ be much smaller than 1. This condition holds for light atoms.

For the second photon energy range, the photoelectric interaction cross section has been determined empirically and numerically (Hu35). Screening effects on the nucleus by the orbital electrons is included in the derivations. Numerical calculations for discrete energy values have been performed and graphed. Values for cross sections are read directly from these graphs.

For photon energies in the third region, when the photon energy is greater than 2 MeV, the total cross section obtained using a relativistic treatment with electron wave function expansion in powers of photon wavelength is given as (Ha36):

$$\sigma(h\nu) = [\sigma^0(h\nu) / (\exp(\pi\alpha - 2\alpha^2(1 - \ln\alpha)))] [(1 - 2/3\delta_1)/(1 - \delta_1/2)]$$

$$[\exp(2\alpha(\tan^{-1}(\alpha/\gamma_1) - \alpha))/(\alpha^{4\delta - 2\alpha})] [(81/8(7 + 4/\alpha^2))^\delta (1 + 0.05\alpha \tan^{-1}(0.63/\alpha))]$$

(2.4)

where ; $\delta_1 = 1 - \gamma_1$,

$$\gamma_1 = (h\nu + m_0 c^2) / m_0 c^2 ,$$

$$\alpha = Z/137, \text{ and}$$

$\sigma^0(h\nu)$ = cross section for the non-relativistic case (Eqn. 2.2).

Other approximations to this equation are available. However, Sauter's equation is a good approximation to experimental results when the energy of the ejected electron is greater than the electron binding energy. The Sauter equation for $\sigma(h\nu)$ (Eqn. 2.3), when the incident photon energy is greater than the electron rest mass energy, reduces to the equation (Ha36):

$$\sigma^0(h\nu) = 2^{1/2} 32/3 \pi r_0^2 Z^5 / 137^4 (m_0 c^2 / h\nu). \quad (2.5)$$

The cross section varies over a wide range, decreasing with increasing photon energy, except when photon energy equals the electron binding energy of the shell involved. The instant jump in cross section value at these photon energies is termed "edge effect". The total cross section per atom, in units of cm^2/atom , will include contributions from electrons in all the occupied shells. K-shell electrons contribute most (80 - 90 %) to the value of the cross section because these electrons are the most tightly bound in the atom. The ratio of the photoelectric cross section of the entire atom to the contribution from the K-shell electron is estimated by (Hu69):

$$\sigma(h\nu) / \sigma(h\nu)_k = 1 + 0.0148(\ln Z)^2 - 0.00079(\ln Z)^3. \quad (2.6)$$

Data for total cross section, compiled by Storm and Israel, have been used in this research to estimate cross section values (St70). As a first approximation, the angular distribution of the photoelectron, taken from equation 2.1, is given for the non-relativistic case as :

$$d N/d\Omega \cong \sin^2(\theta) / (1-\beta\cos(\theta))^4.$$

As the photon energy increases, forward emission of photoelectrons becomes more favored as determined by the cosine term in the denominator of the distribution equation (eqn. 2.1) above.

2.1.2 Compton Scattering

The laws of conservation of energy and momentum govern the inelastic scattering of an electron and the incident photon. In the Compton interaction, only a partial absorption of the photon energy occurs. Compton scattering is the dominant scattering interaction at high photon energies with the scattered electron being responsible for local energy deposition. Expressions for the scattered photon energy as a function of scattering angle, the energy of the recoil electron as a function of scattering angle, and the relationship between scattering angles of the electron and photon are (Fi67):

$$h\nu' = h\nu / (1 + \alpha(1 - \cos \theta)) \quad (2.7a)$$

$$T = h\nu - h\nu' = h\nu \alpha (1 - \cos \theta) / (1 + \alpha (1 - \cos \theta)) \quad (2.7b)$$

$$\cot(\theta_e) = (1 + \alpha) \tan(\theta/2) \quad (2.7c)$$

where: θ_e = electron scattering angle ,

T = electron kinetic energy,

θ = photon scattering angle,

$h\nu$ = incident photon energy,

$h\nu'$ = scattered photon energy, and

$$\alpha = h\nu/m_0c^2.$$

Figure 2.3 describes the Compton interaction. The electron binding energy is assumed negligible compared to the incident photon energy. Cases when this assumption does not hold are not considered in this report. All values of photon scattering angle are allowed (i.e. $0 < \theta < 180^\circ$), and hence, the angle of the Compton electron is constrained to $\pi/2 > \theta_e > 0$. From equation 2.7b above, the energy of the scattered electron would be $0 < T < h\nu(2\alpha)/(1+2\alpha)$.

The cross section for a Compton interaction resulting in an electron scattered into unit solid angle was first calculated by Klein and Nishina using quantum mechanical theory (Ev55). The Klein-Nishina relation is:

$$d\sigma(\theta)/d\Omega = (1/2)r_0^2 \left[\frac{(1 - \cos^2\theta)}{(1 + \alpha(1 - \cos\theta))^2} \right] \left[1 + \frac{\alpha^2(1 - \cos\theta)^2}{(1 + \cos^2\theta)} \right] \frac{1}{(1 + \alpha(1 - \cos\theta))}. \quad (2.8)$$

where: $\alpha = h\nu/m_0c^2$,

θ = photon scattering angle, and

$$r_0 = e^2/m_0c^2.$$

At low photon energies, as α approaches zero, and the Compton cross section reduces to :

$$d\sigma(\theta)/d\Omega = 1/2 r_0^2 (1 - \cos^2\theta). \quad (2.9)$$

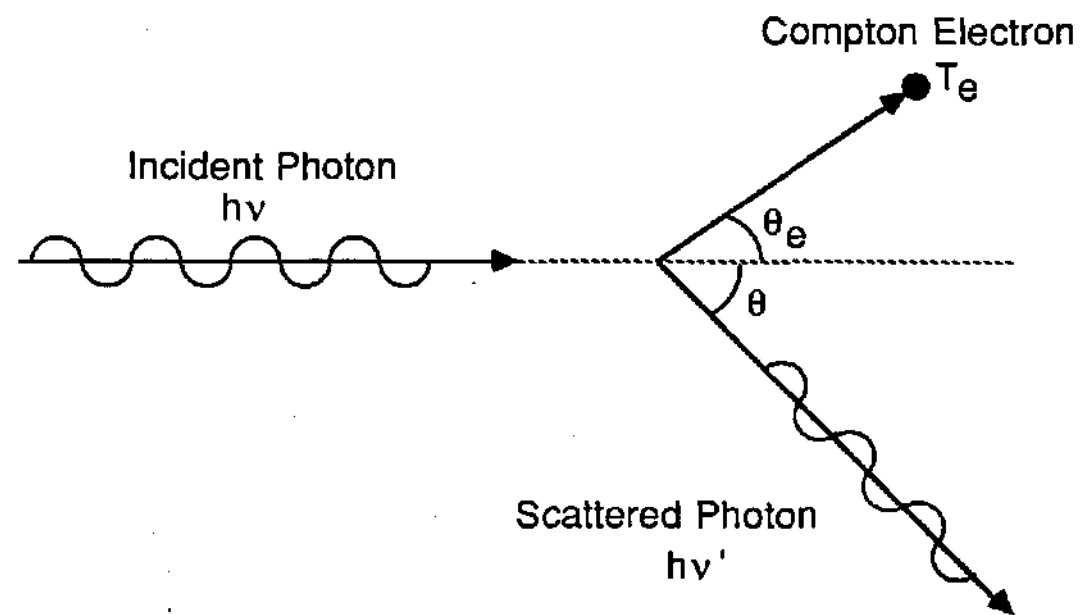


Figure 2.3 Compton scattering of an incident photon from a free electron.

Figure 2.4 shows the plot of Klein-Nishina angular distribution. Forward angular scattering is more prominent at high photon energies. Angular distribution of the Compton electrons can be obtained by substituting the relationship of the electron and photon scattering angles into the form of the Klein-Nishina equation given above.

The differential energy scattering probability is given by multiplying the Klein-Nishina equation by the fractional scattered energy (i.e., $h\nu'/h\nu$). The expression obtained is :

$$d\sigma(\theta)/d\Omega = (1/2)r_0^2 \left[\frac{(1 - \cos^2\theta)}{(1 + \alpha(1 - \cos\theta))^3} \right] \left[1 + \frac{\alpha^2(1 - \cos\theta)^2}{(1 + \cos^2\theta)} \right] (1 + \alpha(1 - \cos\theta)) \quad (2.10)$$

From the above equation and the equation relating the scattering angles of the electron and photon, the differential energy scattering cross section for the Compton electron can be expressed as:

$$d\sigma(h\nu, T)/dT = \pi r_0^2 / \alpha h\nu \left[2 + \frac{T^2}{(h\nu - T)} \left\{ \frac{1}{\alpha^2} + \frac{(h\nu - T)}{h\nu} - 2 \frac{(h\nu - T)}{\alpha T} \right\} \right] \quad (2.11)$$

The total Compton electronic cross section is obtained by integrating the differential cross section over all the scattering angles. Quantities such as average energy and average directional changes per scatter for the photon and recoil electron can be obtained similarly (Ev55). Since only partial absorption of the photon occurs, the difference between the total and scattered cross section is the absorption cross section.

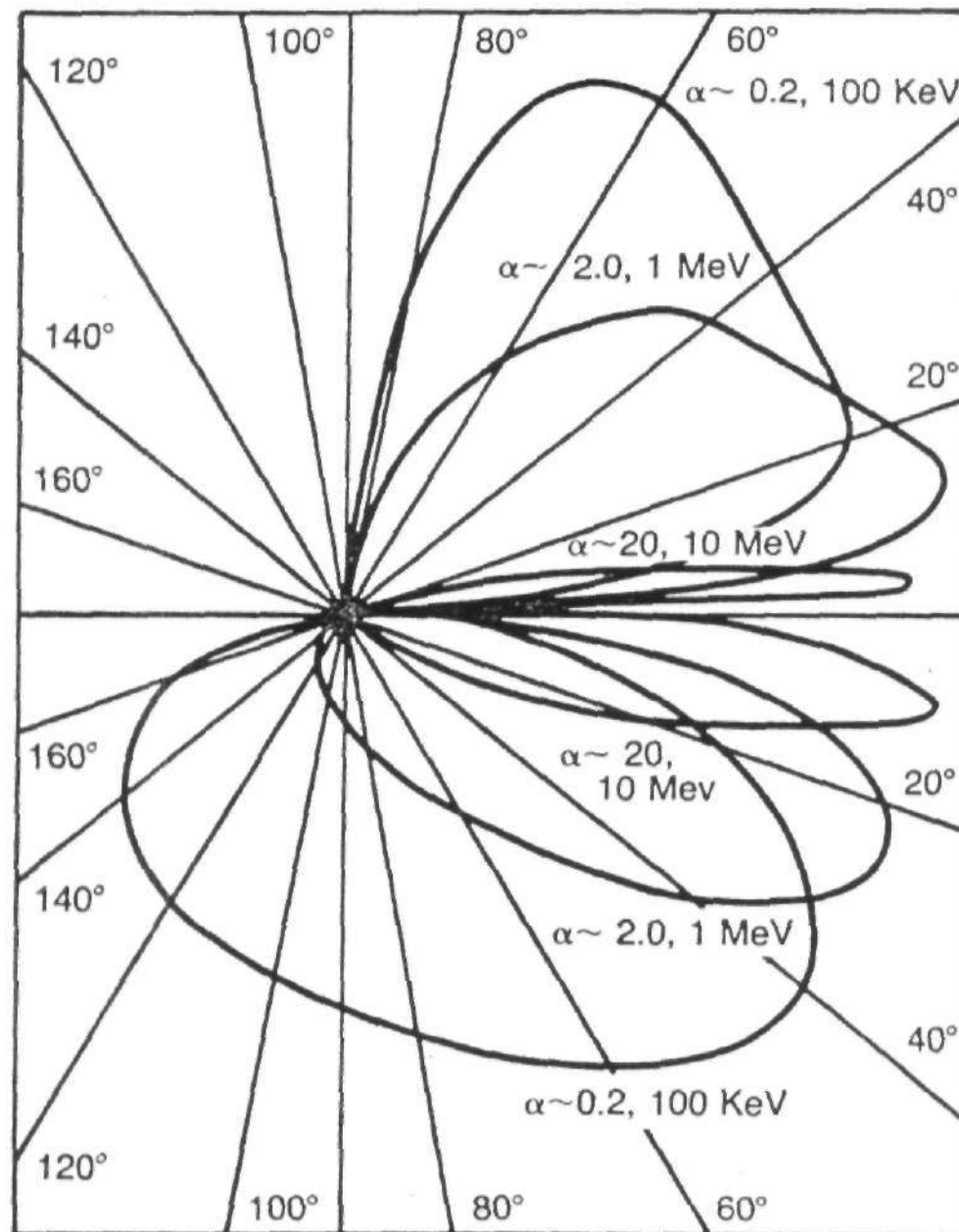


Figure 2.4. Differential cross sections per unit angle for Klein-Nishina scattering of photons at various energies. Compton electron angular distribution shown on top and scattered photon distribution shown on bottom. (An84).

At low photon energies, very little energy is lost by a photon in Compton scattering, i.e, the scattering cross section is equal to the total cross section and approaches a constant. The value of this constant cross section equals that obtained from the Thomson classical scattering cross section. The direction of travel of the recoil electron becomes more forward peaked as the incident photon energy increases and the Compton total cross section decreases with increasing photon energy.

2.1.3 Pair Production

Complete absorption of the incident photon energy may occur when the photon interacts with the electrostatic field of a nucleus, or an electron. In the nuclear coulomb field this interaction occurs at photon energies in excess of 1.022 MeV and results in the creation of positive and negative electron pair to replace the photon. For pair production near the nucleus, and at high photon energies, the recoil kinetic energy of the nucleus is negligible and the electron and positron pair share the excess energy ($h\nu - 1.022 \text{ MeV}$). Each member of the pair may have energies ranging from zero to a maximum value ($h\nu - 1.022 \text{ MeV}$). However, It is most probable that the positron-electron pair share the excess energy equally (Fi67). The positron upon losing all its kinetic energy combines with a free electron to produce two photons (each of energy 0.511 MeV) in an annihilation process.

Pair production in the vicinity of an electron may be neglected in this study. The threshold energy of such an interaction is high; 2.044 MeV (An84).

The contribution from the electron is less than 0.5% in the energy region of interest. However, it can be included by replacing Z^2 by $Z(Z+1)$ in the cross section formulae obtained from consideration of pair production in the vicinity of a nucleus (Ga50).

The cross section for pair production in the vicinity of a nucleus of charge Z is proportional to Z^2 for photon energies less than 20 MeV (Be34). The theoretical expression for the pair production cross section per unit solid angle per energy is obtained by using a plane wave approximation. This cross section as a function of photon energy is given as:

$$d^2\sigma/d\Omega dT = Z^2 r_o^2 \alpha / [(1 + ((T + m_o c^2) / m_o c^2) \sin^2 \theta)^2] F(h\nu, T, \theta, Z). \quad (2.12)$$

$F(h\nu, T, \theta, Z)$ is a complicated function determined by the electronic screening effect. However, the electron angular distribution is more forward peaked with increasing photon energy (Be34). Integrating the differential equation over all solid angle and electron energy results in the equation :

$$\begin{aligned} \sigma(h\nu, Z) &= Z^2 r_o^2 \alpha \int d\theta \int dT F(h\nu, T, \theta, Z) \\ &= Z r_o^2 \alpha H(h\nu, Z) \end{aligned} \quad (2.13)$$

In the limit when $h\nu$ is much greater than $m_o c^2$, $H(h\nu, Z)$ is approximated by;

$$H(h\nu, Z) = [28/9 \ln(183/Z^{1/2}) - 2/27].$$

The angular distribution of the positron-electron pair becomes more forward peaked as their kinetic energy, T , increases. Generally, the root mean square of the angle between the incident photon and the outgoing positron-electron

pair is of the order of θ , where as a first approximation (Te72):

$$\theta = m_0 c^2 / T \quad \text{radians} \quad (2.14)$$

where: T = electron kinetic energy (MeV).

2.2 Electron Interactions

Charged particles, in general, will interact with the coulomb field of atomic electrons and the nucleus. The relevant interactions of electrons below 10 MeV are a) inelastic electron scattering from atomic electrons, b) inelastic nuclear scattering, generally called radiative interaction or Bremsstrahlung, c) elastic nuclear scattering, and d) positron annihilation. All electron interactions which result either in changes in particle direction or energy can be included in the above categories. Elastic collisions with orbital electrons are dominant when the particle energy is such that ionization and excitation are unlikely. To determine the probability and magnitude of changes in direction and energy, the appropriate cross-sections must be determined. Electron interaction cross sections are determined by a combination of theoretical and empirical methods. Various factors are introduced on the basis of comparison with experimentally obtained data.

2.2.1 Inelastic Scattering From Atomic Electrons

Inelastic scattering of electrons from atomic electrons results in energy loss by the incident particle and ionization and excitation of atoms in the

medium. Fast electrons lose most of their energy by this process. Inelastic scattering is classified by the fraction of incident energy lost per interaction. When large fractional energy loss occurs substantial directional change also occurs and the scattered electron carries a significant amount of the total interaction energy. This high energy electron is called a delta ray or a knock-on electron. The minimum energy transfer that will be of significance for the creation of a delta ray will result in ionization of the atom.

The interaction cross section for inelastic scattering, resulting in delta-rays and/or free low-energy electrons, can be used to estimate the amount of energy lost per unit distance travelled in the medium, the scattering angle and the probability of secondary events of interest occurring. Moller (Mo32, Me70) derived the differential energy cross section for inelastic scattering from atomic electrons by considering incident electron energies above some threshold energy A_E . This relation for the scattered electron having energy between E and $E+dE$ is:

$$d\sigma(\varepsilon) = 2\pi Z r_0^2 \{(T+1)^2 / T^2 (T+2)\} \\ [1/\varepsilon - 1/\varepsilon(1-\varepsilon)((2T+1)/(T+1)^2) + 1/(1-\varepsilon)^2 + T^2/(T+1)^2] d\varepsilon. \quad (2.15)$$

where: ε = fractional energy transfer ($\varepsilon_{\max} = 1/2$)

$r_0 = e^2/m_0 c^2$ = classical electron radius

$T = (E - m_0 c^2)/m_0 c^2$;

E = incident electron total energy (MeV); and,

ϵT = kinetic energy of lowest energy electron.

The two electrons are indistinguishable hence the cross section is symmetrical with the interchange of ϵ and $(1 - \epsilon)$. The fractional energy transfer ϵ is therefore constrained to vary between 0 and 1/2, and the electron with the higher energy is considered the primary electron. When ϵ is zero, the cross section for Moller interactions becomes infinite. By setting a low electron energy limit for Moller scattering, such that the scattered electron has at least a cutoff energy, A_E , the cross section will have a finite value. Hence, Moller interactions are threshold interactions with minimum incident electron energies of :

$$E = 2T + m_0c^2 \quad (2.16)$$

where; $T = A_E - m_0c^2$

A_E = cutoff energy.

The total Moller cross section can be obtained by integrating the differential cross section over the minimum and maximum electron energies, $(A_E, \epsilon E)$.

The angular deviation of the scattered electrons is given as:

a) For electrons of lower energy,

$$\cos \theta_L = (\epsilon (T+2) / \epsilon T+2)^{1/2}. \quad (2.17a)$$

b) For higher energy electrons,

$$\cos \theta_H = ((\epsilon+1) (T+2) / (1-\epsilon)T +2)^{1/2}. \quad (2.17b)$$

The energy loss per unit distance travelled for an inelastically scattered electron was determined by Bethe (Be63). By using the Moller cross sections for the region where the interacting electrons can be considered as free, the complete expression for the restricted stopping power equation for an electron or positron of kinetic energy, T , is given as (Ro54);

$$-dT/dx = 2\pi r_0^2 (m_0 c^2 / \beta^2) N Z [\ln[2(\tau + 2)/(I_{adj}/m_0 c^2)^2] + F^{+,-}(\tau, \Delta) - \delta] \quad (2.18)$$

where;

N = atoms/cm³ of scattering medium

m_0 = mass of an electron

I_{adj} = average excitation potential of the atom (MeV)

δ = density effect correction

β = v/c

c = velocity of light in free space

v = velocity of incident electron

$\tau = \gamma - 1$

$\gamma = E / m_0 c^2$

Δ = restricted maximum energy transfer

T_E = kinetic energy cutoff in units of $m_0 c^2$

$F^-(\tau, \Delta) = -1 - \beta^2 + \ln[(\tau - \Delta) \Delta] + \tau/(\tau - \Delta) + [\Delta^2/2 + (2\tau + 1)\ln(1 - \Delta/\tau)] / \gamma^2$, and

$F^+(\tau, \Delta) = \ln(\tau \Delta) - \beta^2 / \tau [\tau + 2\Delta - 3\Delta^2 \gamma/2 - (\Delta - \Delta^3/3)\gamma^2 - (\Delta^2/2 - \tau \Delta^3/3 + \Delta^4/4) \gamma^3]$

where; $y = (\gamma - 1)^{-1}$.

$F^-(\tau, \Delta)$ applies to electron-electron inelastic scattering and is obtained from the Moller scattering cross section. $F^+(\tau, \Delta)$ applies to electron-positron interactions and is derived from Bhabha cross sections for electron-positron inelastic scattering. The stopping power of a compound or mixture is obtained from the Bragg additivity relation (Fi67);

$$-dT/dx = \sum_{j=1}^N p_j \left(\frac{dT}{dx} \right)_j \quad (2.19)$$

where p_j = weight fraction of the j^{th} element in the mixture.

Average values for the ionization potential for mixtures and compounds are given in tables or calculated from the additivity relation (St84);

$$\ln I_{\text{adj}} = \frac{\sum_{i=1}^n p_i Z_i (\ln I_{\text{adj}}(z_i))}{\sum_{i=1}^n p_i Z_i} \quad (2.20)$$

p_i = fraction of the i^{th} element present in compound or mixture

n = total number of elements present in compound or mixture.

Values of I_{adj} for the elements are given in tables (Be83, ICRU84).

The density effect gives a correction for reduction in mean energy loss caused by polarization of the medium. The electric field of the incident electron decreases due to medium polarization, resulting in reduction in the ionization loss process. This causes a decreased energy transfer along the electron path. Analytical expressions for the density effect for solids, liquids

and gases were derived by Sternheimer (St56, St66, St84).

Delta rays are formed along the path of the electron. The number of delta rays with kinetic energy between T and $T+dT$ formed along the path of an electron is given by (Bu63);

$$dn = 2 \pi N Z e^4 / (m_0 v^2 T^2) dT. \quad (2.21)$$

The total number of electrons with energy in excess of T is, therefore;

$$n = [2\pi N Z e^4 / (m_0 v^2)] [(1/T) - (1/2m_0 v^2)] \quad (2.22)$$

where,

N = atoms per cm^3 of scattering medium

Z, e, m_0, T, v are as previously defined.

The scattering angles for lower and higher energy electrons are as given previously.

2.2.2 Inelastic Nuclear Scattering (Bremsstrahlung)

Bremsstrahlung is a radiative energy loss process which occurs when a photon is emitted by a free electron in a coulomb field. Classical electromagnetic theory predicts that an accelerating charged particle will emit electromagnetic radiation. Quantum mechanical theory of bremsstrahlung, formulated by Bethe and Heitler (Be34, He44), confirmed that the emitted radiation has intensity proportional to the square of the product of the charge and its acceleration. For the non-relativistic case, the intensity of the emitted photon is given as (Pa55);

$$I = (Ze)^2 a^2 / (6 \pi \epsilon_0 c^2) \quad (2.23)$$

where ; a = particle acceleration

ϵ_0 = dielectric constant.

The acceleration from a coulomb interaction is proportional to Ze^2/m . The energy radiated by an electron and some other particle of mass M in a similar coulomb field would compare;

$$I_M / I_m = (m/M)^2.$$

Hence, radiative loss for electrons or positrons is considerable when compared with loss from heavy charged particles in the same coulomb field.

At low electron energies, collision loss mechanisms dominate while at high energies bremsstrahlung processes are more important. When the two processes contribute equally to energy loss per unit length travelled, the electron energy is equal to the critical energy of the material. The expression for the critical energy is derived from (Be34):

$$(dE/dX)_{rad} / (dE/dX)_{coll} = ZE/1600 \quad (2.24)$$

and $E_{crit} = 1600 / Z$, where E is in MeV.

The fraction of incident electron energy converted into radiation is (Ko59):

$$f = (3 \times 10^{-4}) ZT / (1 + (3 \times 10^{-4}) ZT) \quad (2.25)$$

where T = initial electron kinetic energy/ $m_0 c^2$.

Deflection of the incident electron due to the bremsstrahlung process is

negligible when compared to deflections from the more frequent elastic scattering by the nucleus or orbital electrons. The scattering angle of the bremsstrahlung photon is forward peaked, i.e., in the direction of the incident electron. In general, the polar scattering angle for this process is assumed to be zero.

The energies of the emitted photon vary from zero up to a maximum equal to the kinetic energy of the incident charged particle. The interaction cross sections with various approximations are given in the paper presented by Koch and Motz (Ko59). For electrons below 50 MeV, cross sections obtained using Born approximations with empirical corrections give good agreement with experimental values. Empirical corrections applied to the Born cross section are classified as a) coulomb correction, b) high frequency limit corrections and c) screening correction.

The screening correction is included in the cross section via the form factor which is derived from the screening contributions of all orbital electrons. The cross section is usually expressed as a function of photon energy and γ , the screening factor. For relativistic incident electrons, expressions of the differential cross section with screening corrections are given by Bethe for different orders of screening (Be34). The screening factor is given as;

$$\gamma = 100 k m_0 c^2 / (E_0 E Z^{1/3})$$

where: E_0 = incident electron energy

E = final electron energy

k = photon energy

a) when $\gamma=0$: complete screening occurs ,and the cross section is expressed as;

$$d\sigma/dk = (Z^2 r_o^2 /137) 4/k \{ [1+(E/E_o)^2]^{-2/3} (E/E_o) \} [\ln(183 Z^{-1/3}) + 1/9 (E/E_o)] \quad (2.26a)$$

b) when $\gamma < 2$: intermediate screening occurs. The cross section is expressed as;

$$d\sigma/dk = (Z^2 r_o^2 /137) 4/k \{ [1+(E/E_o)^2]^{-2/3} (E/E_o) \} [\Phi_1(\gamma) - 1/3 \ln Z - 2/3 (E/E_o) \{ \Phi_2(\gamma)/4 - 1/3 \ln(Z) \}] \quad (2.26b)$$

c) when $2 < \gamma < 15$, the expression for the cross section is;

$$d\sigma/dk = (Z^2 r_o^2 /137) 4/k \{ [1+(E/E_o)^2]^{-2/3} (E/E_o) \} [\ln(2E_o E/m_o c^2 k) - 1/2 - c(\gamma)] \quad (2.26c)$$

d) and when $\gamma > 15$, i.e., $\gamma \gg 1$, no screening occurs, and the cross section is expressed as;

$$d\sigma/dk = (Z^2 r_o^2 /137) 4/k \{ [1+(E/E_o)^2]^{-2/3} (E/E_o) \} [\ln(2E_o E/m_o c^2 k) - 1/2]. \quad (2.26d)$$

The functions $\Phi_1(\gamma)$ and $\Phi_2(\gamma)$ used in equation 2.26b are Bethe-Heitler screening functions based on the Thomas-Fermi atom (Bu60). Equation 2.26b is generally used to express the screen corrected cross section. These functions are expressed as,

$$\Phi_1(\gamma) = 20.867 - 3.242 \gamma + 0.625 \gamma^2, \text{ or}$$

$$= 21.12 - 4.184 \ln(\gamma + 0.952), \text{ when } \gamma \text{ is less than or equal to } 1.$$

$$\Phi_2(\gamma) = 20.029 - 1.930 \gamma - 0.086 \gamma^2, \text{ or}$$

$$= 21.12 - 4.184 \ln(\gamma + 0.952), \text{ when } \gamma \text{ is less than or equal to } 1.$$

The coulomb correction factor modifies the cross section for coulomb distortions of the plane wave used in the Born approximation. The correction term, derived by Davis and coworkers, is given approximately as (Da54):

$$f_c(Z) = a^2 [(1 + a^2)^{-1} + 0.20206 - 0.0369 a^2 - 0.0083 a^4 - 0.002 a^6] \quad (2.27)$$

where, $a = Z/137$.

The Elwert coulomb correction factor is important at low electron energy, i.e., electron energies less than 2 MeV. It is recommended that the Elwert corrections factor be included in the derivation of the cross section when low energy electrons play an important role in the problem to be solved (Ko59). The Elwert correction factor, as a function of incident and secondary electron energies and material atomic number Z , is given as;

$$f_E = \beta_o [1 - \exp(-2\pi a \beta_o)] / [\beta(1 - \exp(2\pi a \beta))] \quad (2.28)$$

where, $\beta_o = v_o / c$

$\beta = v / c$

$v_o = \text{velocity of incident electron}$

v = velocity of final electron

$a = Z/137$ and $a(\beta^{-1} - \beta_0^{-1})$ is much less than 1.

The above correction is limited to low energy electrons and is used for electron energies below 0.1 MeV. For electrons of energies between 0.1 and 2 MeV, empirical corrections used are estimates by Koch and Motz as refined by Berger and Seltzer (Be64).

High frequency corrections are based on the bremsstrahlung process at high electron energy (Fa58). The particle energy limits considered in this research are 10 MeV and below. Neglecting contributions from high frequency corrections will introduce minimal error to estimates of the cross section for the range of beta energy considered. From equation 2.25, less than 4% of the electron energy is converted to bremsstrahlung photons for a 10 MeV electron. The radiative stopping power is expressed in terms of the average energy radiated by a electron. Therefore, the stopping power is written as a product of the number of target nuclei per unit area and the energy radiated per electron, per target, per unit area;

$$-dT = n_V dx \int_0^T k d\sigma(k)/dk$$

where an appropriate cross section is used to express $d\sigma(k)$, and n_V is number density of target nuclei.

2.2.3 Elastic Nuclear Scattering

Elastic scattering contributes most of the angular deflection a beta particle experiences in its interaction processes. From classical collision theory, the differential cross section per atom for an electron scattered from a pure unscreened nucleus is given as (Di30);

$$d\sigma(\theta) = (2\pi e^4 Z^2 / p^2 v^2) (\sin \theta d\theta) / (1 - \cos \theta)^2 \quad (2.29)$$

where p is the momentum of the incident electron and v is the electron velocity. The classical differential cross section is usually called the Rutherford scattering cross section. Using quantum mechanical theory, a more exact formula for the cross section was developed by Mott (Mo32). The Mott expression applies relativistic Dirac theory and the Born approximation but neglects the screening effect on the nucleus. The expression used for this cross section is an approximation given as (Mc48);

$$d\sigma/d\omega = Z^2 / 4r_0^2 (1 - \beta^2) / \beta^4 (1/\sin^4 \theta/2) [1 - \beta^2 \sin^2 \theta/2 + \pi \beta Z/137 (1 - \sin \theta/2) \sin \theta/2] \quad (2.30)$$

where; $d\omega = 2\pi \sin \theta d\theta$, and

$$\beta = v/c.$$

The limiting condition of the above equation is that β is approximately 1 and $Z/137$ be less than 0.2. This condition holds for material of low atomic number through which relativistic particles travel. Generally, the cross section decreases with increasing beta energy, as the $\sin^4 \theta/2$ factor discriminates

against large angular scattering. The majority of the elastic scattering interactions involve small angular deflections. Hence, the net angular deflection is a result of a large number of small deflections. When the net deflection is large, an inelastic collision is thought to have occurred with only a few small angled elastic scatterings, if any at all. Several small angle scatterings are grouped together and described by the theories of "multiple scattering".

The screening corrections may be applied to the Born approximation for elastic scattering by replacing Z by $(Z - F(\theta))$ in equation 2.30 (Be60). $F(\theta)$ is the atomic form factor. Several other methods of including the screening correction to the Born approximation have been developed. The Goudsmit and Saunderson method results in a screened cross section expressed as (Go40);

$$d\sigma(\theta) = (2\pi e^4 Z^2 / (p^2 v^2)) (\sin\theta d\theta) / (1 - \cos\theta + \theta_1/2)^2 \quad (2.31)$$

Where $\theta_1 = h/2\pi p =$ screening angle and p is particle momentum.

Moliere's method of including the screening correction also involves a screening angle similar to that of Goudsmit and Saunderson. The screening angle θ_s derived by Moliere is expressed as;

$$\theta_s^2 = [Z^{1/3}/0.885(137)]^2 [(1-\beta^2)/\beta^2] [1.13 + 3.76(Z/137\beta)^2]. \quad (2.32)$$

A large number of interactions occur which limits the practical

application of the screened cross section of single atoms. A collection of the single atomic scattering is treated together. A net angular multiple scattering deflection is then used to replace the combined effect of many small deflections. The choice of multiple scattering theory determines the extent of correction needed (Go40, Sc55). In this research the Moliere multiple scattering theory is used.

When elastic scattering with the nucleus occurs, the incident electron loses some of its energy to the nucleus. The change in incident particle energy is negligible because the target nucleus is massive compared to the electron. However the electron undergoes a considerable deflection from its incident path. Hence, only a scattering effect is attributed to elastic scattering.

2.3 Continuous Slowing Down Theory

Charged particles lose energy by collisional and radiative energy loss processes. The collisional energy loss process involves ionization and excitation while the radiative loss process generates bremsstrahlung. It is assumed that charged particles lose energy continuously along their path. This continuous loss rate is obtained from the Bethe-Bloch equation and the assumption is called the "continuous slowing down approximation". When the energy of a charged particle exceeds a certain value, it is assumed to be capable of producing secondary particles by discrete interactions such as the production of knock-on electrons and bremsstrahlung. Charged particles with energy below such cutoff value lose energy by slowing down only.

Secondary particles produced are treated similarly to energy loss by discrete or continuous processes.

When charged particles travel even through a thin layer of matter, a large number of small energy losses and a relatively small number of "catastrophic" collisions occur. Describing the many electron interactions, collision by collision, though possible is laborious. Hence, the process is replaced by a multiple-interaction model termed the "random-walk" (Be63). The random walk model considers the particle parameters after two or more interactions have occurred. Multiple interaction processes account for accumulation of a large number of collisions made by an electron in travelling a small fraction of its range. The actual particle path can be traced accurately if the pathlength is replaced by several small steps, of approximate straight lines, with an appropriate angular deviation associated with each step.

2.3.1 Energy Loss By Electrons

The random-walk method describes an approximate point to point motion ascribed to charged particle transport. Bethe's continuous slowing down approximation (CSDA) is used to describe the electron energy loss along its path. The average energy loss per unit distance travelled (stopping power) includes the contributions of bremsstrahlung and ionization (Ro54).

$$(-dE/dx)_{\text{total}} = (-dE/dx)_{\text{rad}} + (-dE/dx)_{\text{coll}} \quad (2.33)$$

Ionization and radiative contributions to stopping power are derived from appropriate corrected cross sections. The electron pathlength is

obtained from:

$$\Delta x = \int_{T_1}^{T_2} [-dE/dx]^{-1} dE$$

where, Δx = step size, $(x_1 - x_2)$

T_1 = kinetic energy of electron at the beginning of step,

T_2 = kinetic energy of electron at end of step.

The energy loss between two steps is determined from

$$\Delta E = E_1 - E_2 = - \int_{x_1}^{x_2} (dE/dx)_{\text{tot}} dx$$

Contributions from catastrophic collisions result in the straggling effect (La44). Rigorous treatment of the straggling effect is omitted because of the random nature of the solution from a Monte Carlo calculation.

2.3.2 Multiple Scattering

Electrons will undergo a large number of elastic and inelastic interactions when passing through a medium. The grouping of many steps of actual physically random collisions into a single step of a condensed random walk requires an appropriate multiple scattering theory. Several scattering models describe electron angular deflections with a varying degree of approximation. The most commonly used models are the Moliere (Be53) and Goudsmit-Saunderson (Go40) theories. In general, only deviations in the polar angle are considered in the multiple scattering theory. Deviations in the

azimuthal angle are always assumed isotropic. The Moliere multiple scattering model was used in this research. A brief treatment of this model is presented below.

The electron path is approximated by a series of straight lines. In approximating the actual pathlength, the step size must be restricted to reduce the error of the approximation. The Moliere scattering model transports electrons in a straight line along a direction related to the initial direction by the scattering angle. The Moliere scattering angle is sampled from a probability distribution function that depends on particle energy, the distance travelled into the medium and the material of the medium through which the particle travels. Schemes for sampling the scattering angles are based on the approach of Messel and Crawford (Me70). Elastic collisions with atomic nuclei contribute most of the deviation in the multiple scattering process.

2.3.2.1 Moliere Multiple Scattering Model

At the end of a transport step, an electron would have deviated from its incident path by an angle Θ (see Figure 2.5). An energy dependent probability distribution function (pdf) is associated with this angle. In Moliere scattering theory, the energy dependent pdf $f(\Theta)$ is expressed in terms of an energy independent pdf $f(\theta)$ of a reduced angle θ . The reduced angle θ is related to Θ by,

$$\theta = \Theta / \chi_0 B^{1/2} . \quad (2.34)$$

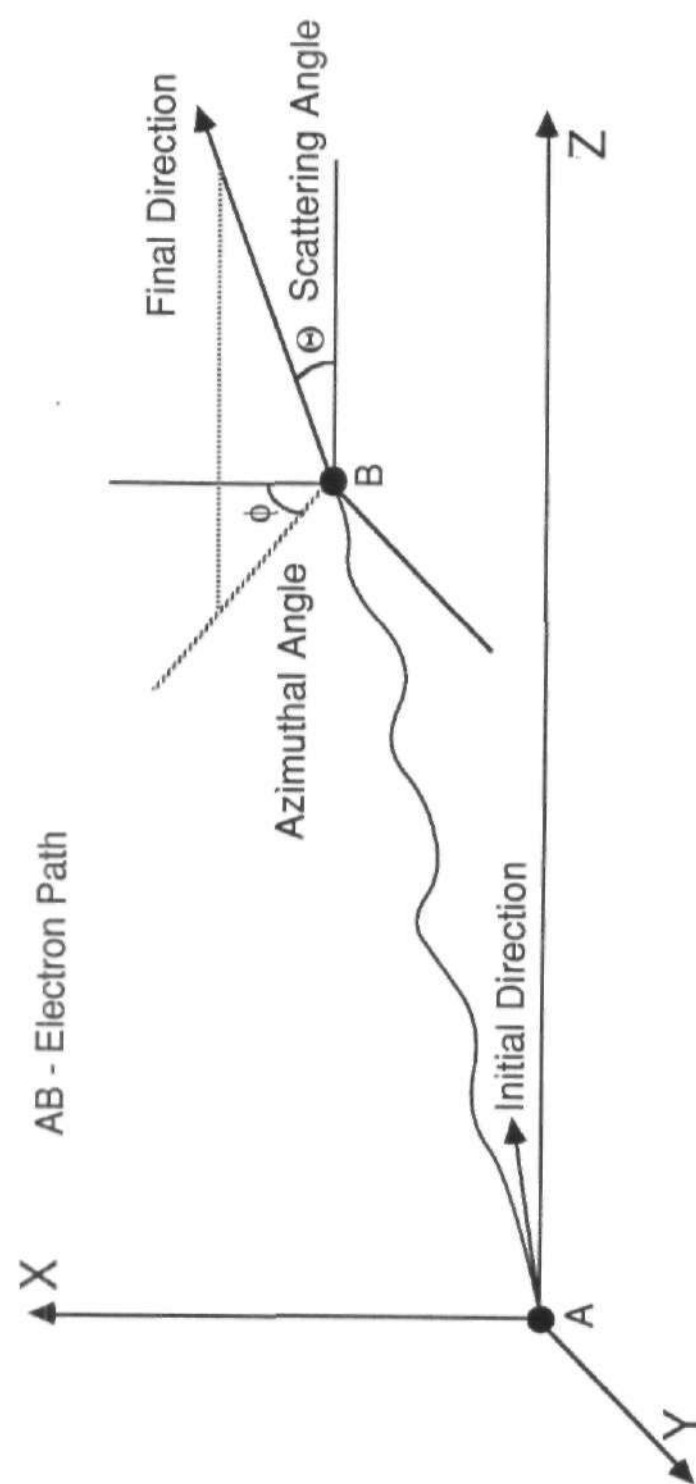


Figure 2.5 Electron multiple scattering geometry.

The variables χ_c and B are evaluated on the basis of the screened scattering cross section per atom developed by Moliere. The variables are functions of the particle energy and the pathlength travelled in the medium. The pdf $f(\theta)$, is a modification proposed by Bethe for $f_m(\theta)$, the Moliere's pdf for the scattering angle. The relationship between the two pdfs is given as (Be53);

$$f(\theta) = f_m(\theta) ((\sin \theta) / \theta)^{1/2}. \quad (2.35)$$

The factor $((\sin \theta) / \theta)^{1/2}$ in the above equation corrects the Moliere theory for large angle scattering that occasionally occurs. The pdf $f_m(\theta)$ is sampled by first sampling θ from $f_r(\theta)$ and then, by using equation 2.34, the scattering angle θ is obtained. Then, the pdf for the Moliere scattering angle $f_m(\theta)$, is related to that of the reduced angle $f_r(\theta)$ by;

$$f_m(\theta) \theta d\theta = f_r(\theta) \theta d\theta. \quad (2.36)$$

The pdf for the reduced angle is expressed in terms of the first three terms of an expansion in the inverse of the variable B (Be53). The form used is;

$$f_r(\theta) = [f^0(\theta) + 1/B f^1(\theta) + 1/B^2 f^2(\theta)] \quad (2.37)$$

Where the general form of the function $f^l(\theta)$ is given as;

$$f^n(\theta) = (n!)^{-1} \int_0^\infty u du J_0(\theta u) \exp\left\{\left(-\frac{u^2}{4}\right) \left(\frac{u^2}{4} \ln \frac{u^2}{4}\right)\right\}^n \quad (2.38)$$

When $n=0$, $f_0(\theta) = 2 \exp(-\theta^2)$.

This term is the gaussian distribution which predicts a bell shaped forward scattering distribution. For higher values of n (i.e., 1 and 2), the solution for equation (2.38) is obtained by numerical methods. Tables of the solutions have been compiled for general usage (Be53).

The parameters B and χ_c are needed to determine completely the values of the reduced pdf $f_r(\theta)$. B is obtained from the transcendental relationship (Be53);

$$B \cdot \ln(B) = b \quad (2.39)$$

where; $b = \ln(\Omega_0)$

$$\Omega_0 = (\chi_c^2 / 1.167 \chi_{aa}^2) = b_c t / \beta^2.$$

χ_c^2 is a parameter dependent on material and is defined as,

$$= \int_E^{E_0} \chi_c'^2(E') \left| \frac{dE}{ds} \right|^{-1} dE'$$

$$\chi_c'^2 = 4\pi N Z^2 / (p^2 v^2)$$

$$\chi_a^2 = a Z^{2/3} [1.13 + 3.76(Z/137\beta)^2]$$

$$a = 6.8 \times 10^{-5}$$

$$\log \chi_{aa}^2 = \frac{1}{\chi_c^2} \int_E^{E_0} \chi_c'^2(E') \log \chi_a^2(E') \left| \frac{dE}{ds} \right|^{-1} dE'$$

This transcendental equation relating B to a given value of b is solved by

iteration techniques.

The limitations of Moliere theory are ;

- a) the number of scatterings in a step must be large enough (i.e., 20 to 30 collisions) to represent true multiple scattering. The variable Ω_0 is related to the number of scatterings that take place per step, i.e, $\Omega_0 > 20$.
- b) the step size must be restricted such that (Be53),

$$\chi_c^2 B = \Theta/\theta < 1.$$

Therefore, the maximum step size is such that, $\chi_c^2 B = 1$. Generally, errors resulting from approximating transport along a curved path by a straight line must be minimal. A maximum allowed fractional error is usually chosen randomly.

2.4 Calculational Models In Internal Dosimetry

Energy deposition in organs of the body from internally deposited radionuclides can be estimated by either the classical method (ICRP59) or by a method developed by the Medical Internal Radiation Dose (MIRD) Committee (Lo68, Lo76).

The classical method is based on the concepts of a maximum permissible concentration of radionuclide, maximum permissible organ or body burden and critical organs. The maximum permissible organ burden of a radionuclide is defined as the quantity of the radionuclide that will deliver to

the organ the maximum permissible dose rate limit. In the determination of the maximum permissible organ burden, q , an effective absorbed energy per disintegration of the radionuclide is defined, i.e., (ICRP59).

$$q = 2.8 \times 10^{-3} \text{ mR} / (f_2 \epsilon) \quad (2.40)$$

where q has units of μCi

R = permissible dose equivalent rate limit (rem /week)

m = mass of organ in grams

f_2 = fraction of body burden in organ of interest

The effective absorbed energy per disintegration ϵ , is defined as;

$$\epsilon = \sum E F(\text{RBE}) n$$

where ; E = total energy absorbed in the organ per disintegration

RBE = relative biological effectiveness

F = ratio of activity of daughter to activity of parent in the organ of interest.

n = relative damage factor.

For photons, the classical method considers the energy absorbed in an organ of a specified effective radius as;

$$E = E_0 f (1 - \exp(-\mu x)) \quad (2.41)$$

where; E_0 = gamma ray energy (MeV)

f = fraction of disintegration that gives the photon type considered.

μ = total coefficient of absorption

x = effective radius of organ (cm).

For alpha and beta particles, the average energy absorbed in the organ of interest is defined as;

$$E = E_{\alpha} f; \text{ for alpha radiation} \quad (2.42a)$$

where E_{α} is the alpha particle energy (MeV),

$$\text{and } E = 1/3 E_{\max} f(1-Z^{1/2}/50)(1+E_{\max}^{1/2}/4); \text{ for beta radiation} \quad (2.42b)$$

where $E_{\max}$ is maximum energy of emitted beta particle.

In using the classical method, all the factors needed to compute the maximum permissible organ burden for a standard man are given for about 250 radionuclides (ICRP59).

The MIRD method attempts to reduce internal dose calculations to a few elementary operations using knowledge of decay schemes and compartmental models of radionuclides. The scheme introduces the term absorbed fraction to define the fraction of the energy released in the source which deposits in the target. The organ containing the radioactive material is called the source while the organ irradiated is called the target organ. The calculation of absorbed dose to the target requires the determination of the total number of nuclear transformations that occur in the source within the time period of interest.

The calculation of radiation absorbed dose can be viewed as the conversion of activity into emitted energy and then into energy absorbed per

unit mass. For a radionuclide emitting one radiation type, the mean absorbed dose D is,

$$D = k(A E \phi)/m$$

where; A = cumulated activity ($\mu\text{Ci} \cdot \text{hours}$)

E = particle average energy (ergs or joules)

m = mass of target organ (grams)

k = conversion factor

ϕ = absorbed fraction of energy in target organ.

A complete dose estimate for a target organ requires summation of the individual contributions from all source organs. The MIRD dosimetry scheme becomes complicated when a radionuclide emits many kinds of radiation. When different source organs contain different proportions of the same or different radionuclides, the MIRD scheme becomes further complicated. The mean absorbed dose to a target organ r_k from a source organ r_h can be written as ;

$$D(r_k \leftarrow r_h) = \frac{A_h}{m_k} \sum_i E_i n_i \phi_i(r_k \leftarrow r_h)$$

where, n_i = number of type i particles emitted per transformation

$\phi_i(r_k \leftarrow r_h)$ = absorbed fraction in target region r_k from source region r_h

for type i radiation.

and E_i , A_h and m_k are as previously defined.

In more convenient notation, the mean absorbed dose is written as,

$$D(r_k \leftarrow r_h) = A_h \sum_i \Delta_i \Phi_i(r_k \leftarrow r_h)$$

where, $\Delta_i = n_i E_i$ = mean energy per transformation

$\Phi_i = \phi_i / m_k$ = specific absorbed fraction.

The mean absorbed dose can be written in terms of unit accumulated activity in the source;

$$D(r_k \leftarrow r_h) = A_h S(r_k \leftarrow r_h)$$

where; $S(r_k \leftarrow r_h) = \sum_i \Delta_i \Phi_i(r_k \leftarrow r_h)$.

The value of the absorbed fraction will depend on the type and energy of the radiation, size and shape of the source and target organs, the distance between source and target, and the composition of the intervening tissue. However, the value of the absorbed fraction will lie between 0 and 1. When radiation energy emitted in a source contributes a significant dose to organs other than itself, the radiation is called penetrating. When the dose contributed to other organs is not significant, the radiation is called nonpenetrating. In developing data for the absorbed fraction for nonpenetrating radiation, the source organ has been considered as the only target organ, and the absorbed fraction is unity, while for any other target the absorbed fraction is zero.

More accurate estimates of the absorbed fractions for beta particles and weak photon emitters are needed to better estimate doses in the fields of radiation therapy and radiation protection.

CHAPTER III

ELECTRON-GAMMA SHOWER (EGS) MODEL

3.1 Introduction

The EGS system of computer codes is a general purpose package for the Monte Carlo simulation of the coupled transport of electrons and photons in any arbitrary geometry. The code can simulate, with good accuracy, radiation with energy from above a few keV up to several MeV. The third version of the EGS code was introduced as a package in 1978 and called EGS3 (Fo78). The EGS3 code was developed for simulation of electromagnetic cascade showers in high energy physics. One attractive feature of the code is that it allows particle simulation in any user defined geometry. One limitation of this code is that it can only accurately simulate photons and electrons above 0.1 and 1.0 MeV respectively. With recent developments, the lower limits have been extended in the new version called EGS4 (Ro85). The lower energy limits for the EGS4 code are kinetic energies of 10 keV for electron and 1 keV for photon simulation. These present cutoff energies make EGS4 suitable for work in internal dosimetry. The code is written in the FORTRAN 77 language but a version in an extended FORTRAN language called MORTAN is also in circulation.

The code simulates the transport of electrons using the condensed history technique (Be63). Creation of secondary electrons (above a cutoff energy, A_E) is simulated and all generations of electrons are followed down

in energy to a cutoff (ECUT) at which point the remaining energies are deposited locally. In transporting photons, the distance between collisions are randomly determined and photon does not lose energy between collisions. The distance to the next collision site is the product of the randomly determined number of mean free paths traversed and the value of the mean free path for the medium at the photon energy considered. Results obtained using the EGS4 code compare well with results from other codes, e.g., ETRAN (Be69, Se74, Ro84).

EGS4 has features that make it versatile and easy to use. The code considers all the physical processes important in the transport of electrons and photons with energies above 10 keV. For photon interactions, the code considers Compton scattering (using Klein-Nishina's cross sections applied to free electrons), pair production (with an approximation for triplet production), and the photoelectric effect (with characteristic x-rays and Auger electrons considered to be locally deposited). An option for the consideration of coherent scattering exists also. Cross sections from tables compiled by Storm and Israel are used in the photon simulation (St70).

Electron-positron transport is simulated using the condensed history technique. The restricted stopping power equation is used to account for continuous energy loss along the particle path (Be64). Bremsstrahlung production, positron annihilation, elastic Moller and Bhabha scattering from electrons, and Moliere multiple scattering from atomic nuclei are all taken into account. The main features of EGS4 include;

- 1) Electron and photon showers can be simulated in any element, compound, or mixture.
- 2) The code is not specific to any given medium. The data preparation code (PEGS4) permits the user to generate cross sections, which are used directly in EGS4, for the processes of interest for virtually any material.
- 3) The code is fully three dimensional and no restriction is placed on the geometrical configuration defined by the user.
- 4) A user written scoring routine allows for inclusion in the output of any desired variable or groups of variables, and statistics.
- 5) The code allows the user to set values for several variables which include;
 - i) cutoff energies for particles transported in various media,
 - ii) desired maximum allowed percent energy loss per step (ESTEPE) due to continuous slowing down of the electron.
 - iii) initial parameters for incident particles, i.e., monoenergetic or spectral energy distribution, isotropic or beam of particles.
 - iv) initial incident particle to be transported, i.e., photon or electron.
- 6) The user can include any form of importance sampling or variance reduction technique.

3.2 Calculational Methods

The random nature of electron-photon interactions is a fundamental reason for the use of the Monte-Carlo method in particle simulation. EGS4 takes a simple approach towards simulating the actual processes as closely as possible by using the Monte Carlo method. No variance reduction technique is used in this research, hence the results obtained should show a real life fluctuation. EGS4 transports individual electrons and photons through the user defined geometry comprising any variety of materials. The type of interaction that occurs at any point in the medium is sampled from the branching ratios of the competing interactions. After the choice of an interaction type is made, the properties of the products of such an interaction are calculated from the appropriate equation and stored in the stack, ready for transport at a later time.

Properties of the secondary particle, produced by the incident particle interaction, are stored and processed on a "last-in, first-out" basis. Initially, only the incident particle is in the stack. This top particle is transported until an interaction occurs, until its energy drops below the cutoff value, or until the particle enters a predetermined portion of the geometry. When the particle interacts producing more than one secondary particle, the one with a lower energy will be placed at the top of the stack. In the latter cases, particle energy is deposited and simulation continues from the particle on the top of the stack. Processing of the incident particle ends when the stack is empty, then simulation of the next history can be started.

3.2.1 Photon History

Photon interactions considered in EGS4 are pair production, Compton scattering, photoelectric effect, and coherent scattering. Photons travel in straight lines and lose no energy between interactions. To describe photon transport, the distance between interaction sites and the choice of interaction type must be determined. The mean free path of a photon is given in terms of the total macroscopic cross section, i.e.,

$$\lambda_t = 1/\Sigma_t.$$

The number of mean free paths transversed between collisions is randomly determined and is given as (Fi67);

$$N_\lambda = \int dx' / \lambda(x')$$

Therefore, the distance travelled between collisions is,

$$\text{distance} = -\ln(R) / \Sigma_0$$

where, Σ_0 is the total interaction cross section.

When considering photon transport through a finite number of regions, each of which is homogeneous, the distance travelled in each region is monitored such that the sum of fractions of the mean free path travelled in each region equals the randomly determined number of mean free path travelled by the incident photon. The steps for photon transport as outlined in the unmodified EGS4 code are,

- a) compute the mean free path at the current location.
- b) compute the distance to the next interaction site for a homogeneous

medium using properties of current location (t_1).

- c) determine distance to the nearest boundary along the photon path
(This is the variable called DNEAR).
- d) let t_2 equal the smaller of t_1 and DNEAR, and let the photon be transported by distance t_2 .
- e) determine fraction of the mean free path left to be travelled. If the result is zero, the photon has travelled the required distance and can have an interaction with the medium.
- f) when answer to step e) is non-zero, i.e. $t_2 \neq \text{DNEAR}$, the photon is about to enter a new region. The material in the new region is checked and if it is different from that of the old region, the process step is routed to step a) , else, process step is directed to step b).

Using the above procedure, photon transport in the various organs within the body is very complicated because of the irregular geometry and the inhomogeneity of body organs. The determination of distance to the nearest organ boundary can only be accomplished by iterative methods. Therefore, a new photon transport model was designed for use in the EGS4 code .

3.2.2 Electron History

Electron interactions considered in EGS4 are elastic coulomb scattering of the nucleus, inelastic electron-electron and electron-positron scattering, positron annihilation and bremsstrahlung. Several interactions occur along a small fraction of the electron path. The cross sections of most of

these interactions are only approximately determined. Hence, simulation of all the electron interactions is omitted and replaced by simulation of groups of these interactions. This procedure is called the random walk technique. The continuous slowing down model is used to treat electron energy loss between discrete interactions and below a certain electron cutoff energy. Cutoff energies are used to distinguish between continuous and discrete electron interactions. An electron interaction that produces a delta ray with energy of at least A_E , or a bremsstrahlung photon with energy of at least A_P , is considered to be a discrete interaction. All other interactions are considered as continuous and are regarded to lose energy only by continuous electron energy loss in the slowing down process. Multiple scattering accounts for most of the particle's directional change.

Due to continuous energy loss along the electron path, the energy dependent cross sections for discrete interactions change along the electron path. To determine the distance to the next interaction site, an additional fictitious interaction is introduced. These fictitious interactions result in straight ahead travel for the electron while the real interactions (discrete interactions) result in changes in particle parameters and the creation of secondary particles. The magnitude of a fictitious interaction is assumed to be such that the total cross section is constant along the electron path, i.e.,

$$\sigma_{t, \text{fict}}(x) = \sigma_{t, \text{real}}(x) + \sigma_{\text{fict}}(x) = \sigma_{t, \text{real}}(x_0)$$

where, t denotes total cross section

x_0 denotes starting position on path

x denotes final position on path.

The location of the next interaction is sampled, as for photon transport, using

$\sigma_{t, \text{real}}(x_0)$ as the total cross section. At the end of the path, the ratio of

$$\sigma_{t, \text{real}}(x) / \sigma_{t, \text{real}}(x_0)$$

is compared to a random number to determine if a real or fictitious interaction has occurred. It has been determined that the application of this procedure, for electron transport, is limited to electron cutoff energy greater than 580 keV for material of low atomic number (Ro84).

Discrete interactions considered in EGS4 are positron annihilation, Moller and Bhabha inelastic electron scattering, and bremsstrahlung production. These interactions are determined to occur randomly by comparing of the ratio of such an interaction to the total interaction cross section.

The deviation along the electron path is modelled according to Moliere multiple scattering theory. The electron path, like that of a photon, is assumed to be a straight line between collisions, with multiple scattering accounting for the directional changes. Step sizes must be kept small so that the true electron path length is not much different from the straight line approximation.

3.3 Computer Code Description

The computational task of the EGS4 code is divided into two parts. First, the preprocessor code for EGS4 (PEGS4) uses theoretical and empirically corrected formulae to compute the various physical quantities needed for use in the simulation process. The second part is the simulation of photon-electron transport using the Monte Carlo method.

The program control flow from subroutine to subroutine is shown in figure 3.1. Each subroutine is structured to solve a particular problem in either the geometry or simulation procedure. The subroutines that make up the EGS4 code can be grouped into a users code and a simulation code. The EGS4 simulation code consists of two user "callable" routines, HATCH and SHOWER, which in turn call other subroutines. Subroutine HATCH reads the cross sections and all the material parameters output from PEGS4 before routine SHOWER is called to initialize the particle to be transported. SHOWER then calls either ELECTR or PHOTON to begin transport of electrons or photons, respectively. Information is transferred to and from all subroutines via common blocks.

Three major subroutines have been written which use a modified version of EGS4 to simulate electron and photon transport in a human phantom. These subroutines (called INDOSE) comprise of the MAIN program, subroutines POSITN (the geometry tracking routine) and AUSGAB (the scoring routine). The code INDOSE was developed to calculate specific absorbed fractions for gamma ray and beta/electrons incident in source

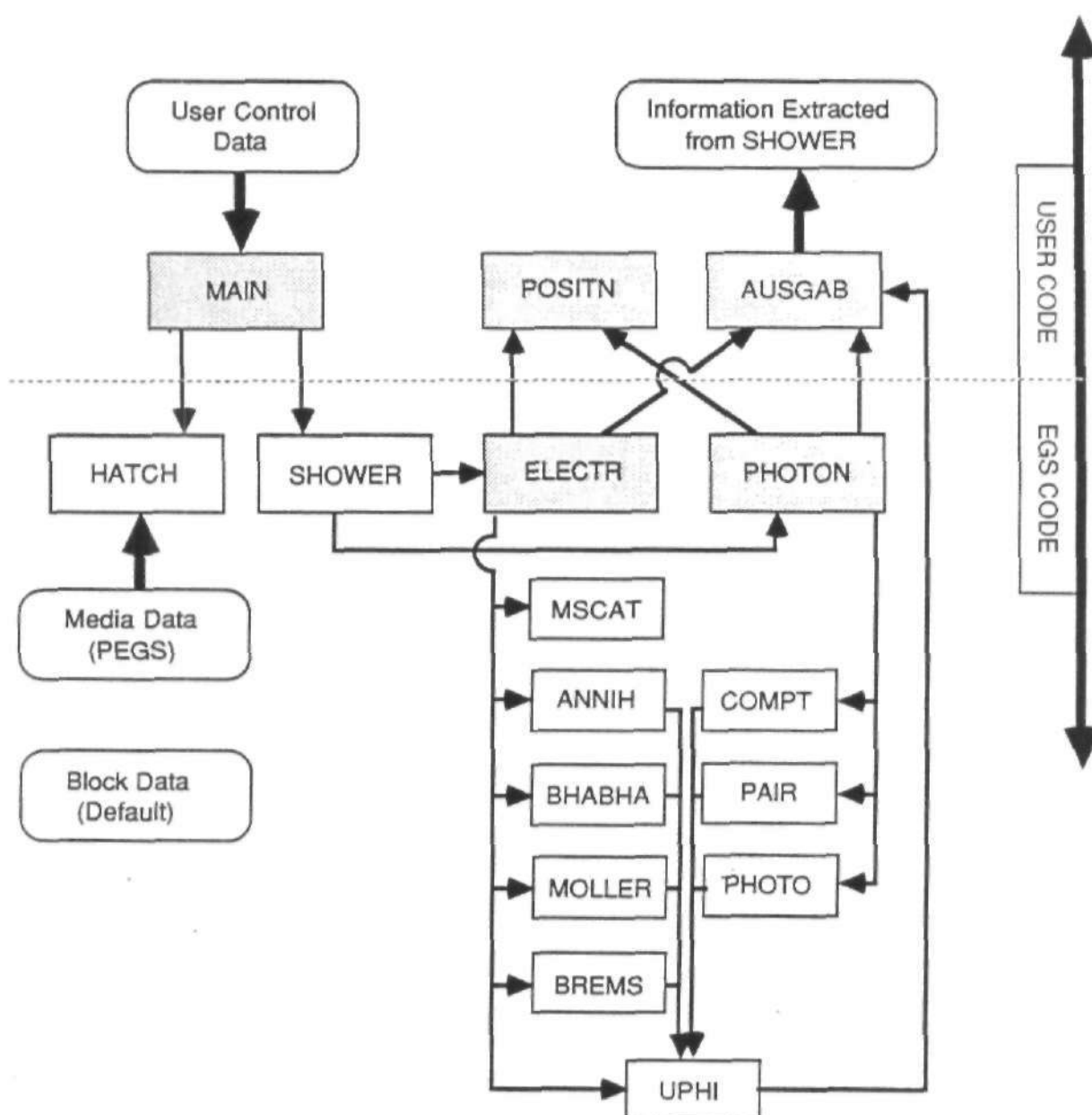


Figure 3.1. Flow control for the Electron-Gamma simulator (EGS4). Shaded sections show area of work in this research. Adapted from Nelson and coworkers (Ne85).

organs of a mathematical phantom. Subroutines ELECTR and PHOTON have been modified to meet the objective of this research. This section presents a description of the user-written code, INDOSE, and the modified version of ELECTR and PHOTON used in this research.

3.3.1 Simulation Code (Electron-Gamma Shower Code System)

The EGS4 code system can realistically simulate electron-photon transport in elements, compounds or mixtures of material with atomic numbers from 1 to 100. The EGS4 simulation code consists of thirteen subroutines as shown in Figure 3.1.

Subroutine PHOTON simulates photon transport. Photon interactions considered in EGS4 are Compton scattering, pair production and the photoelectric effect. Subroutine PHOTON calls subroutines COMPT (for Compton scattering), PAIR (for pair production), and PHOTO (for photoelectric effect) to describe photon interactions. The subroutine PHOTON has been modified extensively for use in this research while the interaction routines are unchanged. These interaction subroutines are written with generous comments and references allowing the user to modify the routines with relative ease.

Subroutine ELECTR simulates electron transport. It calls routines MSCAT, ANNIH, BHABHA, MOLLER, and BREM to describe electron interactions considered in EGS4. Subroutine MSCAT describes multiple scattering that accounts for the directional change of the transported particle. ANNIH describes annihilation interactions. The two 0.511 MeV photons produced

from an annihilation interaction are transported individually. MOLLER is called from ELECTR to describe inelastic electron-electron scattering, while BHABHA describes inelastic electron-positron scattering. Finally, BREM describes bremsstrahlung production. A simpler version of ELECTR was developed to simulate electron transport. The subroutines that describe electron interactions have not been modified, however, they are written with comments and references to allow the user to modify them with ease.

3.3.1.1 Subroutine PHOTON

The photon transport logic used in EGS4 is the straight forward procedure of obtaining an interaction site and then tracing back along the path to find the first surface where the photon entered a medium whose total cross section differs from that of the region where the flight began. This procedure is efficient within a regularly defined geometry. The procedure used in this research determines the next interaction site by using a total cross section, Σ_0 , that is greater than or equal to that of any of the regions (i.e., skeleton, tissue, or lung) for the photon energy considered. The distance traversed to the potential interaction site is taken as;

$$\text{distance} = -(\ln(\text{random number})) / \Sigma_0.$$

The new subroutine PHOTON assumes a constant total cross section along the photon step even if the next interaction site is in a new medium. We can write,

$$\Sigma_0 = \Sigma_F + \Sigma_1$$

Where Σ_0 is the constant cross section

Σ_F is a fictitious cross section

Σ_1 cross section determined for the region of the new interaction site

If the medium at the new site is different from that at the old site, Σ_0 and Σ_1 are different and a fictitious interaction allowing only a straight ahead travel of the photon occurs. Hence, either a real or fictitious interaction occurs at this site. To determine if a "real" interaction occurs, the ratio of total cross section at the site, Σ_1 , to Σ_0 , is compared to a randomly chosen number (0, 1). A "real" interaction occurs at the site if the random number is less than the ratio of cross sections. This procedure gives a photon the correct expectation of reaching any point on its line of travel regardless of how many boundaries are crossed (Sn78). This logic has been incorporated into PHOTON as shown in the flow chart in Figure 3.2.

3.3.1.2 Electron Transport

Electron and positron transport are simulated in subroutine ELECTR. The interactions considered are multiple scattering, annihilation, Moller and Bhabha inelastic scattering, and bremsstrahlung production. Photon and electron transport logic differ in that, while photon interactions are followed collision by collision, electron interactions cannot be so monitored. Electrons, because of the large number of interactions occurring per unit distance travelled, are followed after small fractions of their path length have been traversed. The electron loses energy while in motion and a simple approach

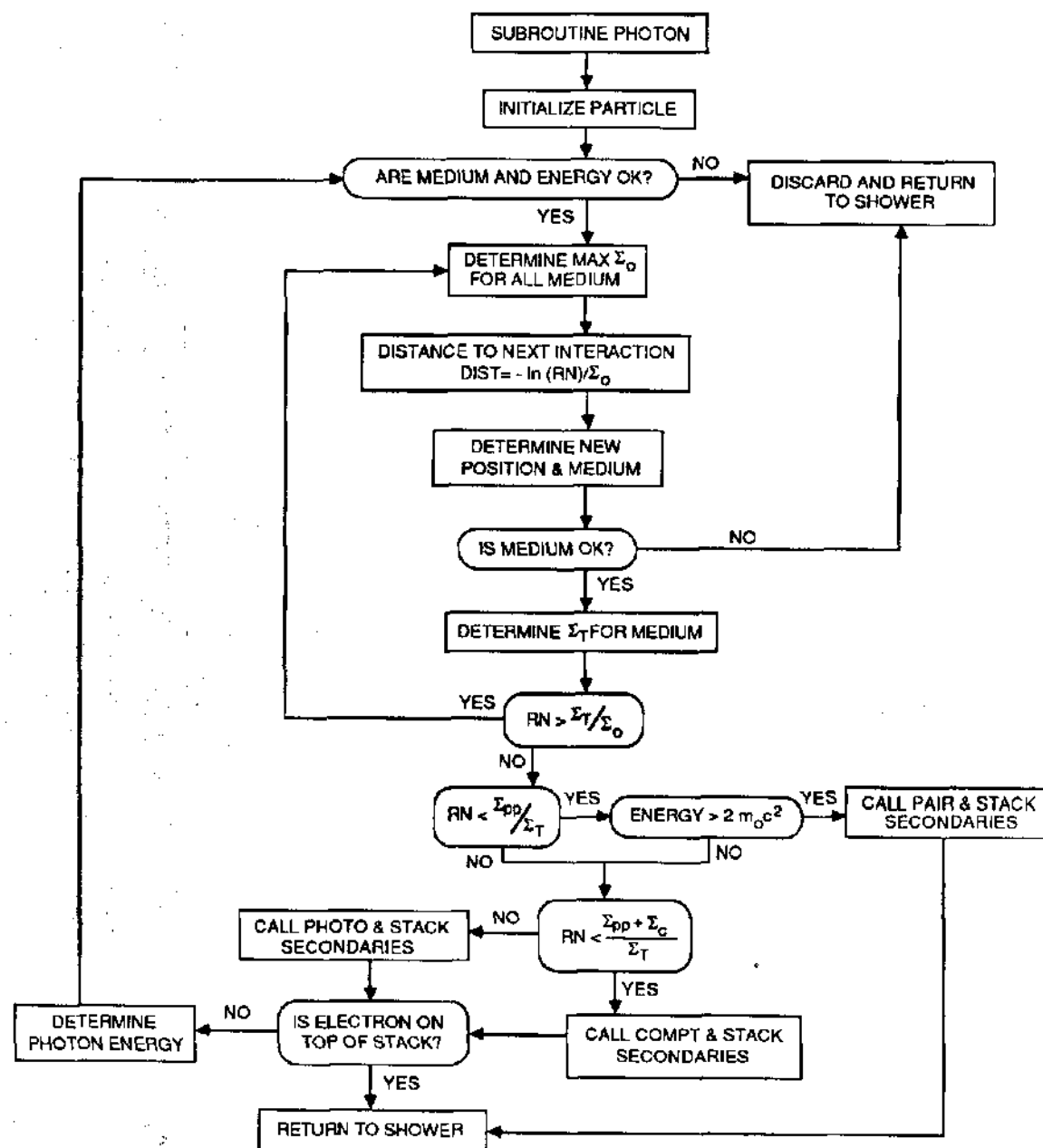


Figure 3.2 Flow chart for photon transport.

to account for this energy loss is the continuous slowing down approximation (CSDA) (Be63).

Cutoff energies are used to distinguish between continuous and discrete interactions. As discussed earlier, the choices of cutoff energies (A_P , A_E) play an important role in determining the accuracy of the final results obtained from the code. An electron interaction that produces delta rays of at least A_E , or a photon of at least A_P , is considered as a discrete event, i.e., secondary particles with energy less than the cutoff energy are considered to lose energy continuously.

In EGS4, the directional change, mostly due to multiple coulomb scattering and soft electron scattering are described by the Moliere multiple scattering theory. Scattering angles are sampled from an appropriate distribution function which depends on the electron energy, the material and the total distance travelled by the particle. The electron path is assumed to be a straight line and in approximating the curved path by a straight line, the step size must be restricted to minimize error. The procedure used in this research for electron transport was to move the electron in a straight line along its initial direction, sample the scattering angle from the appropriate distribution, determine the azimuthal angle randomly and, finally, determine direction of the electron adjusted to the fixed coordinate system using subroutine UPHI.

Step size restrictions to meet the criterion of straight line transport and multiple scattering angle sampling are important in determining the overall

accuracy of electron transport. Step size limitation in EGS4 is achieved by using the minimum step obtained from the following criteria;

- a) random choice of distance to next interaction site, i.e.,

$$\text{step size} = -\ln(\text{random number}) / \Sigma_t$$

- b) distance obtained from an allowed maximum fractional energy loss, K,

$$\text{i.e., step size} = K E_0 / (dE/dx)$$

- c) distance obtained from multiple scattering constraint, i.e.,

$$\text{step size} > 20 \beta^2 / b_c, \text{ where } \chi_c^2 B < 1 \text{ and all the variables are as defined}$$

in chapter 2.

- d) step size must be less than range, i.e.,

$$\text{step size} = E_0 / (dE/dx).$$

At the end of the electron step, an interaction is randomly chosen to occur.

In the modified subroutine ELECTR, the boundary checking requirement has been removed. Errors generated by removal of this requirement are minimal because electron step size is very small. However, in the event of a particle travelling along the boundary of a region the error could be large. The modified subroutine ELECTR is shown in Figure 3.3.

3.3.2 User-written Code

The user code INDOSE was written to use the modified version of the Electron Gamma Shower (EGS4) simulation code to give estimates of the absorbed fraction (AF) of energy emitted from a source region that is absorbed in a target region. The INDOSE code is comprised of three primary

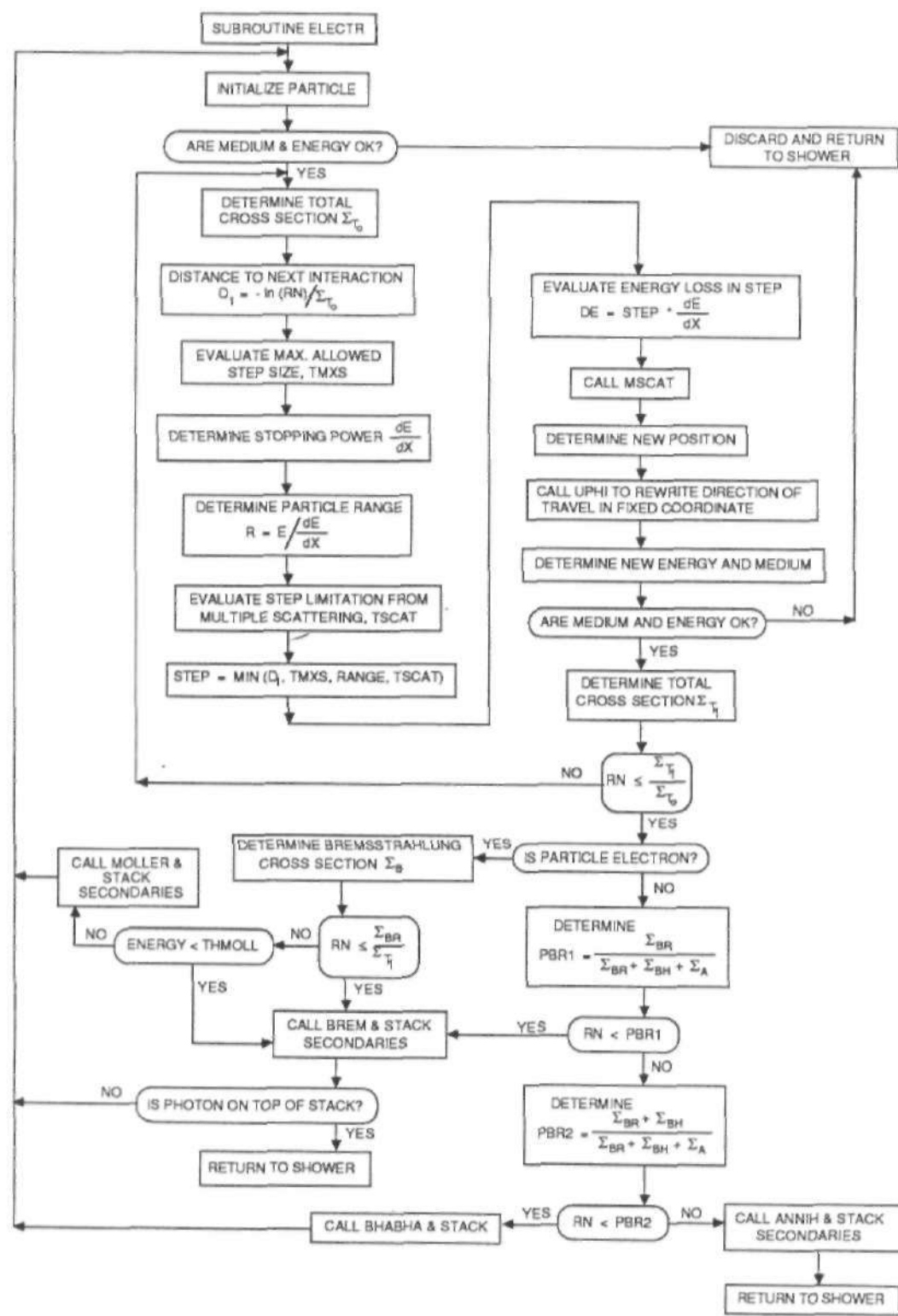


Figure 3.3 Flow chart for electron transport.

sections; the MAIN program, AUSGAB the scoring routine and POSITN the geometry tracking routine. Figure 3.1 illustrates how the user code interacts with other sections of the code. Each section of the user code is discussed below. A listing of each section is provided in Appendix A. The user code transfers and receives information from other sections of the code via common blocks.

3.3.2.1 MAIN Program

MAIN is the first section of the INDOSE code. It supplies all the initialization required for transporting a particle. The nature of the source, the energy and direction of the incident particle are needed to initiate a transport history. Options used in the initialization process are discussed in a different section of this report. The main program also performs a statistical analysis on the results to obtain the relative error from the Monte Carlo process. The output of the final results are formatted in MAIN.

Source Options

Particle transport is initiated from organs described in the geometry representing an adult human. The source description represents a radioactive material which is homogeneously distributed in a organ. Organs considered as sources reflect present practice in nuclear medicine. Sources have been considered to be in the kidneys, heart chambers, lungs, thyroid, bladder contents, stomach contents, spleen, ovaries, testis and the uterus.

The initial position and direction of travel of the particle are chosen randomly within the volume of the organ considered as source. Source

subroutines are called from MAIN to provide the initial particle position and direction. Listings of these source subroutines are given in Appendix B.

Energy Option

The energy of the incident particle can either be a fixed (average) value or described from a known energy spectrum. For photon transport, monoenergetic particles have been used. Particles in the energy range between 10 keV and 10 MeV are been considered in this research. This is because most radionuclides used in nuclear medicine emit photons in this energy range. In beta decay, the electron can either be considered to be emitted at the average energy or the particle energy is chosen from a number-energy distribution. An energy of $1/3$ the maximum beta particle energy is chosen as the average beta energy for calculations. With an appropriate normalized beta spectrum, the value of the electron energy can also be selected.

The MAIN program first calls subroutine HATCH to obtain the cross section data. The call to HATCH is done only once. One particle or history is transported to conclusion (with all its secondaries) before a new incident particle history is started. Each incident particle is initialized before a call to SHOWER is made to start particle transport. On return from SHOWER, all the necessary information from the particle just transported is recorded. A new history is started or the statistical analysis performed if the required number of histories (NCASES) have been performed. The choice of the number of histories determines the accuracy of the result obtained.

3.3.2.2 Subroutine AUSGAB

The subroutine AUSGAB has a very simple structure. It sums up all energy deposited in the regions of the defined geometry. After the occurrence of an interaction involving energy deposition, subroutine AUSGAB is called. The information transferred to AUSGAB includes the region in which the deposition occurs, the type of interaction involved and the energy deposited. A running sum of energy deposited in all regions involved is updated after every interaction (call to AUSGAB).

Energy deposition occurs;

- a) when the photon has energy less than PCUT, the photon cutoff energy,
- b) when the electron has energy less than ECUT, the electron cutoff energy,
- c) during continuous slowing down of an electron ,
- d) when the particle enters a regions outside the geometry of the phantom, i.e., vacuum, and
- e) when a photoelectric interaction has occurred, and
 - i) the energy of the incident photon was below the K-edge binding energy and it is going to be discarded, and
 - ii) a fluorescent photon is discarded with the K-edge binding energy.

The variable IARG is used to define situations where calls are made to AUSGAB.

AUSGAB is called from either the photon or electron transport subroutines when an energy deposition occurs. Scoring from AUSGAB can

be expanded to include several other situations. However, the variable IARG must then be activated for those situations.

3.3.2.3 Subroutine POSITN

This subroutine tracks the particle throughout its movement in the phantom geometry. The geometry used for this research is a mathematical description of an anthropomorphic phantom similar to that used in the ALGAM code (Wa68). A typical dimension and coordinate system of a reference man is shown in figure 3.4. The phantom consists of three principal sections. The torso is represented by an elliptical cylinder, the head and neck represented by an elliptical cylinder topped by half an ellipsoid and the legs section represented by truncated cones. Surfaces of the internal organs are described by quadratic equations.

The inside of the phantom has been subdivided into 53 organ regions (see Table 3.1). Each region is defined by a closed surface with care taken to avoid overlapping volumes. The weight and dimensions used for each organ were as specified in ICRP Publication 23 (ICRP75). Recent modifications in the description of the lungs and heart have been included in this phantom geometry (Co81). A face model was also included in the phantom (Po86).

Subroutines PHOTON and ELECTR call POSITN after a particle is transported. With every advancement to a new location, the routine POSITN is called to determine if the particle has moved to a new region. POSITN assigns a region variable to a particle everytime it is called.

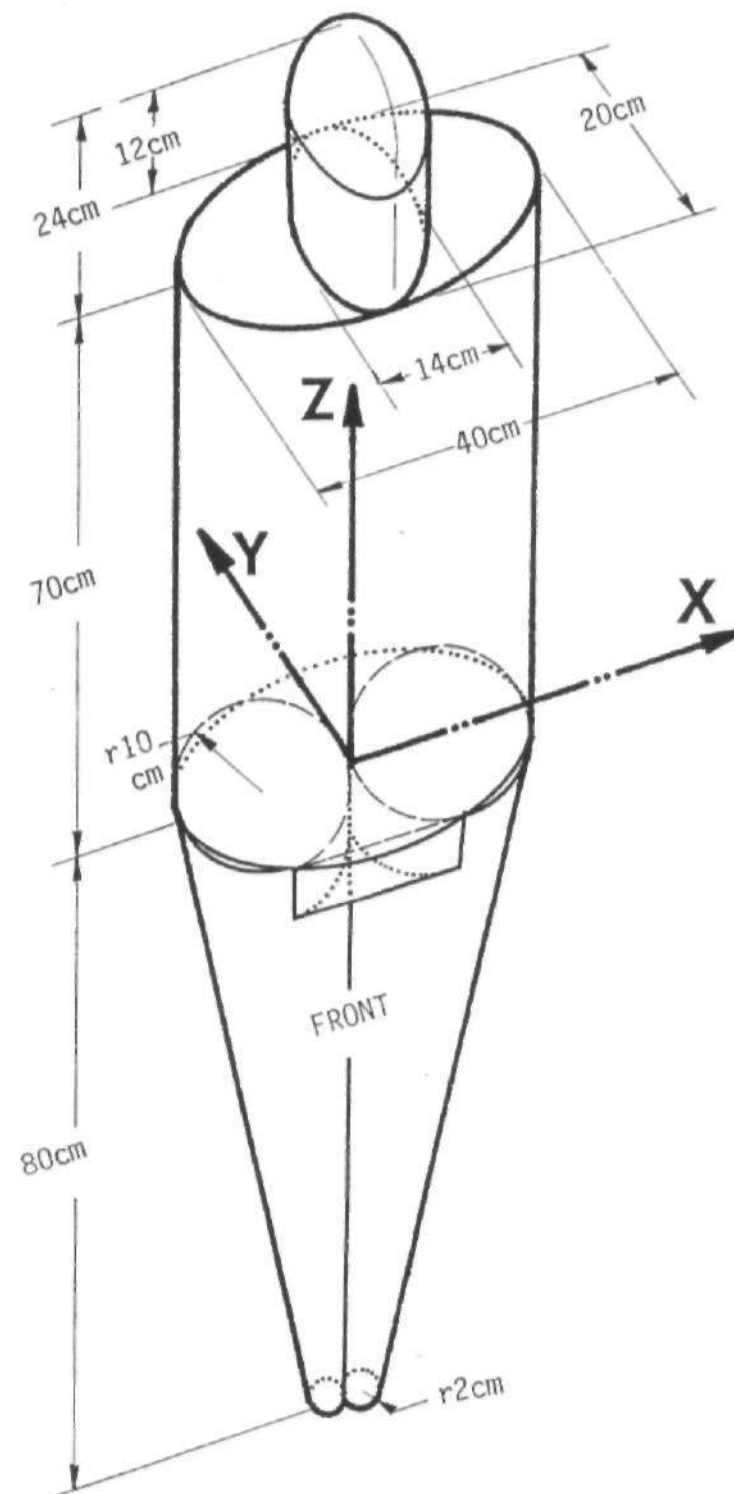


Figure 3.4. Adult human phantom, dimensions and coordinate system (Sn78).

Table 3.1. Masses of source and target organs used in this study

Source Organs	Mass(gms)	Target Organs	Mass(gms)
Bladder Content	200.	Left Adrenal	7.75
Stomach Content	247.	Right Adrenal	7.75
Uterus	65.4	Bladder Wall	45.1
Both Kidneys	284.	Brain	1450.9
Liver	1809.1	Stomach Wall	150.
Both Lungs	1000.	Upper Large Int.	209.
Both Ovaries	8.28	Lower Large Int.	160.
Spleen	173.6	Small Int. + cont.	1044.
Both Testes	37.0	Uterus	65.4
Thyroid	19.6	Left Kidney	142.
Heart Chambers	431.0	Right Kidney	142.
		Liver	1809.1
		Left Lung	463.0
		Right Lung	537.0
		Septum	14.2
		Nares	9.49
		Left Ovary	4.14
		Right Ovary	4.14
		Genitalia	193.7
		Pelvis	900.8
		Ribs	1031.4
		Scapulae	302.
		Skull	1258.2
		Spine	1319.
		Spleen	173.6
		Left Teste	18.5
		Right Teste	18.5
		Thymus	24.8
		Thyroid	19.6
		Heart Wall	299.0
		Face	232.7
		Pancreas	60.3
		Eyes	2.0
		Total Body	70000.0

CHAPTER IV

CROSS SECTION DATA AND OTHER PARAMETERS

The phantom used was considered to be composed of three media, i.e., tissue, skeleton and lungs. The chemical composition and density used for each medium is given in Table 4.1 (ICRP75). Each organ is assumed to be a homogeneous mixture of the elements in the proportions given in Table 4.1. The material cross-section is generated by using the processor code PEGS4. PEGS4 uses theoretical and empirical formulae to compute the various physical quantities needed for each medium and prepares them in a form for use in EGS4.

Certain parameters are chosen in the run of the EGS4 code. These parameters are; ECUT, PCUT (the electron and photon energy cutoffs), AE and AP (the energy cutoffs in the computation of cross section data), ESTEPE (the fractional energy loss per step in the electron transport), and NCASES (the number of histories to run). The accuracy of the result of a calculation depends on the values used for these parameters. Choices for these parameters are discussed below.

4.1 Cross Sections

Cross section values used in EGS4 are the output of the PEGS4 code. PEGS4 uses theoretical and empirical methods to generate material cross sections. PEGS4 maintains a table of atomic number, atomic weight

Table 4.1. Elemental composition of different tissues of the phantom (% by weight)

Element	Skeletal Tissue ¹	Lung ²	Tissue ³
H	7.04	10.21	10.47
C	22.79	10.01	23.02
N	3.87	2.8	2.34
O	48.56	75.96	63.21
Na	0.32	0.19	0.13
Mg	0.11	7.4×10^{-3}	0.015
P	6.94	0.081	0.24
S	0.17	0.23	0.22
Cl	0.14	0.27	0.14
K	0.15	0.20	0.21
Ca	9.91	7.0×10^{-3}	0.0
Fe	8.0×10^{-3}	0.037	6.3×10^{-3}
Zn	4.8×10^{-3}	1.1×10^{-3}	3.2×10^{-3}
Rb	0.0	3.7×10^{-4}	5.7×10^{-4}
Sr	3.2×10^{-3}	5.9×10^{-6}	3.4×10^{-5}
Zr	0.	0.	8.0×10^{-4}
Pb	1.1×10^{-3}	4.1×10^{-5}	1.6×10^{-5}

¹Density 1.4862 gm/cm³

²Density 0.2958 gm/cm³

³Density 0.9869 gm/cm³

and interaction cross sections for elements 1 through 100 on the periodic table. The photon interaction cross section, i.e., for pair production, photoelectric absorption and Compton scattering, was adapted from cross section data compiled by Storm and Israel (St70). The total cross section for a given interaction type is given as;

$$\Sigma_t = N_a \rho \sigma / M$$

where, N_a = Avoradro's number

ρ = density of the medium (gm/cm³)

σ = microscopic cross section of the medium (cm² / atom) for a specific interaction.

$$\sigma = \sum_{i=1}^n p_i \sigma_i$$

$$M = \sum_{i=1}^n p_i A_i$$

σ_i = microscopic cross section for each element, i

p_i = proportion by weight of element i in mixture

A_i = atomic number of element i .

The total cross section is a summation of cross sections over all the possible interaction types at the specified particle energy. A log-log interpolation process is used to determine cross sections at energies between the data points.

Methods of obtaining cross sections for discrete interaction processes

for electrons were discussed in chapter 2. The value of the cross sections depend on the energy cutoff values used. AE and AP denote an energy set beyond which discrete interaction processes are considered possible. ECUT and PCUT are the electron and photon energy cutoffs. Electrons with energies less than ECUT are not transported, neither are photons with energies less than PCUT. The energies of radiations below these cutoffs are deposited locally. The values of AE, AP are limited by the physics of all particle interactions included in the code. The values of 0.522 and 0.001 MeV have been used for AE and AP, respectively. PCUT was set at 0.001 MeV through all the calculations in this research. The value of ECUT was set at 0.6 MeV when electron transport is considered. When electron transport is not considered, ECUT was set at the incident photon energy i.e., this allows all energies from secondary electrons formed in the various photon interactions to be deposited locally.

4.2 PEGS4 Code

The FORTRAN 77 version of the PEGS4 code was used to generate material data needed for particle transport. PEGS provides other services which include:

- i) Evaluation of mathematical functions at selected points e.g., density effect correction.
- ii) Selection of energy cutoffs.

The PEGS code contains a MAIN program, BLOCK DATA subprogram, 12 subroutines and 85 functions. No modifications were made to the PEGS

code. The input data for PEGS4 describes each medium and assigns cutoff energies for radiation interactions. PEGS4 code considers the media used as composed of homogeneous mixtures of the elemental composition listed in table 4.1. Cross sections and other data for these media were determined for discrete energy values between 0.522 and 10 MeV for electron interactions and for between 0.001 and 10 MeV for photon interactions. Cross sections for any intermediate energy is determined by an interpolation method. The output from PEGS is called XTION.DAT. The data file XTION.DAT is very lengthy and has not been included in this report, however, a copy of XTION.DAT is available on tape.

4.3 Selection Of Maximum Allowed Fractional Energy Loss For Electron Transport (ESTEPE)

The accuracy of electron transport depends on the step size between interactions. This is the case because the curved path of an electron is approximated by a straight line travel. The constraints placed on the step size were discussed in chapter 2.

In the transport of electrons of energy below 10 MeV, it has been found necessary to impose a limitation on the maximum fractional energy loss per step. This constraint is similar to that in the code ETRAN (Be63, Co74). The choice of the maximum fractional energy loss per step (ESTEPE) was determined from the results of a series of calculations. These calculations were intended to determine the absorbed fraction for a 2 MeV electron source in the thyroid. Results from these calculations are presented in Figure 4.1.

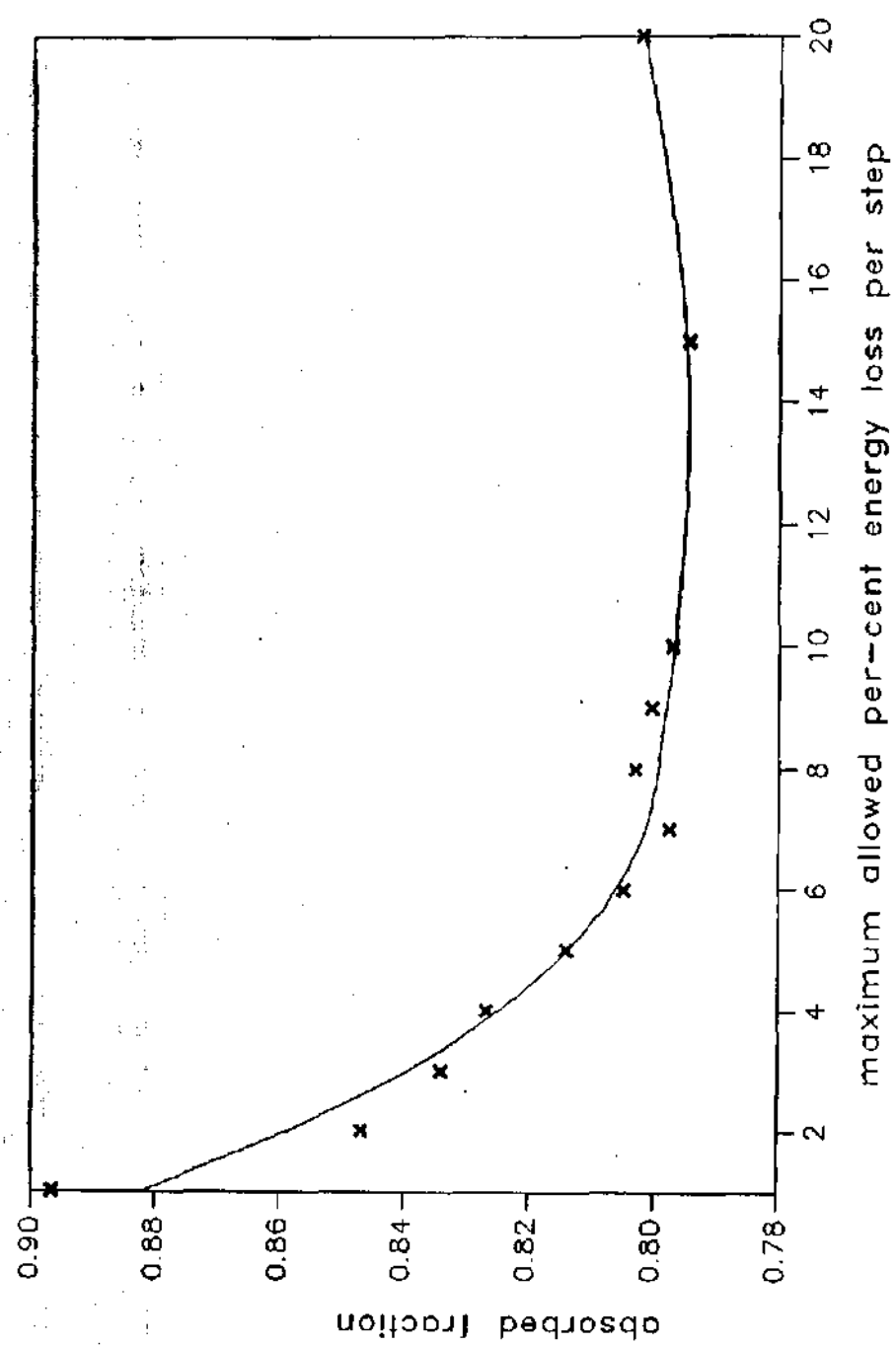


Figure 4.1. Determination of maximum allowed percent energy loss per step for electron transport. Plot of absorbed fraction in the thyroid for 2 MeV electrons versus allowed percent loss.

The problem of choosing an appropriate ESTEPE is solved by varying ESTEPE until the absorbed fraction no longer changes significantly.

ESTEPE was set at 8% for all the calculations in this research. Small changes in this value produces no changes in the results of calculations performed.

4.4 Comparing ALGAM And INDOSE-EGS Codes

ALGAM is a Monte Carlo code used to transport monoenergetic photons in an anthropomorphic phantom. The code has been used to provide estimates of the fraction of the initial photon energy absorbed in a target for a source of photons is any source organ in the phantom (Sn69). ALGAM does not transport secondary electrons produced during the transport of incident photons. All the energy of such secondaries are considered to be locally deposited. INDOSE was developed to consider the contribution to photon transport from these secondary electrons. Differences in results obtained from ALGAM and INDOSE (for photon transport) will be due to differences in the cross sections, energy deposition logic and phantom geometry.

Photon interaction cross sections for the material that defines an organ in the phantom are needed for use in the transport of a photon and determine the type interaction which would occur at any stage of particle transport. These interaction cross sections are determined from a combination of theoretical and empirical methods. Generally, these cross section are compiled in tabular form for ready use in the Monte Carlo

processes. The cross sections are usually correlated to the best experimental data available at the time of compilation. The cross sections used in ALGAM were compiled by Grodstein (Gr57) and reviewed by McGinnis (Mc59). The cross sections used in INDOSE-EGS were compiled by Storm and Israel (St70). The difference in these cross section data is not expected to be large for photon energies below 10 MeV.

The present photon transport logic in INDOSE-EGS is very similar to that of ALGAM. However, ALGAM uses a weighting procedure to determine energy deposition at interaction sites while energy deposition in INDOSE-EGS is via electron transport only. For example, when photoelectric absorption occurs, all the photon energy is given to an electron and the electron deposits energy in the medium.

In ALGAM, a weight, initially set at unity, is associated with every photon. The weight at the next site, $W(n+1)$, is determined from the particle weight at the previous site $W(n)$, such that,

$$W(n+1) = W(n) [\Sigma(\text{Compton}) / \Sigma(\text{total})]$$

and the energy deposited at the $(n+1)^{\text{st}}$ site, by a photon coming from the previous interaction site n , is,

$$\Delta E(n+1) = W(n) \{ [\Sigma(\text{photon}) / \Sigma(\text{total})] E(n) +$$

$$\{ [\Sigma(\text{Compton}) / \Sigma(\text{total})] \{ E(n) - E(n-1) \} + \{ [\Sigma(\text{pair}) / \Sigma(\text{total})] \{ E(n) - 1.22 \} \} \}.$$

When pair production occurs at a site, ALGAM only transport one photon with a energy 0.511 MeV but with weight of,

$$W(n+1) = 2 \times W(n) \{ \Sigma(\text{pair}) / \Sigma(\text{total}) \}.$$

Hence, in ALGAM the photon is always partially scattered, even in a photoelectric absorption interaction. The weighting technique improves the precision of a Monte Carlo calculation. However, the results with or without weighting should converge to the same value.

The human phantom is assumed to be composed to 3 media, the lung, tissue and skeletal. The phantom media used in both codes have the elemental composition as defined in ICRP23 (ICRP74). The geometry used in INDOSE-EGS was adapted from that used in ALGAM. Modifications to the description of the lungs and heart were made. A new definition for the face was also introduced into the phantom. Differences in results from INDOSE-EGS and ALGAM calculations will occur especially those associated with the lungs and near by organs because the right lung is 16% bigger than the left lung in the new model.

CHAPTER V

RESULTS FROM THE INDOSE-EGS CODE

5.1 Introduction

The computer code INDOSE-EGS was developed to run on the VAX 8650 computer that is housed in the Zachry Engineering Building at Texas A&M University. This version of the code written in FORTRAN 77, was designed to determine the contribution a detailed consideration of beta/electron transport makes in internal dose estimation. This task was separated into two sections.

The first section was to consider beta/electron sources as incident particles. Using the INDOSE code, calculations of absorbed fractions of the electron energy deposited in the source organs and nearby organs were performed. Detailed consideration was given to bremsstrahlung production by electron interactions. The second section considered photons as the incident radiation. Detailed consideration was given to the resulting charged particles produced during photon interactions. Calculations of specific absorbed fractions of energy were performed for eight monoenergetic photons. Only data for organs of clinical importance are listed in the results presented. However, data for other minor organs were obtained but not included in this report. Sources of photons and electrons used in calculations were assumed to be uniformly distributed in homogeneous media (i.e.,

source organs).

Results from the first section of the problem are presented as absorbed fractions (AF) in the target organs (i.e., source organs and nearby organs that receive a substantial amount of energy from the radiation). The general assumption, that the absorbed fraction for non-penetrating radiation is unity if the target organ is also the source organ, and zero when the target organ is not the source organ, has been determined to be too sweeping. Also, in the computation of AF for an electron source, we have obtained an idea of the other target organs whose exposure must be considered.

The results from photon transport calculations are presented as specific absorbed fractions. This is in keeping with the results presented in MIRD publications (Sn78).

5.2 Absorbed Fractions For Electron Sources (Non-penetrating Radiation)

In the computation of the absorbed fraction of energy for electron sources, the organs considered as source organs were the lungs, thyroid, kidneys and liver. Sources in the bladder and stomach contents were also considered. Calculations for absorbed fractions were performed for nine monoenergetic electron sources ranging from 0.5 to 5.5 MeV. In each calculation, 10,000 electron histories were traced. Tables 5.1 through 5.6 present results obtained from the INDOSE-EGS code. The coefficients of variation of the absorbed fraction for different organs are also listed. Estimates of absorbed fractions with coefficients of variation greater than 50%

Table 5.1. Absorbed fraction of electron energy and coefficient of variation (%). Electron source in bladder contents.

Target organs	Total energy of electron (kinetic + rest mass energy)				
	1.0	2.0	3.0	4.0	6.0
Bladder contents	9.83E-1 [*] < 0.05 ^{**}	9.36E-1 0.1	8.84E-1 0.1	8.32E-1 0.1	7.29E-1 0.1
Bladder wall	9.56E-3 2.7	4.76E-2 1.1	6.39E-2 0.8	6.92E-2 0.7	7.02E-2 0.5
Stomach wall	-. ^{***}	1.50E-6 45.7	3.18E-6 36.2	3.30E-6 28.9	2.95E-6 21.5
Liver	9.71E-6 31.5	2.39E-5 18.9	2.33E-5 19.8	3.85E-5 19.8	6.31E-5 18.1
Genitalia	1.06E-5 24.5	2.58E-5 20.0	3.39E-5 15.9	4.93E-5 12.9	4.94E-5 14.0

^{*} Absorbed fraction of energy

^{**} Coefficient of variation (%)

^{***} Coefficient of variation greater than 50%

Table 5.2. Absorbed fraction of electron energy and coefficient of variation (%). Electron source in stomach contents.

Total energy of electron (kinetic + rest mass energy)					
Target organs	1.0	2.0	3.0	4.0	6.0
Stomach contents	9.83E-1 [*] < 0.05 ^{**}	9.34E-1 0.1	8.79E-1 0.1	8.25E-1 0.1	7.18E-1 0.2
Stomach wall	9.92E-3 2.7	5.42E-2 1.1	9.95E-2 0.8	1.27E-1 0.6	1.48E-1 0.4
Left kidney	1.07E-5 25.0	2.45E-5 21.5	3.31E-5 16.5	3.83E-5 15.0	6.07E-5 14.1
Right kidney	1.65E-6 48.2	5.22E-6 27.8	9.35E-6 26.4	1.53E-5 30.4	3.13E-5 28.2
Liver	6.51E-5 13.3	1.42E-4 8.2	1.96E-4 7.8	2.14E-4 7.4	3.02E-4 7.1
Left lung	3.99E-5 15.1	8.14E-5 11.4	1.29E-4 9.9	1.53E-4 8.9	3.46E-4 7.8
Right lung	1.24E-5 28.9	2.44E-5 14.1	4.76E-5 16.2	5.06E-5 14.4	7.30E-5 14.0
Spine	5.76E-5 14.6	8.46E-5 9.0	1.09E-4 7.3	1.31E-4 7.7	1.34E-4 6.9
Spleen	4.41E-5 18.7	6.33E-5 13.9	6.61E-5 10.9	8.92E-5 9.8	1.09E-4 9.6
Heart wall	1.76E-5 25.1	3.14E-5 22.3	3.63E-5 16.3	4.13E-5 15.3	5.61E-5 12.5
Heart chambers	9.66E-6 29.0	3.26E-5 15.4	5.89E-5 13.7	6.17E-5 13.3	8.05E-5 11.8
Pancreas	2.36E-5 16.4	5.03E-5 19.8	5.82E-5 15.4	8.26E-5 13.5	1.09E-3 5.5

^{*} Absorbed fraction of energy

^{**} Coefficient of variation (%)

Table 5.3. Absorbed fraction of electron energy and coefficient of variation (%). Electron source in liver.

Target organs	Total energy of electron(kinetic + rest mass energy)				
	1.0	2.0	3.0	4.0	6.0
Liver	9.88E-1 [*] 0.1 ^{**}	9.54E-1 0.2	9.17E-1 0.2	8.86E-1 0.3	8.23E-1 0.4
Right lung	8.11E-4 29.5	1.59E-4 21.9	8.52E-4 17.7	2.46E-3 12.6	7.06E-3 8.1
Left lung	--- ^{***}	4.16E-5 38.4	1.83E-5 33.5	8.77E-5 39.0	1.03E-4 30.0
Right kidney	---	4.86E-5 42.2	2.00E-5 28.0	4.81E-5 28.0	3.05E-4 27.4
Left kidney	---	---	---	---	---
Spine	5.48E-4 41.5	8.95E-5 29.0	1.34E-4 17.8	1.57E-7 19.0	1.40E-4 25.4
Heart wall	---	2.79E-5 45.6	4.65E-5 39.7	4.62E-5 36.5	1.09E-4 34.9
Heart chambers	---	2.24E-5 38.9	3.23E-5 26.8	1.01E-4 44.0	5.01E-5 24.4
Spleen	---	---	1.38E-5 46.9	---	1.11E-5 37.4

^{*} Absorbed fraction of energy

^{**} Coefficient of variation (%)

^{***} Coefficient of variation greater than 50%

Table 5.4. Absorbed fraction of electron energy and coefficient of variation (%). Electron source in thyroid.

Total energy of electron (kinetic + rest mass energy)					
Target organs	1.0	2.0	3.0	4.0	6.0
Thyroid	9.55E-1 [*] 0.2 ^{**}	8.14E-1 0.4	6.77E-1 0.5	5.46E-1 0.6	3.77E-1 0.7
Brain	5.44E-5 40.6	7.77E-5 33.5	1.61E-4 32.8	1.88E-4 25.6	1.91E-4 23.2
Spine	5.94E-5 42.6	5.73E-5 32.3	4.57E-5 23.4	7.88E-5 17.9	9.98E-5 32.4
Skull	5.71E-5 36.5	1.18E-4 18.0	2.77E-4 25.5	2.22E-4 17.4	4.39E-4 21.1
Face	3.20E-2 4.7	1.42E-1 1.9	2.41E-1 1.3	3.18E-1 1.0	3.87E-1 0.8

^{*} Absorbed fraction of energy

^{**} Coefficient of variation (%)

Table 5.5. Absorbed fraction of electron energy and coefficient of variation (%). Electron source in kidneys

Target organs	Total energy of electron (kinetic + rest mass energy)				
	1.0	2.0	3.0	4.0	6.0
Kidneys	9.81E-1 [*] 1.0 ^{**}	9.17E-1 1.1	8.42E-1 1.1	7.73E-1 1.2	6.42E-1 1.3
Stomach wall	-. ^{***}	9.57E-6 44.2	1.35E-5 44.6	1.42E-5 29.4	4.03E-5 38.0
Liver	1.08E-4 24.7	2.78E-4 18.8	4.59E-4 23.7	7.45E-4 17.7	2.82E-3 11.1
Left lung	-. ^{***}	2.02E-5 41.3	5.86E-5 32.5	6.63E-5 38.2	7.81E-5 31.4
Right lung	-. ^{***}	3.19E-5 36.6	4.82E-5 31.1	5.55E-5 39.8	9.20E-5 23.9
Spine	1.68E-4 24.9	3.59E-4 16.9	3.96E-4 13.9	6.25E-4 14.8	3.48E-3 9.8
Spleen	8.07E-5 31.4	7.11E-5 40.1	1.66E-4 37.1	5.29E-4 26.7	2.90E-3 12.4

^{*} Absorbed fraction of energy

^{**} Coefficient of variation (%)

^{***} Coefficient of variation greater than 50%

Table 5.6. Absorbed fraction of energy and coefficient of variation (%) . Electron source in lungs

Total energy of electron (kinetic + rest mass energy)					
Target organs	1.0	2.0	3.0	4.0	6.0
Lungs	9.70E-1 [*] 1.1 ^{**}	8.79E-1 1.2	7.81E-1 1.2	6.88E-1 1.3	5.33E-1 1.4
Liver	8.82E-5 28.7	1.78E-4 22.9	1.74E-3 15.1	6.32E-3 8.9	1.56E-2 6.0
Spine	1.36E-4 25.2	1.39E-4 20.6	1.85E-4 21.3	2.09E-4 18.6	1.50E-4 12.6
Heart wall	7.52E-4 31.6	3.69E-3 13.2	7.48E-3 8.6	1.01E-2 7.1	1.27E-2 5.8
Heart chambers	7.05E-4 31.6	4.52E-3 11.7	8.50E-3 8.6	1.06E-2 7.5	1.50E-2 5.9

^{*} Absorbed fraction of energy

^{**} Coefficient of variation (%)

were not reported because the uncertainty in such results could be as much as a factor of 2 or 3 (Sn78).

Results are reported for target organs into which substantial amount of energy is deposited. The absorbed fraction of energy depends on the size, shape, composition of both source and target regions, distance and composition between source and target regions. Generally, the absorbed fraction of energy for a target organ which is also the source organ decreases with increasing electron energy, while the absorbed fraction of energy when the target organ is not the source organ increases with increasing electron energy. Target organs for which exposure estimates from beta radiation must be considered depend on the source organ. For example, when the electron source is homogeneously distributed in the liver, it was found that doses to the lungs, right kidney, spleen, heart wall, heart chambers, and spleen must be considered.

Figures 5.1 to 5.6 present the variation of absorbed fraction with energy for selected source organs. The results can be grouped into two classes. The first class includes the special situation in which the source organ is not the target organ while the second class represents the situation in which the source organ is also the target organ.

Figures 5.1 and 5.2 present results for electron sources in the bladder content and the stomach content. These results represent two cases of the class I situation. Results for this class show an increase in the absorbed

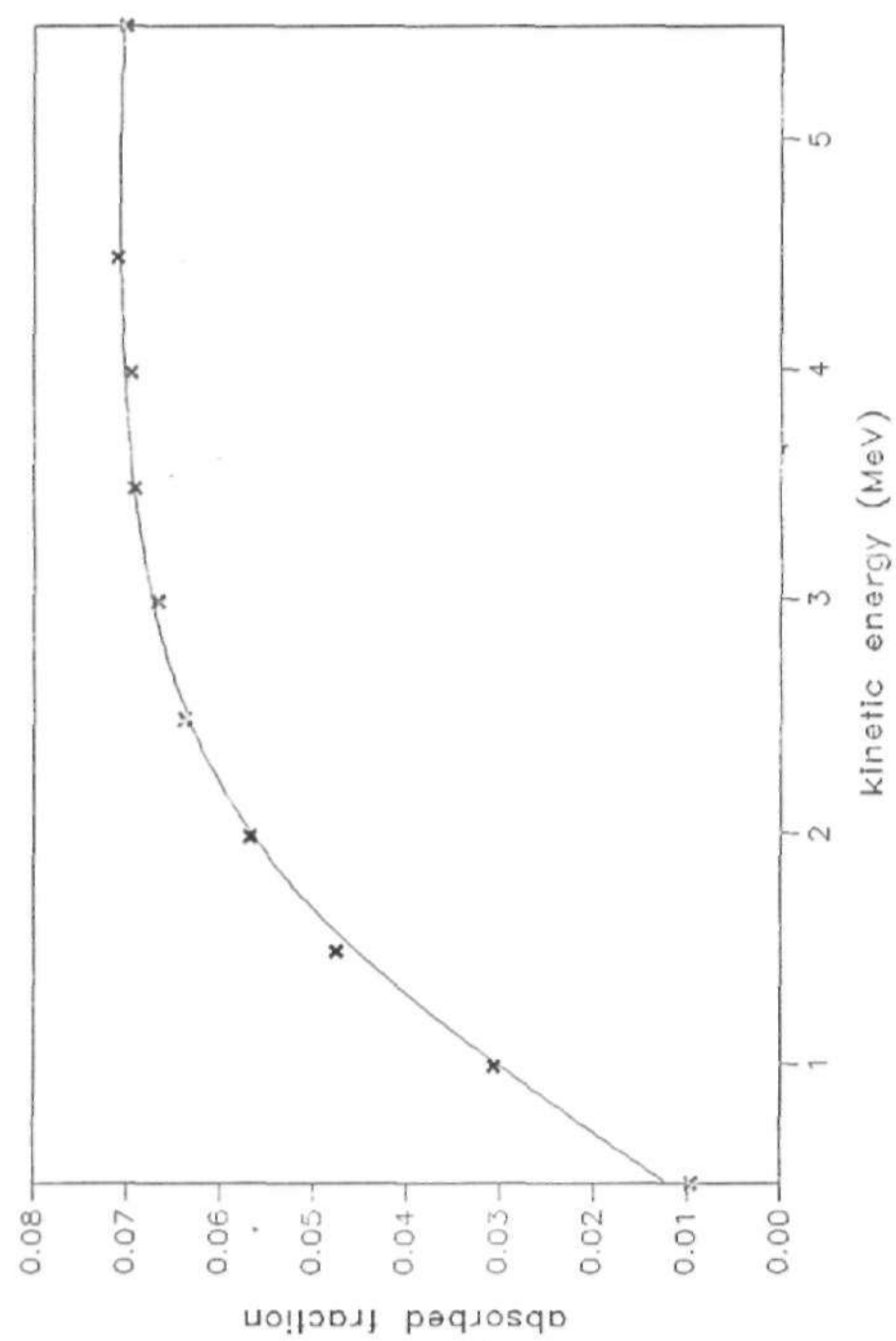


Figure 5.1. Absorbed fraction of electron energy for monoenergetic electron sources in bladder contents. Target organ is bladder wall.

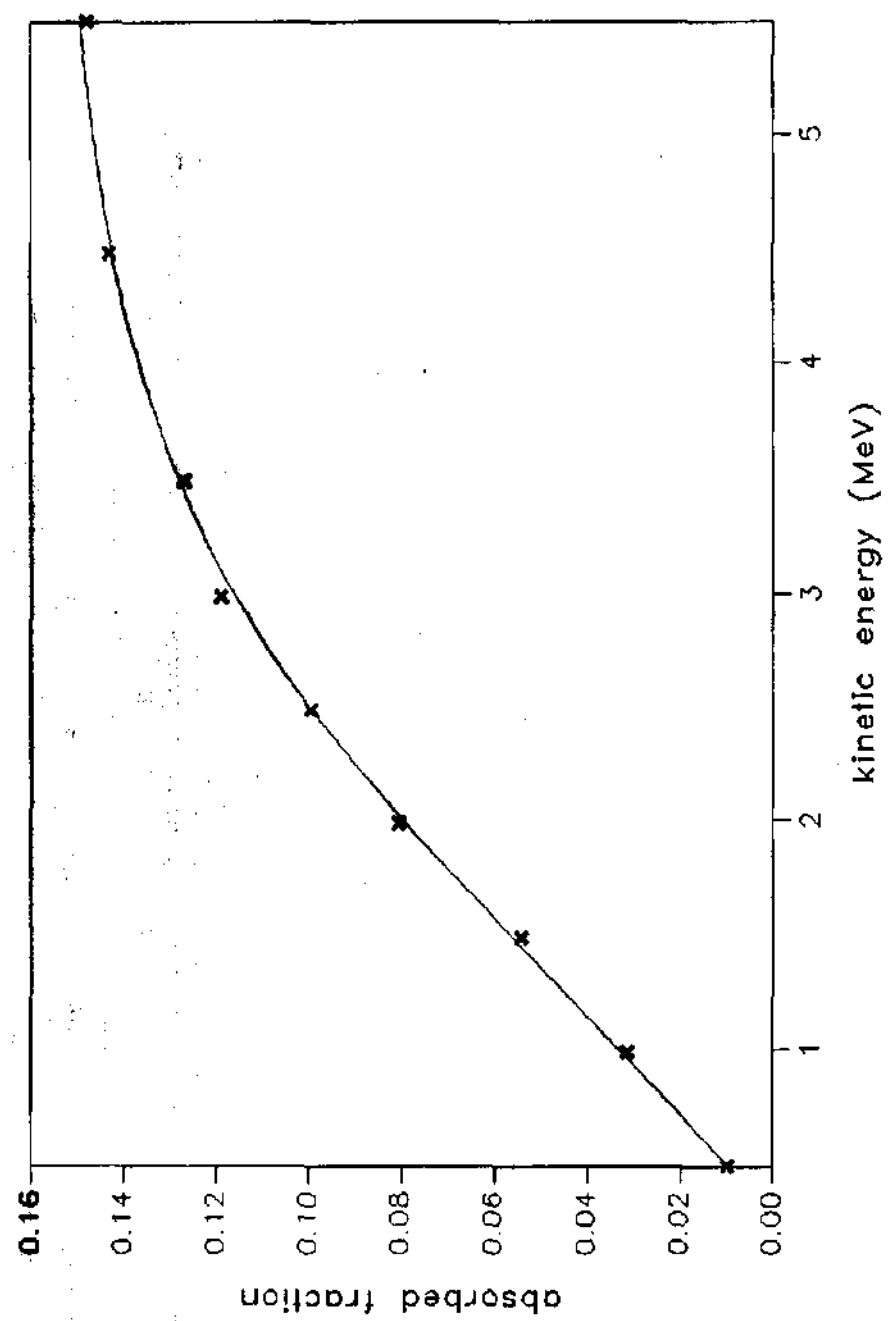


Figure 5.2. Absorbed fraction of electron energy for monoenergetic electron sources in stomach contents. Target organ is stomach wall.

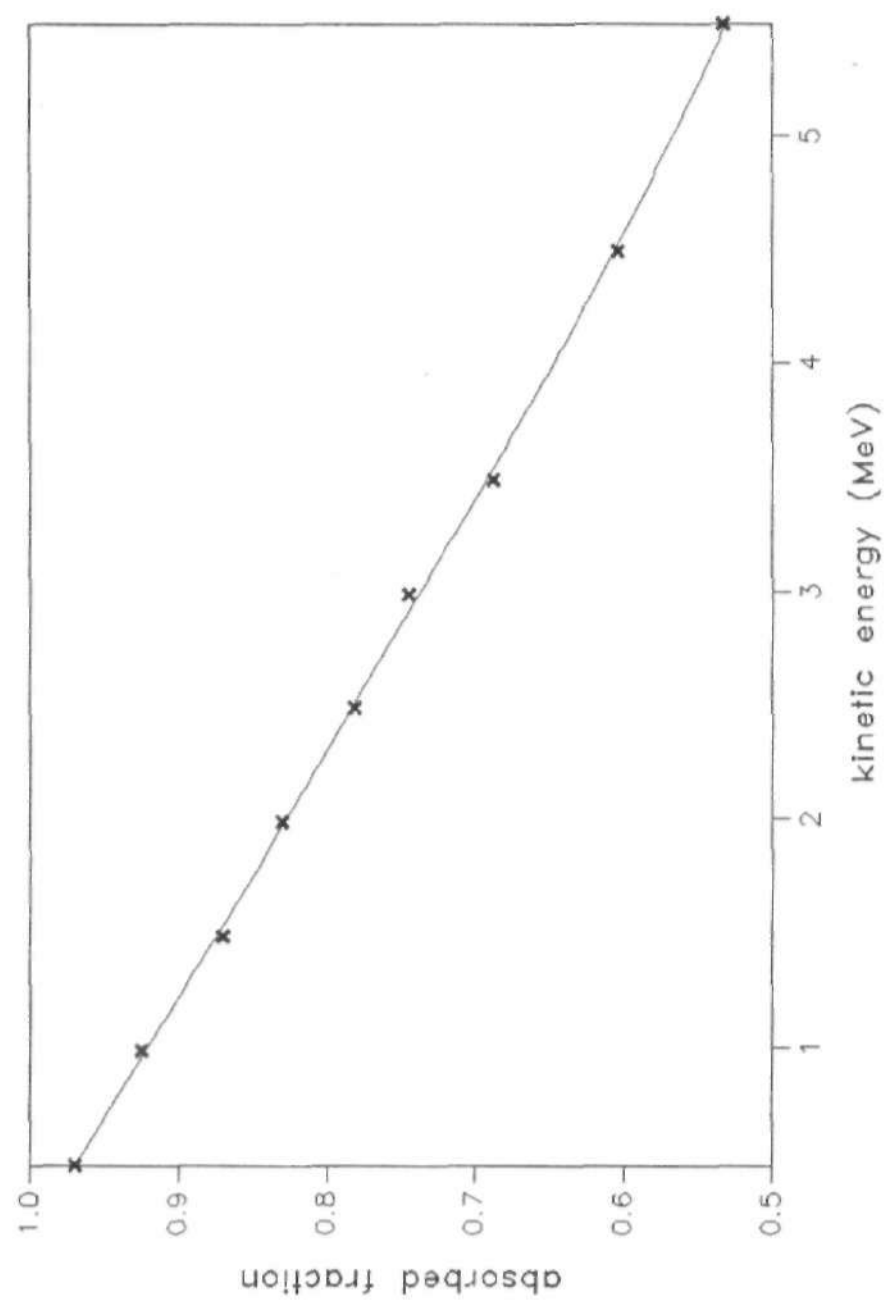


Figure 5.3. Absorbed fraction of electron energy for monoenergetic electron sources in lungs. Target organ is lungs.

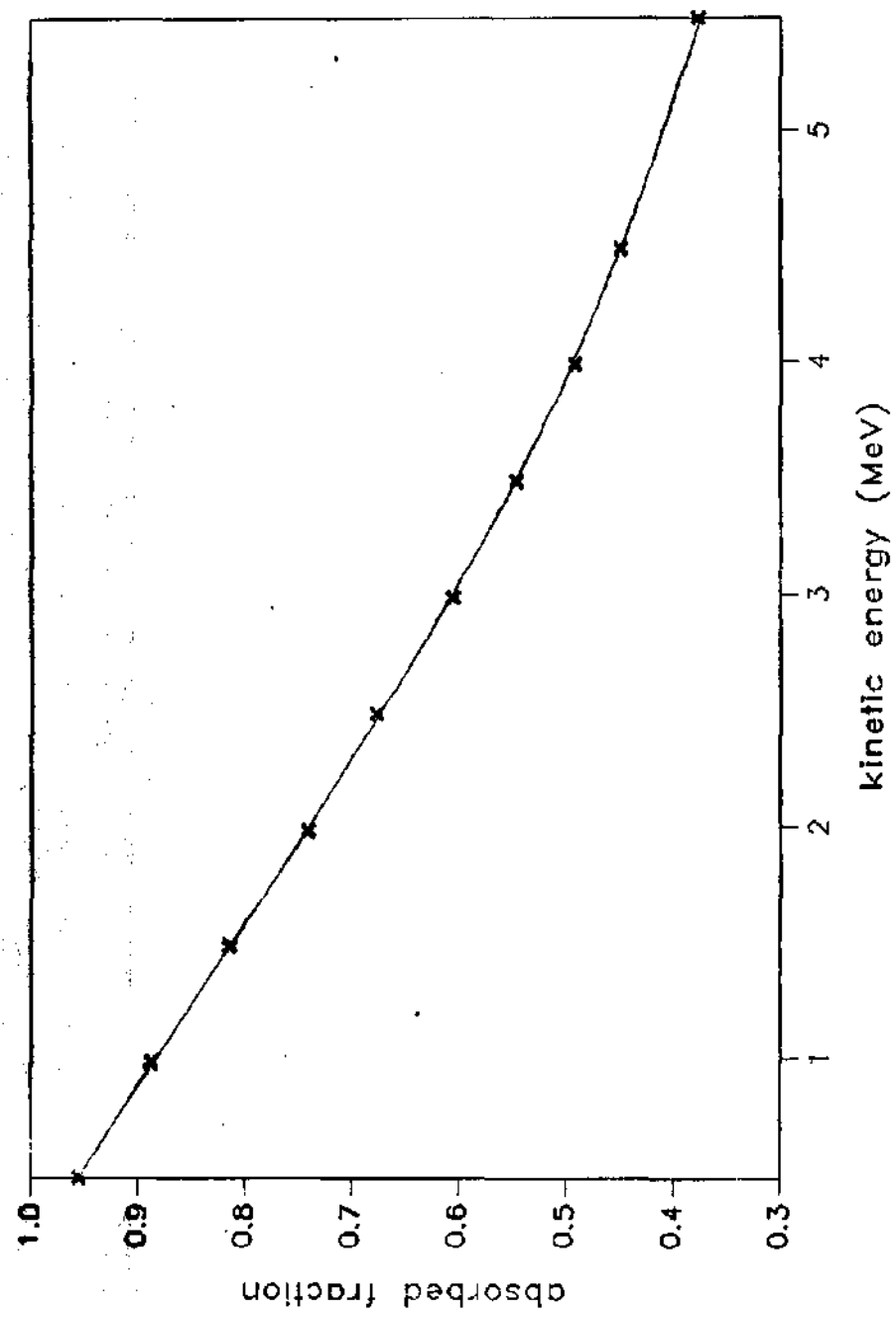


Figure 5.4. Absorbed fraction of electron energy for monoenergetic electron sources in thyroid. Target organ is thyroid.

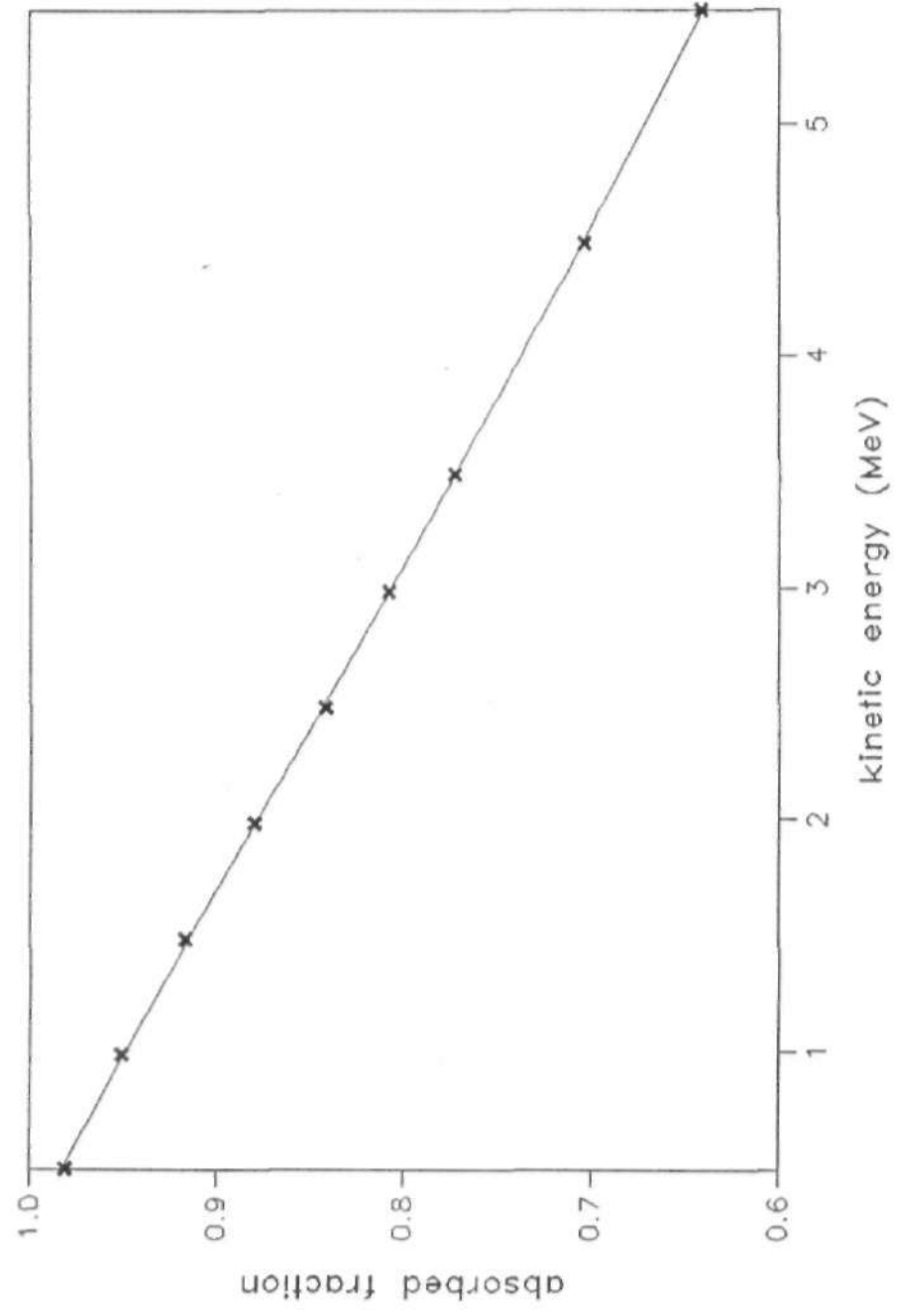


Figure 5.5. Absorbed fraction of electron energy for monoenergetic electron sources in kidneys. Target organ is kidneys.

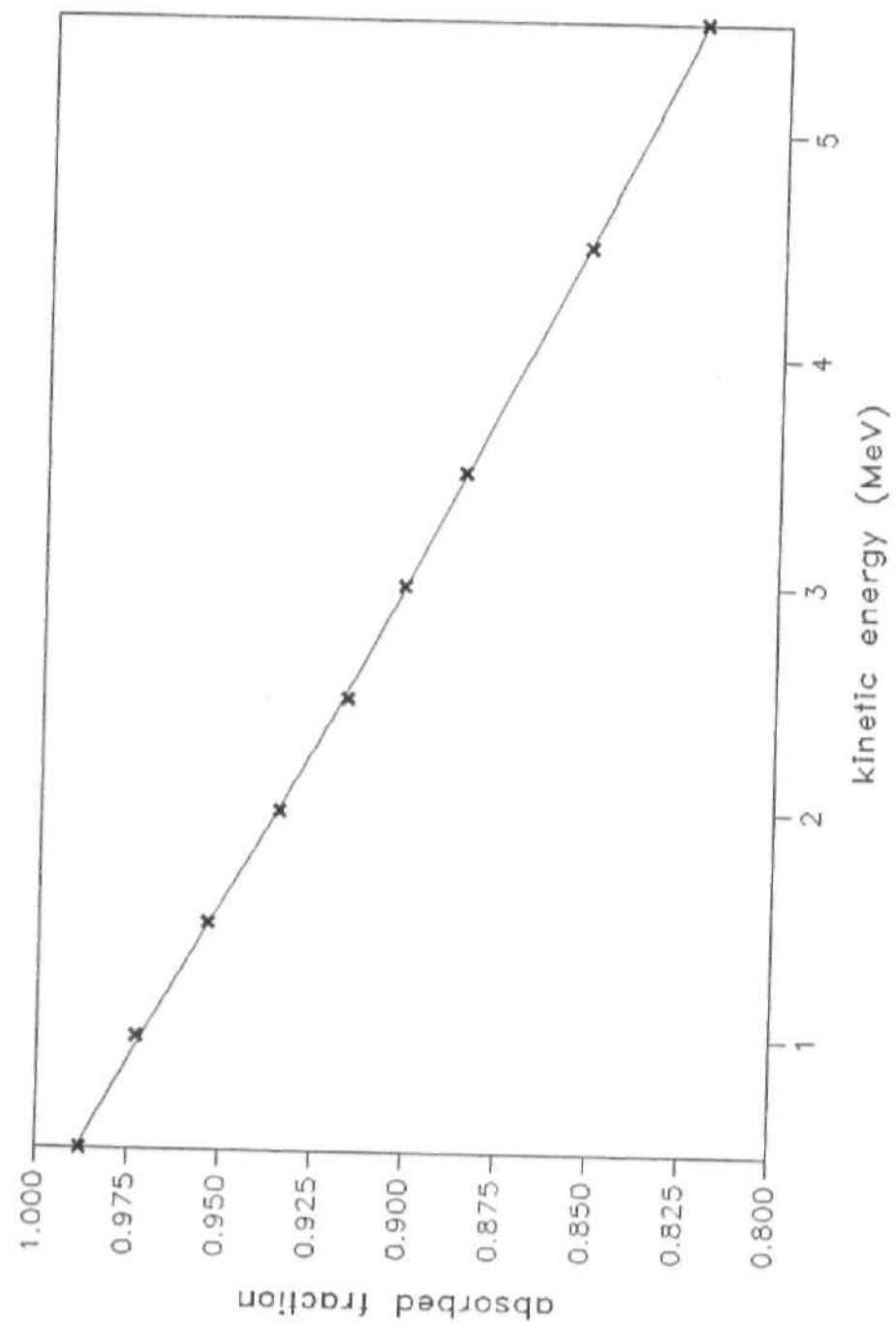


Figure 5.6. Absorbed fraction of electron energy for monoenergetic electron sources in liver. Target organ is liver.

fraction of energy with increasing electron energy. However, the absorbed fraction levels off to a constant value at high electron energies. The increase in absorbed fraction with increasing electron energy can be explained by noting that electron range increase with energy. Hence, as more electrons reach the nearby organs, energy deposition to these organs increases. When the electron range exceeds the distance to the outer wall of a nearby organ, the fraction of energy deposited in this organ approaches a constant. This can be explained by the fact that most electrons lose essentially no energy in escaping the contents, in addition, the wall is thin and only a fraction of the energy is deposited. Since betas (electrons) lose energy continuously the curve begins to flatten out.

Figures 5.3 through 5.6 present results for sources in lungs, thyroid, kidneys and liver. These results represent four cases of the class II situation. In this class of organs, the absorbed fraction decreases linearly with increasing electron energy. This result is to be expected since the "ability" of an electron to escape the source organ should increase as the electron energy increases. This conclusion can be justified by consideration of the electron range-energy curve. Note also that, for this class of organs, at any fixed electron energy the absorbed fraction increases as the volume of the organ increases. This result is reasonable because the number of electrons that escape the organ volume is proportional to the surface area of the organ. For example, the thyroid gland (Fig. 5.3) has a high surface to volume ratio whereas the surface to volume ratio of the liver (Fig. 5.6) is significantly

smaller. The lungs deviate from this general conclusion slightly because this organ is assumed to have a density of 0.2958 g/cm^3 rather than 0.9869 g/cm^3 for normal tissue.

Presently, absorbed fractions of energy for non-penetrating radiation are assumed to be unity when the source organ is also the target organ and zero otherwise. The results reported here obtained from the calculations of absorbed fractions of energy for monoenergetic electrons imply an over estimation of absorbed energy (dose) to the source organs and a gross underestimation to the nearby organs. For example, up to 50% error in the calculation of energy absorbed in the thyroid can be made for a source of 4 MeV electrons. When the source radionuclide are beta particles from phosphorus-32, an average beta particle energy of 0.57 MeV (i.e., 1/3 of maximum energy of 1.7 MeV) is assumed and an absorbed fraction for the thyroid of 0.95 is obtained from Figure 5.4 for the thyroid. Therefore, it is clear that the basic assumption regarding non-penetration radiation should be modified to include changes of absorbed fraction with particle energy.

5.3 Specific Absorbed Fractions For Photon Sources (INDOSE-EGS Code)

Estimates of specific absorbed fractions of energy were performed for 8 monoenergetic photon sources ranging from 0.02 to 4.0 MeV. In each calculation, 100,000 histories of uniformly distributed photons were traced for 10 source organs. Tables 5.7 through 5.16 present results of specific

absorbed fractions for the various source organs. The organs and regions considered were; bladder contents, stomach contents, heart chambers, liver, uterus, lungs, kidneys, testes, thyroid and ovaries. The coefficient of variation of the absorbed fractions for the target organs are also presented. In some instances, the coefficients of variation in the calculations are as large as the estimates. In such cases, the results are considered unreliable. No estimates of specific absorbed fractions are given when the coefficient of variation exceeds 50%. However, results of absorbed fractions are given but considered unreliable when the coefficient of variation lie between 20% and 50%. In such cases, other methods are used to estimate the specific absorbed fractions. Results from Monte Carlo methods are considered accurate when the coefficients of variation lie between 20 and 50% (Sn78).

Results of specific absorbed fractions calculated using the INDOSE-EGS code are of the same order of magnitude as those reported in the MIRD publications (Sn78). No significant differences are noticed between results using either code. However, when the lungs are the target organ, results obtained from INDOSE-EGS code, for source organs close to the lungs were found to be twice as large as results reported in the MIRD publications. The differences in results are more pronounced at low photon energies and are due to the modified lung model.

The INDOSE-EGS code can be used to calculate specific absorbed fractions for photon sources, either, when charged particle products of photon

Table 5.7 Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particle transported. Source in Bladder contents

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0	1.5	2.0	4.0
Bladder	1.43E-3*	3.11E-4	1.31E-4	1.70E-4	1.83E-4	1.76E-4	1.62E-4	1.30E-4
wall	1.2**	2.4	2.5	2.4	2.5	2.5	2.5	2.2
Stomach	---***	9.70E-7	1.09E-6	1.13E-6	9.53E-7	1.39E-6	1.33E-6	1.03E-6
wall	---	22.8	16.1	14.6	16.5	15.8	15.3	17.8
Kidneys	---	1.01E-6	1.18E-6	1.32E-6	1.43E-6	1.50E-6	1.38E-6	1.33E-6
	---	26.5	17.5	14.5	15.9	17.2	18.2	18.5
Liver	---	7.28E-7	7.62E-7	8.70E-7	9.54E-7	1.00E-6	9.93E-7	9.79E-7
	---	7.8	5.9	5.2	5.4	5.6	5.7	6.0
Lungs	---	1.73E-7	2.60E-7	4.30E-7	5.67E-7	7.94E-7	6.46E-7	7.71E-7
	---	29.5	19.7	13.6	13.1	12.2	12.7	12.2
Panc	---	8.16E-7	9.29E-7	8.28E-7	1.09E-6	1.61E-6	1.48E-6	6.43E-7
-reas	---	40.1	28.7	26.9	23.3	25.0	26.4	31.1
Spleen	---	5.65E-7	6.22E-7	9.88E-7	7.90E-7	8.54E-7	1.04E-6	8.33E-7
	---	28.5	19.9	15.6	18.3	18.2	17.3	20.8
Thyroid	---	---	---	---	---	---	---	---
Heart	---	---	1.40E-7	22.1E-7	2.41E-7	4.40E-7	2.43E-7	4.36E-7
wall	---	---	25.3	20.1	22.8	19.2	23.7	18.8
Heart	---	1.15E-7	2.18E-7	3.59E-7	2.80E-7	3.69E-7	4.07E-7	4.56E-7
chambers	---	39.8	20.2	15.5	18.2	17.4	17.1	16.7
Face	---	---	---	---	---	---	---	---
Total body	1.41E-5	7.91E-6	4.22E-6	4.72E-6	4.86E-6	4.69E-6	4.50E-6	3.81E-6

* Specific absorbed fraction of energy (per gm)

** Coefficient of variation (%)

*** Coefficient of variation greater than 50%

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Table 5.8. Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particles transported. Source in Stomach contents

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0	1.5	2.0	4.0
Bladder wall	*** --	*** --	7.20E-7* 29.1**	1.43E-6 20.6	3.84E-7 32.5	1.62E-6 25.8	1.91E-6 23.9	9.38E-7 29.3
Stomach wall	8.73E-4 0.8	2.24E-4 1.5	9.45E-5 1.6	1.26E-4 1.6	1.32E-4 1.7	1.22E-4 1.8	1.23E-4 1.8	9.58E-5 1.8
Kidneys	7.42E-7 21.7	1.31E-5 10.8	7.93E-6 8.5	8.36E-6 8.0	9.11E-6 9.2	7.48E-6 9.7	8.03E-6 10.0	6.81E-6 11.6
Liver	5.61E-7 9.9	7.63E-6 2.4	4.91E-6 2.3	5.40E-6 2.2	5.25E-6 2.4	5.19E-6 2.5	4.93E-6 2.7	4.29E-6 2.9
Lungs	1.60E-6 7.9	9.80E-6 6.1	3.92E-5 4.7	8.50E-6 4.1	9.57E-6 4.2	9.60E-6 4.6	9.26E-6 4.6	7.98E-6 4.9
Panc-reas	7.12E-5 4.8	7.59E-5 4.2	3.84E-5 4.2	3.90E-5 4.4	3.82E-5 4.8	3.90E-5 5.0	3.47E-5 5.3	3.43E-5 5.2
Spleen	1.18E-5 7.0	4.08E-5 3.3	1.97E-5 3.5	2.22E-5 3.4	2.31E-5 3.7	2.34E-5 3.9	2.04E-5 4.2	1.86E-5 4.4
Thymus	---	---	8.62E-7 45.4	2.29E-6 29.3	2.07E-6 33.1	2.57E-6 30.6	1.25E-6 38.6	1.28E-6 37.6
Thyroid	---	---	---	---	---	---	---	9.33E-7 49.0
Heart wall	8.71E-7 19.5	1.11E-5 4.9	5.79E-6 4.8	6.44E-6 4.7	6.40E-6 5.1	7.16E-6 5.1	6.12E-6 5.5	4.53E-5 5.0
Heart chambers	3.70E-7 25.0	8.34E-6 4.7	6.34E-6 4.0	5.84E-6 4.1	5.79E-6 4.5	6.16E-6 4.7	5.98E-6 4.8	5.52E-6 1.3
Face	---	1.92E-7 45.2	9.81E-8 23.6	2.79E-7 26.3	3.05E-7 25.6	2.24E-7 28.4	4.49E-7 23.8	3.17E-7 27.6
Total boby	1.41E-5	7.54E-6	3.94E-6	4.47E-6	4.65E-6	4.49E-6	4.30E-6	3.66E-6

* Specific absorbed fraction of energy (per gm)

** Coefficient of variation (%)

*** Coefficient of variation greater than 50%

Table 5.9. Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particles transported. Source in Heart chambers

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0	1.5	2.0	4.0
Bladder wall	--- ^{***}	---	---	---	---	---	5.62E-7 [*] 42.2 ^{**}	3.07E-7 35.8
Stomach wall	---	5.94E-6 9.5	3.79E-6 8.7	3.52E-6 8.1	4.05E-6 9.0	4.14E-6 9.0	3.83E-6 9.7	3.46E-6 10.3
Kidneys	---	2.77E-6 14.4	2.09E-6 12.9	2.37E-6 11.2	2.25E-6 12.4	2.02E-6 13.0	2.31E-6 13.4	2.28E-6 14.0
Liver	7.17E-7 8.8	7.98E-6 2.4	4.64E-6 2.4	4.79E-6 2.3	4.82E-6 2.5	4.77E-5 2.7	4.89E-6 2.7	4.23E-6 2.9
Lungs	4.11E-5 2.6	4.97E-5 1.7	2.83E-5 1.8	3.92E-5 1.6	4.31E-5 1.7	4.25E-5 1.8	4.11E-5 1.8	3.22E-5 2.1
Panc-reas	---	7.69E-6 12.9	5.56E-6 9.9	6.49E-6 10.3	6.53E-6 11.4	4.81E-6 13.7	5.09E-6 14.0	6.78E-6 12.0
Spleen	---	5.27E-6 9.4	3.09E-6 8.9	3.31E-6 8.5	3.32E-6 9.3	3.26E-6 9.7	3.92E-6 9.6	2.98E-6 11.2
Thymus	1.25E-5 17.9	3.39E-5 9.4	1.53E-5 9.1	1.88E-5 9.7	1.99E-5 10.4	1.63E-5 11.6	1.83E-5 11.4	1.55E-5 11.6
Thyroid	---	2.44E-6 40.8	2.65E-6 30.2	1.91E-6 26.8	2.28E-6 29.6	2.63E-6 33.9	1.77E-6 32.0	3.78E-7 38.3
Heart wall	4.08E-4 0.9	1.10E-4 1.5	5.11E-5 1.6	6.19E-5 1.6	6.47E-5 1.7	6.22E-5 1.8	5.85E-5 1.8	4.53E-5 1.9
Heart chambers	8.58E-4 0.4	1.99E-4 0.9	8.88E-5 1.0	1.17E-4 1.0	1.20E-4 1.1	1.14E-4 1.1	1.05E-4 1.2	8.48E-5 1.3
Face	---	1.70E-6 14.0	1.76E-6 10.49	2.03E-6 9.3	2.20E-6 10.0	2.43E-6 10.3	2.05E-6 10.8	1.65E-6 12.5
Total body	1.42E-5	7.90E-6	4.02E-6	4.54E-6	4.76E-6	4.63E-6	4.44E-6	3.76E-6

* Specific absorbed fraction of energy (per gm)

** Coefficient of variation (%)

*** Coefficient of variation greater than 50%

Table 5.10. Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particles transported. Source in Liver

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0	1.5	2.0	4.0
Bladder wall	*** -.-	6.85E-7* 48.5**	7.83E-7 34.0	1.49E-6 23.8	8.06E-7 27.9	1.17E-7 26.5	1.16E-6 28.2	8.98E-7 25.7
Stomach wall	6.02E-7 33.1	7.78E-6 8.2	4.92E-6 7.3	4.94E-6 7.2	4.84E-6 8.2	4.67E-6 8.5	5.36E-6 8.3	4.72E-6 8.1
Kidneys	5.17E-6 8.2	1.66E-5 12.0	8.98E-6 9.2	1.09E-5 4.4	1.04E-5 9.1	1.01E-5 9.05	9.68E-4 5.4	8.38E-6 10.1
Liver	4.28E-4 0.2	1.07E-4 0.6	4.75E-5 0.7	6.25E-5 0.6	6.40E-5 0.7	6.06E-5 0.7	5.65E-5 0.8	4.48E-5 0.9
Lungs	1.18E-5 10.0	1.73E-5 5.0	9.93E-6 4.7	1.41E-5 4.1	1.60E-5 4.4	1.61E-5 4.3	1.52E-5 4.8	1.12E-6 5.6
Panc-reas	4.31E-6 19.5	1.71E-5 8.8	8.96E-5 8.1	1.22E-5 7.7	1.02E-5 9.2	1.01E-5 9.8	1.05E-5 9.6	8.59E-6 10.7
Spleen	-.---	3.98E-6 10.8	3.42E-6 8.9	3.20E-6 8.7	2.92E-6 9.7	2.96E-6 10.2	3.04E-6 10.3	2.61E-6 11.5
Thymus	-.---	2.19E-6 35.3	1.21E-6 24.2	1.24E-6 29.8	8.53E-6 36.0	1.73E-6 32.9	-.---	1.26E-6 44.2
Heart wall	2.07E-6 12.7	9.86E-6 5.2	5.72E-6 4.9	6.37E-6 4.6	5.86E-6 5.4	6.66E-6 5.3	5.39E-6 5.7	4.58E-6 6.1
Heart chambers	8.31E-7 16.6	1.06E-5 4.2	6.36E-6 3.9	6.84E-6 3.8	7.31E-6 4.2	6.91E-6 4.4	6.49E-6 4.6	5.60E-6 5.1
Face	-.---	2.80E-7 36.1	2.21E-7 24.6	3.56E-7 22.6	3.62E-7 23.2	5.04E-7 21.2	5.55E-7 21.2	5.75E-7 21.8
Total body	1.41E-5	7.32E-6	3.73E-6	4.31E-6	4.47E-6	4.32E-6	4.12E-6	3.57E-6

* Specific absorbed fraction of energy (per gm)

** Coefficient of variation (%)

*** Coefficient of variation greater than 50%

Table 5.11. Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particles transported. Source in Uterus

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0	1.5	2.0	4.0
Bladder wall	6.92E-5 [*] 5.6	6.68E-5 5.1	3.28E-5 4.9	3.61E-5 5.1	3.97E-5 5.3	3.86E-5 5.4	3.89E-5 5.3	3.06E-5 4.8
Stomach wall	--- ^{***}	2.63E-6 14.1	2.85E-6 9.5	2.67E-6 9.7	2.67E-6 11.2	2.94E-6 11.1	2.09E-6 12.7	2.36E-6 11.8
Kidneys	---	2.96E-6 13.9	2.75E-6 10.4	2.47E-6 10.2	2.71E-6 11.3	2.43E-6 12.2	2.66E-6 12.5	2.43E-6 13.2
Liver	---	1.57E-6 5.3	1.59E-6 4.1	1.66E-6 3.7	1.82E-6 4.0	1.74E-6 4.3	1.73E-6 4.4	1.63E-6 4.7
Lungs	---	4.92E-7 22.2	6.43E-7 4.3	8.84E-7 9.5	1.12E-6 9.6	1.18E-6 9.8	1.29E-6 10.5	1.13E-6 10.2
Uterus	8.03E-3 0.3	9.77E-4 1.1	4.06E-4 1.2	6.02E-4 1.1	6.21E-4 1.2	5.71E-4 1.3	5.29E-4 1.4	3.56E-4 1.7
Ovaries	6.42E-5 20.4	8.67E-5 16.2	4.50E-5 15.5	4.64E-5 15.4	4.07E-5 19.1	5.20E-5 18.0	3.99E-5 20.5	3.20E-5 19.5
Testis	---	4.40E-6 30.0	4.19E-6 23.9	4.27E-6 23.2	4.15E-6 28.6	3.93E-6 28.9	3.66E-6 28.4	4.09E-6 25.7
Panc- reas	---	1.76E-6 26.8	1.63E-6 18.2	2.34E-6 16.7	2.22E-6 18.8	1.22E-6 23.8	1.78E-6 21.6	2.32E-6 20.6
Spleen	---	1.52E-6 17.3	1.08E-6 13.7	1.82E-6 11.4	1.58E-6 13.7	1.86E-6 13.3	1.54E-6 14.3	1.32E-6 16.4
Heart wall	---	3.10E-7 29.9	3.77E-7 19.0	4.24E-7 14.9	5.13E-7 17.2	5.93E-7 15.8	8.06E-7 14.8	7.61E-7 15.8
Heart chambers	---	5.94E-7 18.1	3.97E-7 15.6	7.08E-7 11.1	5.19E-7 13.6	7.20E-7 12.8	7.23E-7 13.0	7.44E-7 13.3
Total body	1.42E-5	8.69E-6	4.66E-6	5.06E-6	5.17E-6	5.03E-6	4.78E-6	4.09E-6

* Specific absorbed fraction of energy (per gm)

** Coefficient of variation (%)

*** Coefficient of variation greater than 50%

Table 5.12. Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particles transported. Source in Lungs

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0	1.5	2.0	4.0
Bladder wall	--- ^{***}	---	1.66E-7 [*] 41.4 ^{**}	---	---	1.96E-7 47.7	3.69E-7 40.4	8.02E-7 36.3
Stomach wall	3.92E-6 13.0	6.08E-6 8.9	3.49E-6 9.0	3.38E-6 8.9	3.10E-6 10.4	3.14E-6 11.0	2.77E-6 11.6	1.89E-6 12.7
Kidneys	---	4.07E-6 12.0	2.68E-6 11.0	3.03E-6 10.6	3.08E-6 12.0	2.80E-6 12.6	2.28E-6 14.2	2.01E-6 15.8
Liver	1.07E-5 2.2	1.00E-5 2.2	4.63E-6 2.4	4.55E-6 2.5	4.58E-6 2.7	3.93E-6 3.0	3.60E-6 3.2	2.61E-6 3.8
Lungs	4.96E-4 0.6	6.69E-5 1.6	2.92E-5 1.7	3.92E-5 1.6	3.88E-5 1.8	3.50E-5 2.0	3.18E-5 2.1	2.20E-5 2.5
Panc- reas	---	8.23E-6 12.4	4.43E-6 11.5	4.22E-6 13.1	4.09E-6 14.8	4.28E-6 15.1	5.24E-6 14.0	2.98E-6 18.3
Spleen	6.15E-6 9.6	8.96E-6 7.3	4.39E-6 7.7	4.23E-6 7.8	4.56E-6 8.6	3.23E-6 10.3	3.61E-6 10.1	2.18E-6 13.2
Thymus	6.81E-6 24.2	2.02E-5 12.6	7.39E-6 13.6	6.94E-6 15.4	6.27E-6 18.0	6.61E-6 18.7	6.65E-6 18.9	3.92E-6 23.1
Thyroid	---	2.08E-6 40.5	2.17E-6 23.8	3.26E-6 24.9	2.40E-6 33.1	2.43E-6 33.1	3.79E-6 27.5	2.97E-6 32.5
Heart wall	4.15E-5 2.8	2.12E-5 3.5	1.01E-5 3.7	9.20E-6 4.0	8.57E-6 4.6	7.61E-6 5.0	6.85E-6 5.2	5.28E-6 5.6
Heart chambers	4.39E-5 2.3	2.79E-5 2.6	1.23E-5 2.8	1.18E-5 3.0	1.13E-5 3.4	9.86E-6 3.8	9.11E-6 4.0	7.47E-6 4.4
Face	---	2.29E-6 12.2	1.56E-6 10.3	2.00E-6 9.7	2.14E-6 10.5	1.87E-6 11.7	2.25E-6 11.0	1.54E-6 12.5
Total body	1.40E-5	5.92E-6	2.64E-6	2.67E-6	2.59E-6	2.41E-6	2.20E-6	1.71E-6

* Specific absorbed fraction of energy (per gm)

** Coefficient of variation (%)

*** Coefficient of variation greater than 50%

Table 5.13. Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particle transported.
Source in Kidneys

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0	1.5	2.0	4.0
Bladder wall	*** 37.2	1.23E-6 37.2	1.16E-6 25.3	1.56E-6 22.2	1.68E-6 25.4	1.49E-6 25.7	9.49E-7 27.2	1.42E-6 24.9
Stomach wall	6.68E-7 31.2	1.38E-5 6.2	8.25E-6 5.6	8.49E-6 5.5	8.82E-6 6.3	9.02E-6 6.3	9.08E-6 6.4	7.29E-6 6.6
Kidneys	2.00E-3 0.5	2.85E-4 1.4	1.21E-4 1.5	1.77E-4 1.4	1.78E-4 1.5	1.69E-4 1.6	1.54E-4 1.7	1.12E-4 2.0
Liver	5.28E-6 3.2	1.54E-5 1.7	8.92E-6 1.7	9.79E-6 1.6	9.88E-6 1.8	9.70E-6 1.9	9.39E-6 2.0	8.17E-6 2.1
Lungs	1.39E-7 37.8	5.03E-6 6.0	4.27E-6 4.5	5.82E-6 3.9	6.74E-6 4.0	7.24E-6 4.1	6.61E-5 4.5	6.25E-6 4.6
Panc-reas	3.94E-6 20.4	2.34E-5 7.0	1.39E-5 6.9	1.68E-5 6.5	1.63E-5 7.5	1.52E-5 7.8	1.33E-5 8.4	1.15E-5 8.6
Spleen	3.42E-5 4.1	3.67E-5 3.6	1.72E-5 3.8	2.22E-5 3.5	2.24E-5 3.9	2.10E-5 4.1	2.17E-5 4.1	1.70E-5 4.8
Thymus	*** 42.2	1.72E-6 42.2	5.32E-7 35.3	7.16E-7 35.3	1.21E-6 41.7	9.72E-7 44.4	1.35E-6 33.7	1.27E-6 39.4
Heart wall	1.98E-7 40.8	4.91E-6 7.3	3.20E-6 6.1	3.55E-6 6.1	3.89E-6 6.5	3.63E-6 7.0	3.87E-6 6.9	3.44E-6 7.0
Heart chambers	1.40E-7 40.5	5.56E-6 5.8	3.96E-6 5.0	4.53E-6 4.7	4.25E-6 5.3	4.00E-6 5.7	4.42E-6 5.6	4.38E-6 5.7
Face	*** 40.4	*** 40.4	1.62E-7 40.4	2.23E-7 26.3	3.13E-7 25.2	2.93E-7 27.5	3.69E-7 24.7	4.32E-7 22.8
Total body	1.39E-5	7.24E-6	3.83E-6	4.33E-6	4.48E-6	4.37E-6	4.17E-6	3.54E-6

* Specific absorbed fraction of energy (per gm)

** Coefficient of variation (%)

*** Coefficient of variation greater than 50%

Table 5.14. Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particles transported.
Source in Testes

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0	1.5	2.0	4.0
Bladder wall	1.55E-6 [*] 37.8 ^{**}	2.00E-5 9.2	1.20E-5 8.6	1.28E-5 8.4	1.31E-5 9.1	1.35E-5 8.9	1.29E-5 8.5	1.16E-5 8.2
Stomach wall	-- ^{***}	--	2.61E-7 31.1	4.44E-7 24.9	4.89E-7 26.9	5.33E-7 25.0	7.21E-7 23.0	3.71E-7 29.0
Kidneys	--	--	2.06E-7 35.9	3.17E-7 29.2	5.07E-7 25.8	5.90E-7 27.5	5.45E-7 29.1	2.92E-7 38.6
Liver	--	1.35E-7 18.0	1.78E-7 11.6	3.05E-7 8.8	3.42E-7 9.0	3.75E-7 9.1	3.45E-7 9.5	4.73E-7 8.7
Lungs	--	--	6.45E-8 43.3	1.87E-7 19.5	2.96E-7 18.5	2.73E-7 22.0	3.46E-7 19.2	3.56E-7 19.0
Uterus	--	4.40E-6 16.2	4.45E-6 11.8	3.80E-6 12.1	5.38E-6 12.2	4.12E-6 13.7	4.54E-6 13.7	2.63E-6 18.1
Testis	1.23E-2 0.6	1.31E-3 1.8	5.79E-4 1.9	8.60E-4 1.7	8.68E-4 1.9	7.95E-4 2.1	7.08E-4 2.2	4.83E-4 2.6
Panc-reas	--	--	--	4.51E-7 40.6	--	--	8.16E-7 39.4	6.15E-7 40.1
Spleen	--	--	1.45E-7 41.1	1.77E-7 33.8	3.17E-7 28.2	2.87E-7 28.5	4.82E-7 26.6	3.44E-7 30.9
Heart wall	--	--	8.44E-8 42.4	8.14E-8 38.5	5.30E-8 40.6	1.58E-7 29.0	9.95E-8 35.4	1.39E-7 31.5
Heart chambers	--	--	8.08E-8 34.8	9.36E-8 30.6	1.27E-7 26.8	1.34E-7 32.1	2.45E-7 23.4	1.91E-7 25.5
Total body	1.22E-5	5.23E-6	2.85E-6	3.48E-6	3.65E-6	3.56E-6	3.41E-6	2.91E-6

^{*} Specific absorbed fraction of energy (per gm)

^{**} Coefficient of variation (%)

^{***} Coefficient of variation greater than 50%

Table 5.15. Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particles transported. Source in Thyroid

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0 ^a	1.5	2.0	4.0
Stomach wall	---	---	5.23E-7 26.7 ^{**}	3.54E-7 24.9	3.19E-7 20.6	4.27E-7 27.8	5.67E-7 23.8	4.87E-7 28.2
Kidneys	---	---	1.54E-7 50.0	2.72E-7 35.7	2.81E-7 23.6	3.90E-7 32.1	2.29E-7 38.7	4.11E-7 33.1
Liver	---	3.63E-7 11.4	3.33E-7 8.6	4.31E-7 7.3	5.32E-7 5.1	5.03E-7 7.8	5.39E-7 8.0	5.25E-7 8.2
Lungs	---	5.94E-6 5.3	4.34E-6 4.3	5.91E-6 3.8	7.16E-6 2.8	7.21E-6 4.1	7.28E-6 4.1	6.01E-6 4.8
Panc reas	---	---	3.08E-7 45.6	5.83E-7 33.0	3.29E-7 33.0	1.00E-7 38.9	5.74E-7 40.3	4.67E-7 40.2
Spleen	---	4.05E-7 33.3	3.22E-7 25.3	3.69E-7 21.9	4.00E-7 17.2	4.55E-7 24.7	5.93E-7 23.1	6.21E-7 25.3
Thymus	---	1.83E-5 13.2	8.51E-6 13.3	1.15E-5 12.1	1.09E-5 10.4	9.19E-6 15.0	1.21E-5 14.4	1.01E-5 15.4
Thyroid	1.79E-2 0.4	1.86E-3 1.5	7.62E-4 1.6	1.16E-3 1.4	1.17E-3 1.1	1.05E-3 1.7	9.11E-4 1.8	5.57E-4 2.2
Heart wall	---	2.14E-6 11.0	1.46E-6 8.8	1.64E-6 8.8	1.96E-6 6.3	1.87E-6 9.6	1.69E-6 9.8	1.79E-6 9.2
Heart chambers	---	3.58E-6 7.2	2.50E-6 6.2	2.84E-6 5.8	2.93E-6 5.2	3.31E-6 6.4	2.94E-6 6.8	2.98E-6 6.9
Face	1.36E-3 0.5	2.77E-4 1.1	1.19E-4 1.2	1.71E-4 1.1	1.79E-4 0.8	1.69E-4 1.2	1.62E-4 1.3	1.28E-4 1.4
Total body	1.34E-5	5.47E-6	2.69E-6	3.25E-6	3.43E-6	3.30E-6	3.15E-6	2.65E-6

^a200,000 photon histories

* Specific absorbed fraction of energy (per gm)

** Coefficient of variation (%)

*** Coefficient of variation greater than 50%

Table 5.16 Specific absorbed fraction of photon energy and coefficient of variation (%). Charged particles transported. Source in Ovaries

Target organs	Photon energy (MeV)							
	0.02	0.05	0.1	0.5	1.0	1.5	2.0	4.0
Bladder wall	4.49E-6 [*] 22.1 ^{**}	2.97E-5 7.6	1.55E-5 7.5	1.59E-5 7.4	1.62E-5 8.0	1.74E-5 7.9	1.37E-5 8.8	1.27E-5 9.4
Stomach wall	-- ^{***}	3.42E-6 12.3	2.73E-6 10.2	2.16E-6 10.2	2.30E-6 11.4	2.27E-6 12.6	2.35E-6 12.0	2.53E-6 12.5
Kidneys	--	3.67E-6 12.4	2.97E-6 10.1	3.16E-6 9.5	3.35E-6 10.3	3.23E-6 11.5	3.60E-6 11.1	3.03E-6 12.1
Liver	--	2.04E-6 4.7	1.64E-6 3.9	1.85E-6 3.6	1.88E-6 3.9	1.97E-6 4.0	1.88E-6 4.2	1.49E-6 4.4
Lungs	--	4.19E-7 23.2	4.47E-7 11.4	9.90E-7 9.4	1.11E-6 9.7	1.23E-6 9.3	1.50E-6 9.3	1.63E-6 9.4
Uterus	5.37E-5 5.3	8.84E-5 3.7	4.11E-5 3.9	4.35E-5 4.0	4.45E-5 4.4	4.23E-5 4.6	4.22E-5 4.8	3.71E-5 4.9
Ovaries	3.19E-2 0.8	2.74E-3 2.7	1.16E-3 2.7	1.75E-3 2.6	1.79E-3 2.8	1.53E-3 3.1	1.26E-3 3.3	9.77E-4 3.5
Testis	--	2.87E-6 40.1	2.84E-6 26.0	3.68E-6 25.8	3.12E-6 31.2	2.16E-6 33.9	3.51E-6 34.1	3.73E-6 35.3
Panc-reas	--	1.27E-6 31.7	1.94E-6 18.3	1.73E-6 18.6	2.21E-6 18.0	1.93E-6 20.1	1.56E-6 22.4	3.20E-6 24.5
Spleen	--	1.45E-6 17.6	1.54E-6 12.0	2.18E-6 10.2	2.16E-6 11.8	1.88E-6 12.9	1.69E-6 15.0	1.08E-6 16.9
Heart wall	--	2.80E-7 29.0	4.76E-7 17.3	6.16E-7 13.4	7.35E-7 15.2	5.73E-7 16.5	7.84E-7 14.5	8.26E-7 12.4
Heart chambers	--	3.05E-7 24.2	4.00E-7 15.1	5.82E-7 11.6	6.00E-7 13.3	8.75E-7 11.9	7.59E-7 12.9	7.31E-7 12.4
Total body	1.43E-5	8.74E-6	4.68E-6	5.00E-6	5.15E-6	4.94E-6	4.72E-6	4.19E-6

* Specific absorbed fraction of energy (per gm)

** Coefficient of variation (%)

*** Coefficient of variation greater than 50%

interactions are considered as locally deposited, or transported as incident particles. Results obtained from the first group of calculations can be compared with results in MIRD publications. This comparison would provide a means of assessing the applicability of the INDOSE-EGS code to internal dosimetry calculations. To determine the contribution consideration of electron/beta transport makes to internal dosimetry estimates, results obtained from the second group of calculations are compared with results from the first group. The results of the comparisons are presented below.

5.3.1 Comparison Of INDOSE-EGS And MIRD Results

The Electron-Gamma Simulation (EGS) code was originally developed for use in problems related to high energy physics. The code was extensively tested and benchmarked (Ro84). With the fourth version of the EGS (i.e., EGS4) the applicability of the code was extended to the low energy regions. To realize the objective of this research, the EGS was modified to allow its applications in internal dosimetry calculations. It is therefore desirable to evaluate the accuracy of the modified code.

Evaluation of the INDOSE-EGS was accomplished by comparing specific absorbed fractions of photon energy obtained in this research with published results (Sn78). Since results in MIRD publications considers only photon transport (i.e., local deposition of all secondary electron energies), calculations performed with INDOSE are made with electron transport cutoff energy, (ECUT), high enough to cause all secondary electrons produced from photon interactions to be deposited locally. Figures 5.7 and 5.8 present

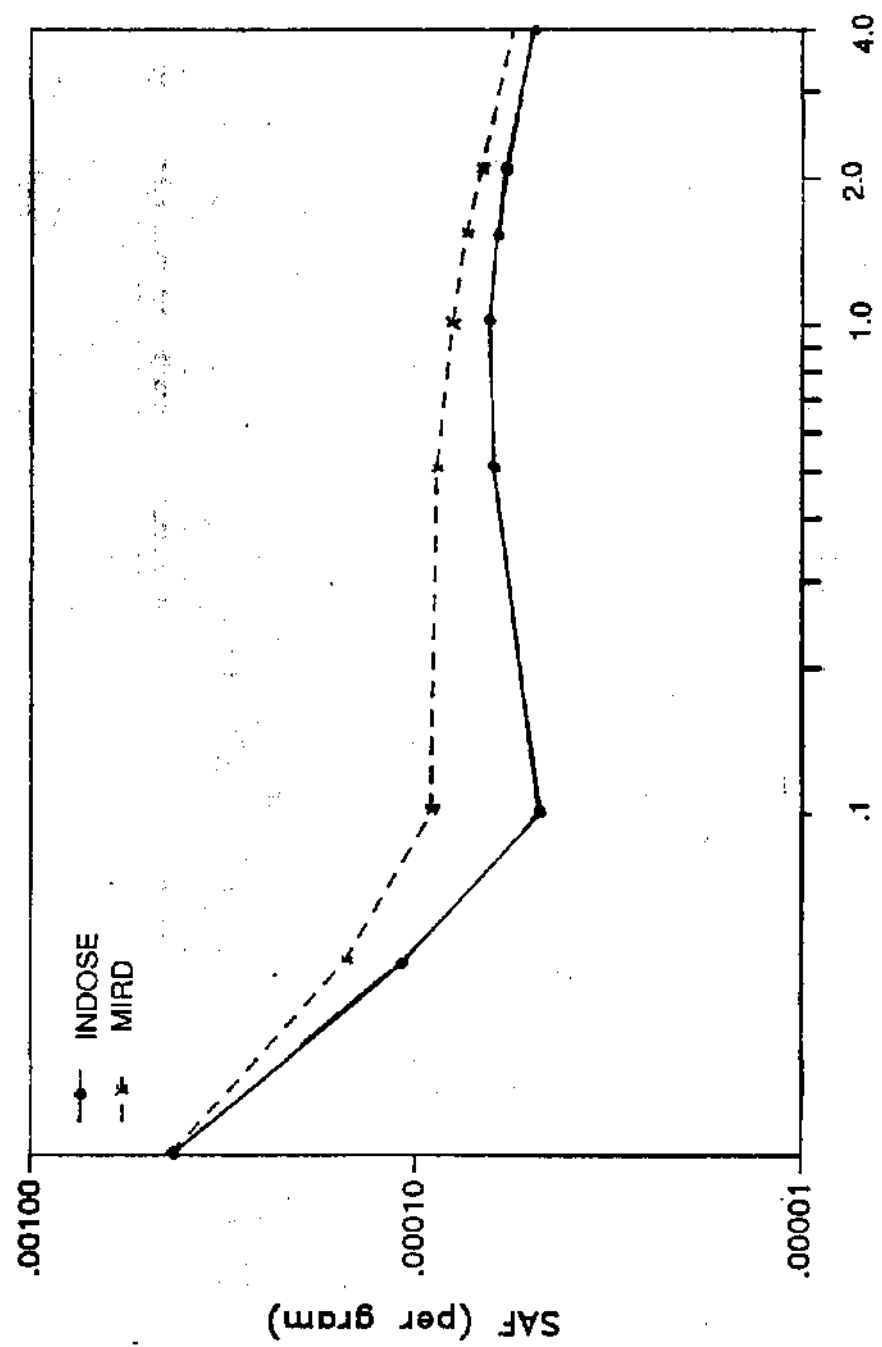


Figure 5.7. Comparison of INDOSE and MIRD data for monoenergetic photon sources. Target and source organs are the liver. Secondary electron transport was not considered.

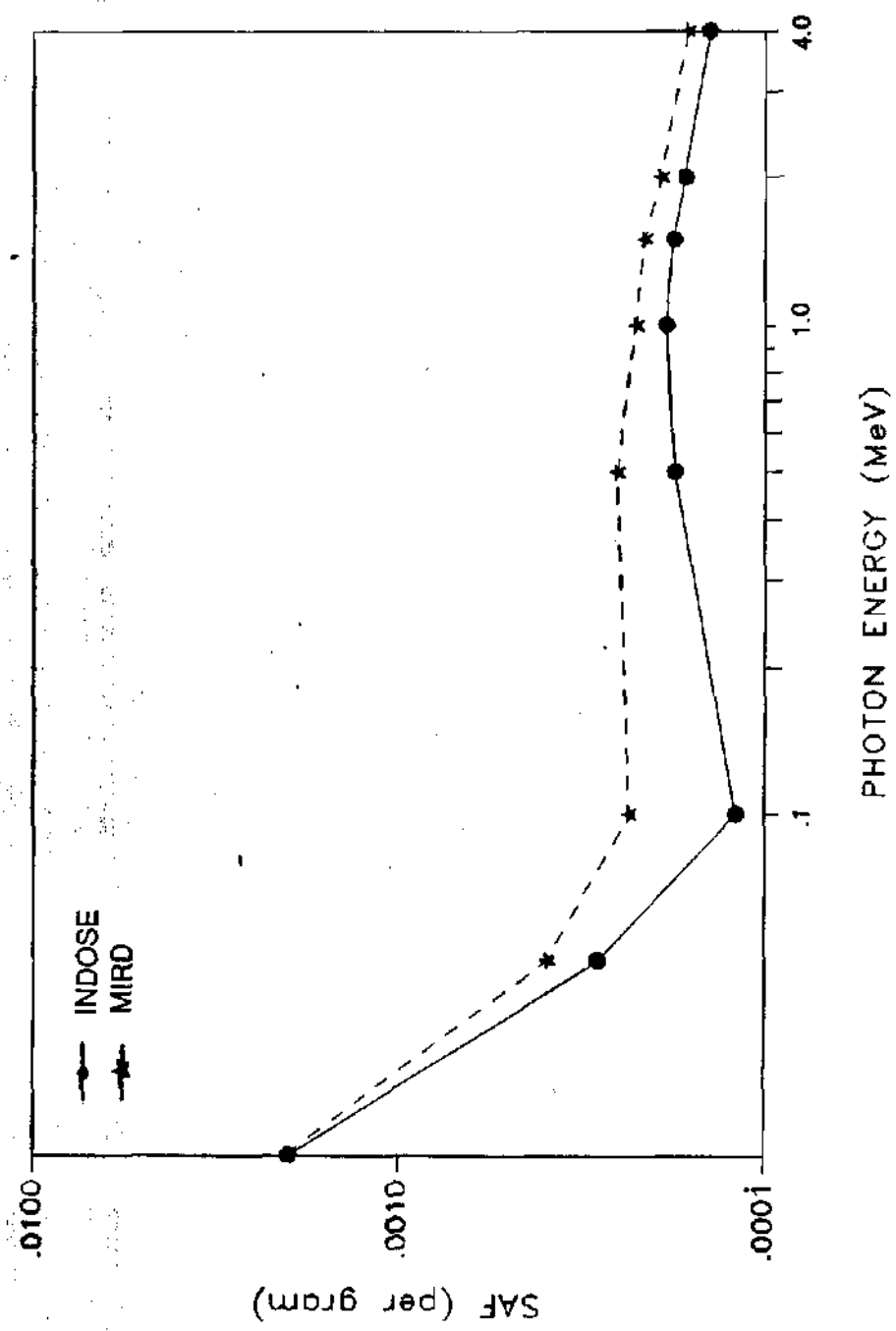


Figure 5.8. Comparison of INDOSE and MIRD data for monoenergetic photon sources. Target and source organs are the kidneys. Secondary electron transport was not considered.

comparisons of the two computer codes for the liver and kidneys as source and target organs. It should be noted that, although the absolute values are slightly different, the shapes are very similar. This shape follows closely that of the mass absorption coefficient of tissue over the same energy region. (see Figure 2.1).

The results for specific absorbed fractions obtained from INDOSE-EGS agree well with MIRD results. These results provide some confidence in the accuracy and applicability of the INDOSE-EGS code for internal dose estimation.

5.3.2 Comparison Of INDOSE Code Results With And Without Electron Transport

The question this research attempts to answer concerns the contributions a detailed consideration of beta/electron transport makes to internal dosimetry calculations. To answer this question, the INDOSE-EGS code was developed. To answered the question more specifically results obtained from this code when charged particles are considered can be compared with results when these radiations were not considered. This is accomplished by selecting the value of ECUT, which induces or cuts off electron transport in the INDOSE-EGS code.

Figures 5.9 and 5.10 provide comparisons of calculations from the INDOSE with and without electron transport for the thyroid and kidneys as source and target organs. These examples represent typical cases when source organs are also the target organs. As can be seen from these figures,

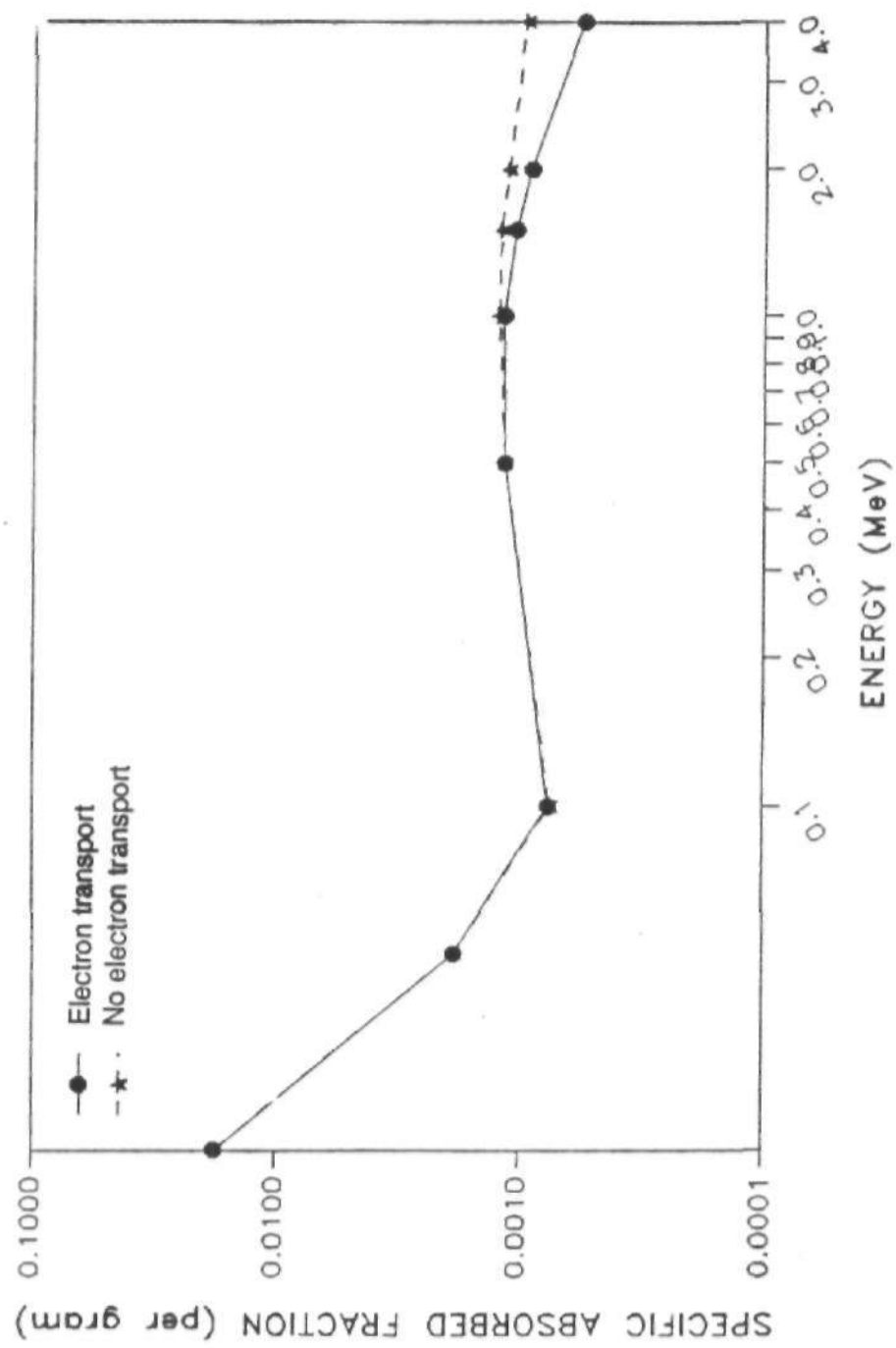


Figure 5.9a. Specific absorbed fractions, with and without transport of secondary electrons, for monoenergetic photon sources in the thyroid. Target organ is thyroid. Coefficients of variation for these data, along with the numerical values of SAF, are given in Table 5.15. See Figure 5.9b.

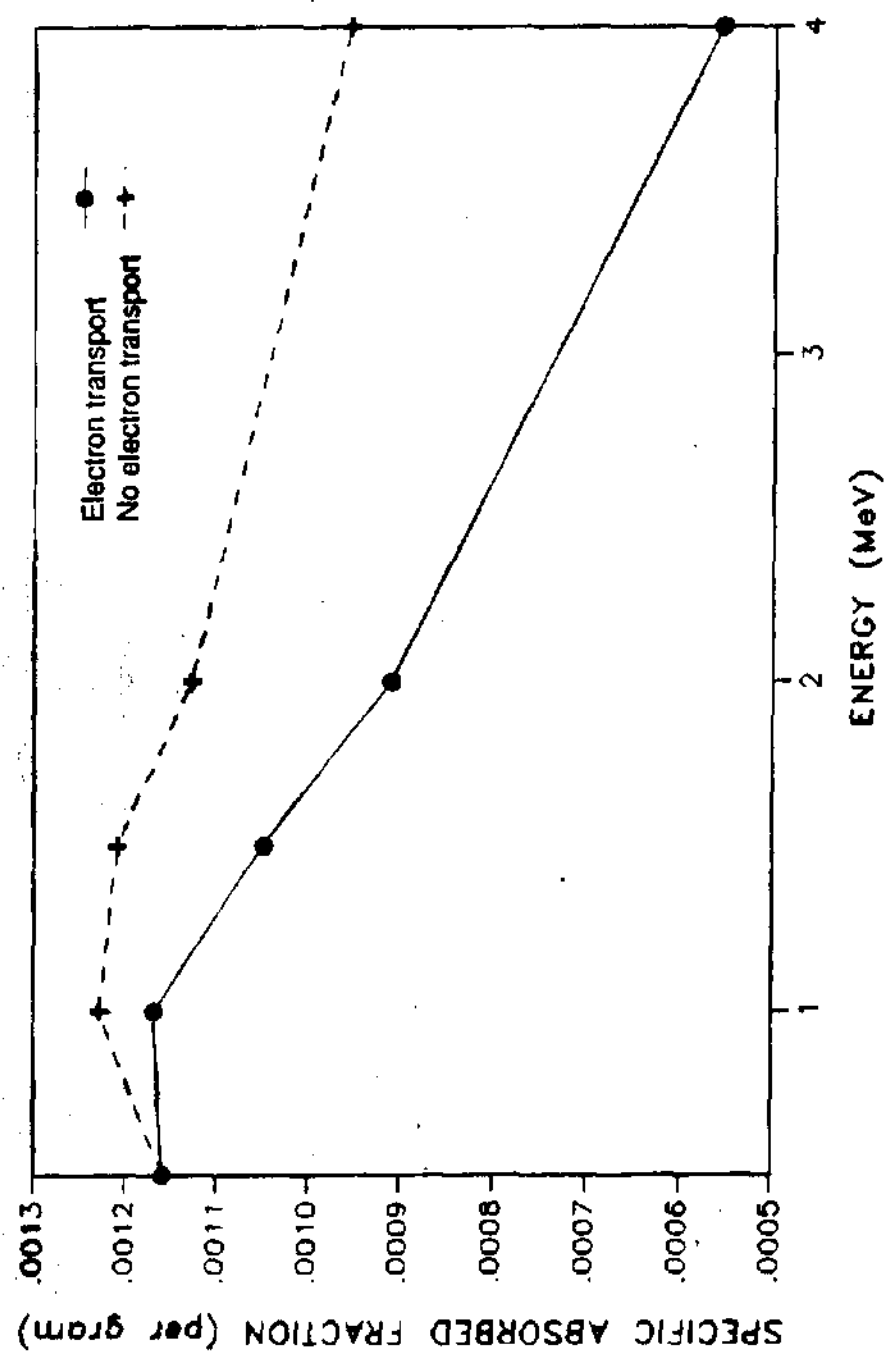


Figure 5.9b. Expansion of Figure 5.9a. for photon energies greater than 0.5 MeV.

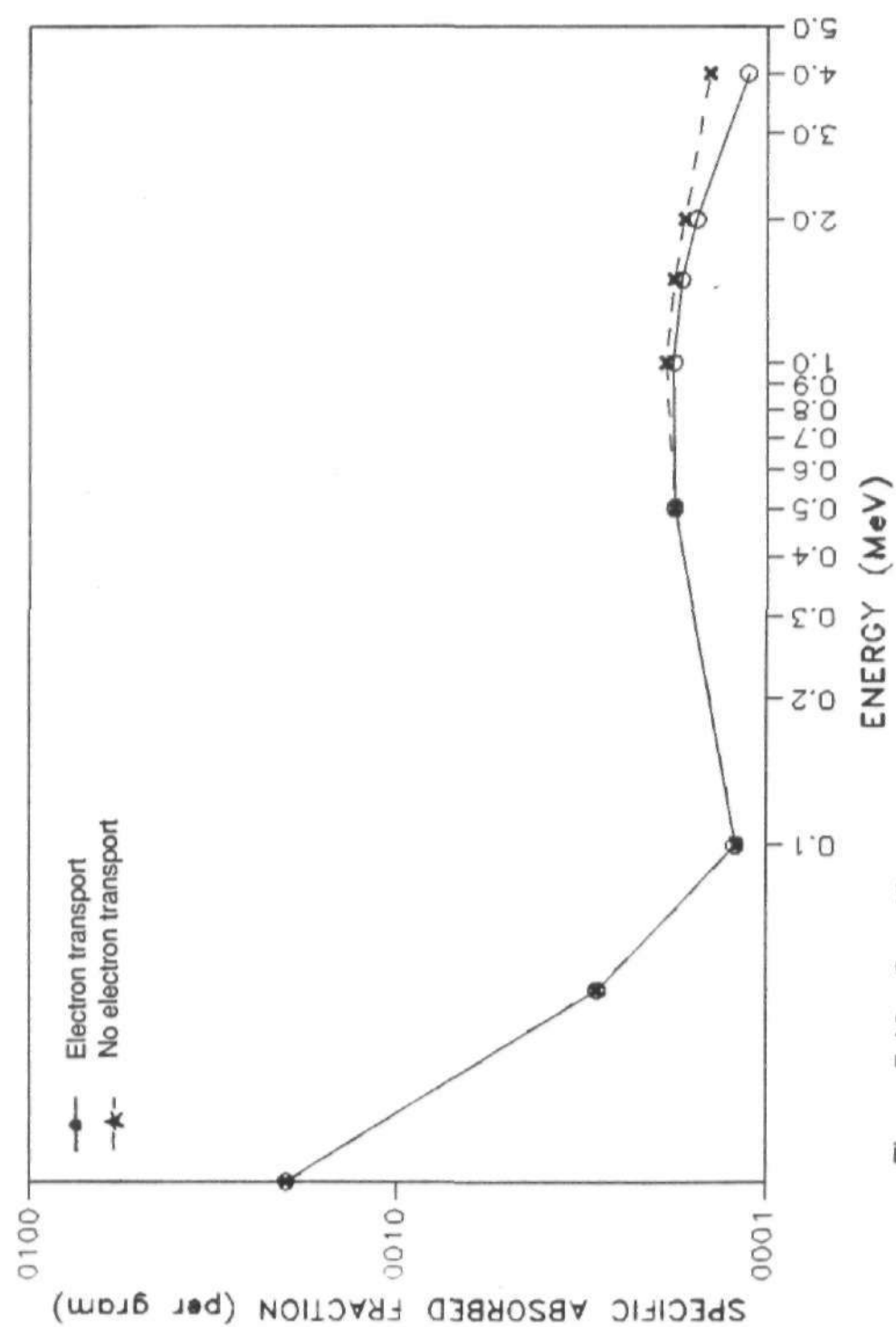


Figure 5.10a. Specific absorbed fractions, with and without transport of secondary electrons, for monoenergetic photon sources in the kidneys. Target organ are the kidneys. Coefficients of variation for these data, along with the numerical values of SAF, are given in Table 5.13. See Figure 5.10b.

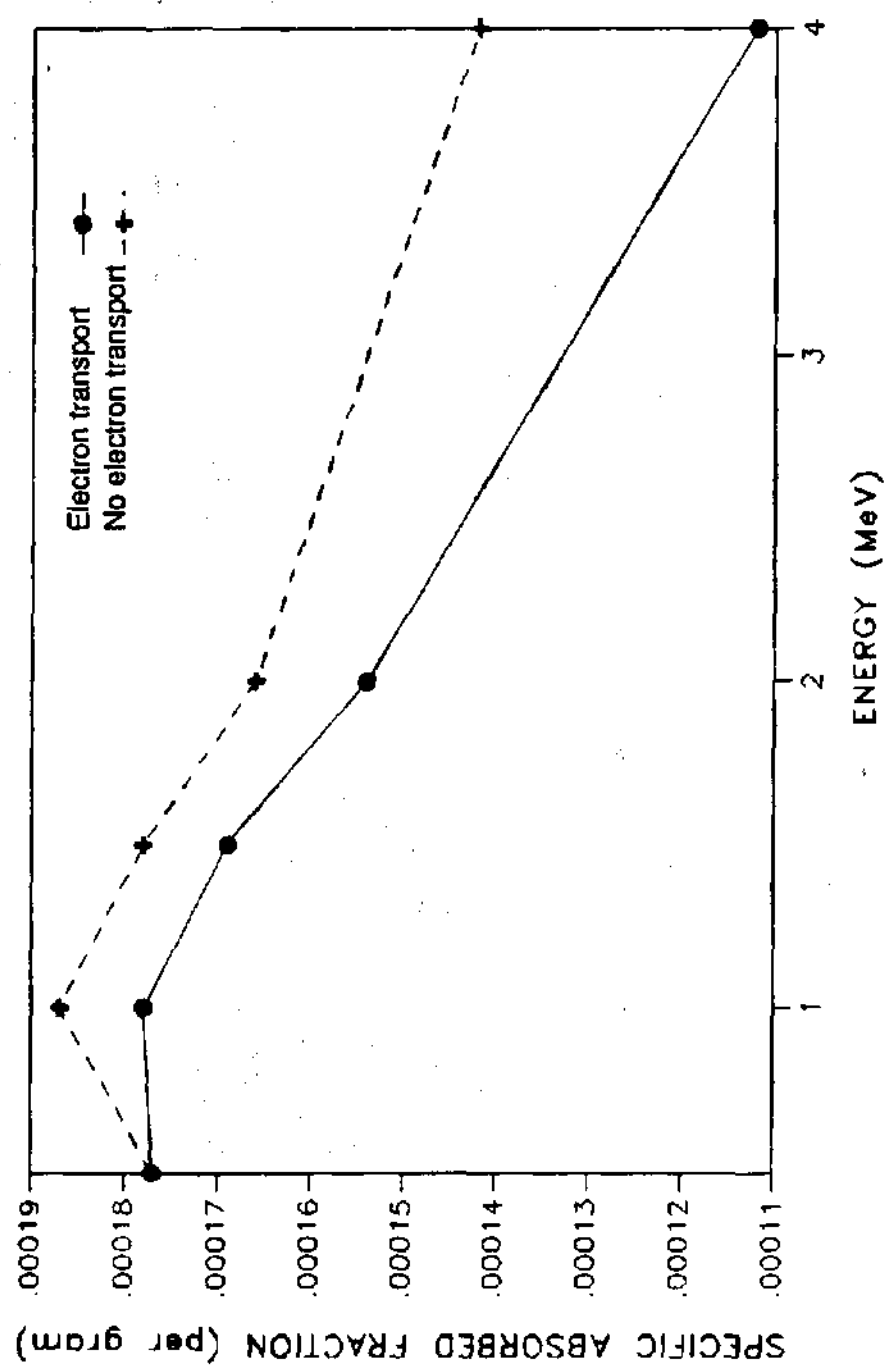


Figure 5.10b. Expansion of Figure 5.10a. for photon energies greater than 0.5 MeV.

the results, with and without electron transport, are virtually identical at low photon energies. This is expected since the photoelectric effect dominates at very low energies. Since photoelectrons from these interactions have very low energies and short ranges, their energies may be considered to be deposited locally. However, at high photon energies other photon interaction processes begin to become relatively important, and the results begin to differ. This difference increases with increasing photon energy and can be explained by noting that secondary electrons, from photon interactions, have higher energies and therefore a longer range, allowing some of these electrons to escape from the source organ.

In conclusion, it should be noted that significant differences in the results of specific absorbed fractions of energy occurs for high energy photons when charged particle products are considered. From figures 5.9 and 5.10, it should be noted that these differences begin to appear for photon energies greater than 1 MeV.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This research demonstrates analytically the significance of secondary electrons and bremsstrahlung production in photon/electron interactions when considered in internal dosimetry calculations. The objective of this research was to develop a code that will be used to determine the contributions beta transport make to absorbed fraction of photon radiation, and the variation of absorbed fraction of electron radiation from unity for different radiation energies. The code INDOSE, uses a modified version of the Electron-Gamma Shower (EGS4) (Fo78) to transport radiation particles. INDOSE-EGS was used to calculate absorbed fractions of energy for monoenergetic electron and photon sources in various organs of a mathematically defined phantom representing an adult human. Based on the results obtained from calculations using INDOSE, the objective of this research has been realized.

Previously, it has been assumed that the absorbed fractions of energy for non-penetrating radiation were always unity when the source organ was also the target organ and zero otherwise. However, this is an over estimation of the absorbed dose to the source organ. More seriously, is the underestimation of the absorbed dose to organs adjacent to the source organ. Results obtained in this research have shown that the absorbed fractions of energy vary considerably from unity. For example, when the source organ is the target organ, the absorbed fraction for a 4 MeV electron source in the thyroid is about 0.5 whereas, absorbed fraction for the same radiation in the liver is about 0.87. The difference is largest for high energy radiation when the organ has a small mass and a large surface area. In addition, calculations

using the INDOSE code have shown that absorbed fractions for electron radiation vary linearly, decreasing with increasing radiation energy, when the source organ is also the target organ. When the source organ is not the target, absorbed fractions increase gradually and level off at a maximum. Results obtained from this research give quantitatively the absorbed fractions both to the source organ and other organs which receive substantial amounts of energy from the incident radiation.

Results of specific absorbed fraction of energy for photon radiation show that results obtained with the INDOSE code compare favorably with those from MIRD publications (Sn78). When secondary electrons from photon interactions are considered, the absorbed fractions are significantly different for high energy incident photon radiation. This difference begins to be apparent at photon energies in excess of 0.5 MeV. Below this energy, consideration of electron transport does not contribute significantly to the result and the assumptions used in the MIRD calculations are valid.

In its present version, INDOSE uses the random walk approach to transport electrons. This approach includes the continuous slowing down and a multiple scattering approximation. Future work on this code should include a more rigorous solution which will treat electron transport interaction by interaction as is done for photon transport. Other developments should include a non-uniform source distribution to represent real life situations. For example, advances in nuclear medicine allow tomographic images of radionuclide distributions in the body. This possibility allows more accurate assessment of the variation of absorbed dose with time and hence, a better treatment by using the appropriate amount of radionuclide.

Recently, a blood model was developed (Hu86). This model sought to calculate the dose delivered to various organs from radiation source in the

blood. Incorporating the blood model into INDOSE will allow estimates of dose to the wall of blood vessels and organs with walls. This information will be very valuable in treatments involving the heart. Finally, it is recommended that absorbed fractions and 'S' factors presently used in internal dose estimation should be recalculated to reflect the important contributions of beta transport.

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APPENDIX A**PROGRAM LISTING OF USER-WRITTEN CODE (INDOSE)**

```

C *****
C *** MAIN ***
C *****
character*16 namorg(54)
COMMON/BOUNDS/ECUT(120),PCUT(120),VACDST
COMMON/MEDIA/NMED,RLC(10),RLDU(10),RHO(10),MSG(10),MGE(10),MSEKE(
*10),MEKE(10),MLEKE(10),MCMFP(10),MRANGE(10),IRAYLM(10)
COMMON/MEDIAC/MEDIA(24,10)
CHARACTER*4 MEDIA
COMMON/MISC/KMPI,KMPO,DUNIT,NOSCAT,MED(120),RHOR(120),IRAYLR(120),
*masorg(120)
real masorg
common/epcont/edep,tstep,tustep,ustep,tvstep,vstep,ldisc,iold,ir
*new,rhof,eold,ew,eke,elke,beta2,gle,tscat,lausfl(25)
COMMON/USEFUL/PZERO,PRM,PRMT2,RM,MEDIUM,MEDOLD,IBLOBE
DOUBLE PRECISION PZERO,PRM,PRMT2
C COMMONS NEEDED
COMMON/TOTALS/ESUM(120),saf(120),cosvar(120),eave(120),avar(120),
*estd(120),esumsg(120),pntcv(120),ncoll(120)
C FOR ENERGY CONSERVATION CHECK
DOUBLE PRECISION EI,ESUM,EKIN,TOTKE,ETOT
C DOUBLE PRECISION
C CREATE A TEMPORARY ARRAY AND DEFINE THE MEDIA, NEXT
CHARACTER TEMP(24,3)
data temp/'S','K','E','L','E','T','A','L',16*' ','T','I','S','S',
*'U','E',18*' ','L','U','N','G',20*' '/'
open(unit=12,file='xtion.dat',status='old')
open(unit=4,file='patche.dat',status='old')
open(unit=6,file='reslt.dat',status='new')
open(unit=8,file='dummy.dat',status='scratch')
NREG=54
C THE NUMBER OF REGIONS---A LOCAL VARIABLE ONLY
C THREE MEDIA WILL BE USED
NMED=3
DO 11 J=1,NMED
DO 21 I=1,24
MEDIA(I,J)=TEMP(I,J)
21 CONTINUE
22 CONTINUE
11 CONTINUE
12 CONTINUE
MED(54)=0
C REGION 54 IS VACUUM
call region
C SET ENERGY CUTOFFS FOR EACH REGION NEXT
DO 31 I=1,NREG
ECUT(I)=0.6
PCUT(I)=0.005
c iraylr=1
31 CONTINUE
read(4,301)isourc
301 format(12)
32 CONTINUE
C HATCH-CALL
CALL HATCH
read(4,301)istep

```

```

C      INITIALIZATION-FOR-AUSGAB
DO 41 I=1,120
    ESUM(I)=0.00
    esumsg(i)=0.
    estd(i)=0.
    ncoll(i)=0.
    evar(i)=0.
    saf(i)=0.
41  CONTINUE
42  CONTINUE
C      ZERO THE ENERGY BALANCE ARRAY
    estep=istep/100.
    do 77 medium=1,3
        call fixtmx(estep,medium)
77  continue
    read(4,771) ncases.e1
771  format(17,f5.3)
C      DETERMINATION-OF-INCIDENT-PARTICLE-PROPERTIES
    do 61 i=1,ncases
        iqi=0
C      INCIDENT PARTICLE IS AN( ELECTRON iqi=-1, photon iqi=0)
C      INCIDENT ENERGY (TOTAL) IN MEV, EI
C      Ekin=Ei-PRM
C      K.E. OF ELECTRON---PRM IS THE REST MASS
        if(isourc.eq.1) call kidney(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.2) call beam(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.3) call ovaries(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.4) call testes(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.5) call stomach(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.6) call bladder(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.7) call liver(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.8) call uterus(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.9) call lungs(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.10) call heart(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.11) call thyroid(xi,yi,zi,ui,vi,wi,iri)
        if(isourc.eq.12) call spleen(xi,yi,zi,ui,vi,wi,iri)
C      incident particle starts in region source iri
        wti=1.
C      WEIGHT FACTOR---NOT USED IN CALCULATION, BUT
C      IS A PARAMETER IN SUBROUTINE SHOWER; HENCE DEFINE
C      AS UNITY
        ICODE=-1
C      AN OUTPUTTING PARAMETER, INVENTED TO MARK THE
C      INCIDENT PARTICLES
C      STEP 7. SHOWER-CALL
        CALL SHOWER(IQI,EI,XI,YI,ZI,UI,VI,WI,IRI,WTI)
        do 55 j=1,nreg
            eave(j)=eave(j) + esum(j)
            esumsg(j)= esumsg(j) + esum(j)**2
            esum(j)=0.
55  continue
C      END OF SHOWER-CALL LOOP
61  CONTINUE
62  CONTINUE
C      OUTPUT-OF-RESULTS
        TOTKE=NCASES*EI

```

```

c      OR USE NEXT TOTKE IF INCIDENT PARTICLE IS ELECTRON
c      totke=ncases*(ei -prm)
c      TOTAL K.E. INVOLVED IN RUN
      WRITE(6,80)EI,NCASES,Iq1,Isourc
80     FORMAT(//,' INCIDENT TOTAL ENERGY OF particle=',F12.3,' MEV',/, '
* NUMBER OF CASES IN RUN=',I7,/, ' charge of particle is ',i3,
*/, ' ENERGY DEPOSITION SUMMARY:source is in organ',i6,/)
c      CALCULATE AND PRINT OUT THE FRACTION OF ENERGY
c      DEPOSITED IN EACH REGION
      ETOT=0.D0
      call nameor(namorg)
      write(6,211)
211     format(39x,'abs fract',7x,'spe abs frac',7x,'%cv')
      DO 91 I=1,NREG-1
      ETOT=ETOT+Eave(I)
      if (eave(I).eq.0)go to 91
      evar(I)=(esumsq(I)/ncases-((eave(I)/ncases)**2))/(ncases-1)
      esum(I)=eave(I)
      Eave(I)=Eave(I)/TOTKE
      saf(I)=eave(I)/masorg(I)
      if(evar(I).gt.0.)then
      estd(I)=sqrt(evar(I))
      else
      estd(I)=0.
      endif
      coevar(I)=estd(I)/(esum(I)/ncases)
      pcntcv(I)=coevar(I)*100.
c      FRACTION IN EACH REGION
      WRITE(6,100)namorg(I),eave(I),saf(I),pcntcv(I)
100     FORMAT(' FRACTION IN REGION',a16,2x,2e15.8,4x,f8.2)
91     CONTINUE
92     CONTINUE
      i=nreg
      etot=etot+eave(i)
      eave(i)=eave(i)/totke
c      fraction in each region
      write(6,100) namorg(i),eave(i)
      tbsaf=(1.-eave(i))/70000.
      write(6,101)tbsaf
101     format(//,' total body abs fraction= ', e15.8)
      ETOT=ETOT/TOTKE
c      THE TOTAL FRACTION OF ENERGY IN RUN
      WRITE(6,110)ETOT
110     FORMAT(//,' TOTAL ENERGY FRACTION IN RUN=',G15.7,/, ' WHICH SHOU
*LD BE CLOSE TO UNITY')
      write(6,111)noscatt
111     format(//,' total # of no multiple scatt = ',i6)
46     continue
47     continue
      STOP
      END

```

```

C   LAST STATEMENT OF MAIN
      SUBROUTINE AUSGAB(IARG)
      COMMON/EPCONT/EDEP,TSTEP,TUSTEP,USTEP,TVSTEP,VSTEP, IDISC,IOLD,IR
      *NEW,RHOF,EOLD,ENEW,EKE,ELKE,BETA2, GLE,TSCAT,IAUSFL(25)
      DOUBLE PRECISION EDEP
      COMMON/STACK/E(40),X(40),Y(40),Z(40),U(40),V(40),W(40),W
      *T(40),IQ(40),Ir(40),np,j0
      DOUBLE PRECISION E
C   COMMONS NEEDED IN AUSGAB
      COMMON/TOTALS/esum(120),saf(120),coevvar(120),eave(120),evar(120),
      *estd(120),esumsq(120),pcntcv(120),ncoll(120)
C   FOR ENERGY CONSERVATION CHECK
      DOUBLE PRECISION ESUM
C   DOUBLE PRECISION
C   KEEP A RUNNING SUM OF THE ENERGY DEPOSITED IN EACH REGION
      if (edep.lt.0.)then
        write(6,100)iarg
100    format(/,' edep is negative at iarg= ',i3)
        endif
      if(iarg.lt.5)then
        ESUM(IR(NP))=ESUM(IR(NP)) + EDEP
      endif
      edep=0.
      RETURN
      END
C   LAST STATEMENT OF SUBROUTINE AUSGAB

```

```

SUBROUTINE POSITN
COMMON/EPCONT/EDEP,TSTEP,TUSTEP,USTEP,TVSTEP,VSTEP, IDISC,IOLD,IR
*NEW,RHOF,EOLD,ENEW,EKE,ELKE,BETA2, GLE,TSCAT,IAUSFL(25)
DOUBLE PRECISION EDEP
COMMON/STACK/E(40),X(40),Y(40),Z(40),U(40),V(40),W(40),W
*T(40),IQ(40),IR(40),NP,JO
DOUBLE PRECISION E
COMMON/MISC/KMPI,KMPO,DUNIT,NOSCAT,MED(120),RHOR(120),IRAYLR(120),
*MASORG(120)
REAL MASORG
COMMON/USEFUL/PZERO,PRM,PRMT2,RM,MEDIUM,MEDOLD,IBLOBE
DOUBLE PRECISION PZERO,PRM,PRMT2

C      IF(Z(NP).LE.70.) GO TO 20
C HEAD
      TH=X(NP)*X(NP)/49.+Y(NP)*Y(NP)/100.
      IF(Z(NP).LT.85.5) GO TO 10
      IF(TH+(Z(NP)-85.5)**2/72.25.LE.1.) GO TO 11
5      IR(NP)=54
      MED(IR(NP))=0
      JO = 107
      RETURN
10 IF(TH.GT.1.) GO TO 5
C
11 CALL HEAD
C
12 IF(JO.EQ.22) GO TO 16
      IF(JO.EQ.78) GO TO 18
      MED(IR(NP))=2
      RETURN
16 MED(IR(NP))=3
      RETURN
18 MED(IR(NP))=1
      RETURN
20 IF(Z(NP).LT.0.) GO TO 24
C TRUNK
      IF(X(NP)*X(NP)/400.+Y(NP)*Y(NP)/100..GT.1.)GO TO 5
C
      CALL TRUNK
C
      GO TO 12
C LEGS
24 TERM=Z(NP)/10.+10.

```

```

      JO = 101
      IF(X(NP))26,32,29
26  IF((X(NP)+TERM)**2+Y(NP)**2.GT.TERM**2) GO TO 32
C
27  CALL LEGS
C
      GO TO 12
29  IF((X(NP)-TERM)**2+Y(NP)**2.GT.TERM**2) GO TO 32
      GO TO 27
32  IF(Y(NP))33,5,5
33  IF(Z(NP).LT.-4.8) GO TO 5
      IF(X(NP))35,27,36
35  IF(X(NP)*10.+Z(NP)+100.)5,5,37
36  IF(-X(NP)*10.+Z(NP)+100.)5,5,37
37  IF(Y(NP)*10.+Z(NP)+100.)5,5,38
38  JO=67
      GO TO 27
      END
C *****
      SUBROUTINE TRUNK
C  FOR STANDARD REFERENCE MAN ORGANS, 104. (2/28/86)
      COMMON/STACK/E(40),X(40),Y(40),Z(40),U(40),V(40),W(40),W
      *T(40),IQ(40),IR(40),NP,JO
      DOUBLE PRECISION E
C
      XX=X(NP)*X(NP)
      YY=Y(NP)*Y(NP)
      ZZ=Z(NP)*Z(NP)
C..RIGHT & LEFT BLOOD TUBES
      IF(Z(NP).GT.69.0) GO TO 530
      ARX=(X(NP)+(17.9-0.02029*Z(NP)))**2
      ALX=(X(NP)-(17.9-0.02029*Z(NP)))**2
      IF(ARX+(Y(NP)+2.5)**2.GT.0.25) GO TO 540
550  IR(NP)=49
      JO=107
      RETURN
540  IF(ALX+(Y(NP)+2.5)**2.GT.0.25) GO TO 530
      GO TO 550
C..CNY=(Y/9.8)**2 -- TEST FOR RT. AND LEFT ARM BONES AND SPINE
530  CNY=YY/96.04
      IF(XX/289.+CNY.LE.1.) GO TO 15
      IF(XX/392.04+CNY.LT.1.) GO TO 6
      IF(Z(NP).LT.69.8) GO TO 13
6  TA1=(Z(NP)*1.4-2635.8)/193.2
      TB1=X(NP)/1.4
      TC1=YY/7.29-(Z(NP)+69.0)**2/19044.
      IF((TA1-TB1)**2+TC1.GT.0.) GO TO 11
      IF(Z(NP).GT.69.0) GO TO 12
      IR(NP)=26
      JO=78
      RETURN
11  IF((TA1+TB1)**2+TC1.GT.0.) GO TO 12
      IF(Z(NP).GT.69.0) GO TO 12
      IR(NP)=25
      JO=78
      RETURN

```

```

12 IF(Z(NP).LT.69.8) GO TO 16
   IF(XX/46.24+CNY.LT.1.) GO TO 16
C SKIN
13 IR(NP)=35
   JO=82
   RETURN
C TISSUE
14 IR(NP)=43
   JO=92
   RETURN
15 IF(XX/4.+(Y(NP)-5.5)**2/6.25.GT.1.) GO TO 16
   IF(Z(NP).LT.22.) GO TO 3
   IR(NP)=34
   JO=78
   RETURN
16 IF(Z(NP).LE.27.) GO TO 3
   IF(Z(NP).LE.43.) GO TO 2
CLAVICLES AND SCAPULAE.
17 IF(Y(NP).LT.0.) GO TO 101
   IF(Z(NP).LT.50.9) GO TO 103
   IF(Z(NP).GT.67.3) GO TO 103
   S=Y(NP)/SQRT(XX+YY)
   IF(S.LT..2425356.OR.S.GT..624695) GO TO 103
   IF(XX/289.+CNY.LE.1.) GO TO 103
   IF(XX/361.+CNY.GT.1.) GO TO 14
   IR(NP)=32
   JO=78
   RETURN
101 IF(Z(NP).LT.67.4617.OR.Z(NP).GT.69.0383) GO TO 103
   IF((Z(NP)-68.25)**2+(20.-SQRT(X(NP)*X(NP)+(Y(NP)-11.1)**2
1 ))**2.GT.0.62141689) GO TO 14
   COTPHI=(11.1-Y(NP))/ABS(X(NP))
   IF(COTPHI.LT..8941588 .OR. COTPHI.GT.7.034148 ) GO TO 14
   IR(NP)=27
   JO=78
   RETURN
C LUNGS
103 YPZ=YY/56.25+(Z(NP)-43.5)**2/576.
   IF(Z(NP).GT.67.5)GOTO 109
   IF((X(NP)+8.5)**2/25.+YPZ.GT.1.) GO TO 106
   IF(Z(NP).LT.43.5) GO TO 106
   IF(Z(NP).LT.46.0) GO TO 104
   IF(Z(NP).GT.54.0) GO TO 104
   IF(Y(NP).GT.1.5) GO TO 104
   IF(X(NP).GT.-5.4) GO TO 109
C
   IF(X(NP).GT.-4.5) GO TO 109
104 IR(NP)=19
   JO=22
   RETURN
106 IF((X(NP)-8.5)**2/25.+YPZ.GT.1.) GO TO 109
   IF(Z(NP).GT.67.5)GOTO 109
   IF(Z(NP).LT.43.5) GO TO 109
   IF(Z(NP).GT.55.0) GO TO 107
   IF(Y(NP).GT.1.0) GO TO 107
   IF(X(NP).LT.8.0) GO TO 109
107 IR(NP)=18
   JO=22

```

```

      RETURN
C HEART
109 X1=X(NP)-1.
    Y1=Y(NP)+1.8
    Z1=Z(NP)-50.
    TX=X1*.6571-Y1*.4727-Z1*.5664
    TX2=TX*TX
    TY=-0.4640*X1-0.3249*Y1-0.8241*Z1
    TY2=TY*TY
    TZ=X1*.5736-Y1*.8191
    TZ2=TZ*TZ
    IF(TX.LT.0.0) GO TO 400
    IF(TX2/53.29+TY2/13.69+TZ2/3.24.LT.1.0) GO TO 410
    IF(TX2/73.96+TY2/25.0+TZ2/9.61.GT.1.0) GO TO 430
405 IR(NP)=46
    JO=107
    RETURN
410 IR(NP)=47
    JO=107
    RETURN
430 IF(TZ.GT.0.0) GO TO 120
    IF(TX2/64.0+TY2/19.36+TZ2/40.96.LT.1.0) GO TO 410
    IF(TX2/73.96+TY2/25.0+TZ2/49.0.GT.1.0) GO TO 120
    GO TO 405
400 IF(TZ.LT.0.0) GO TO 440
    IF(TX2/26.01+TY2/22.09+TZ2/3.24.LT.1.0) GO TO 410
    IF(TX2/29.16+TY2/25.0+TZ2/4.41.LT.1.0) GO TO 405
    IF(TX2/26.01+TY2/22.09+TZ2/44.89.LT.1.0) GO TO 410
    IF(TX2/29.16+TY2/25.0+TZ2/49.0.LT.1.0) GO TO 405
    GO TO 120
440 IF(TX2/26.01+TY2/22.09+TZ2/7.84.LT.1.0) GO TO 410
    IF(TX2/29.16+TY2/25.0+TZ2/9.61.LT.1.0) GO TO 405
C RIBS AND THYMUS
120 IF(XX/272.25+YY/86.49.LT.1.)GO TO 122
    IF(XX/289.+YY/96.04.GT.1.) GO TO 14
    N=(Z(NP)-35.1)/1.4
    K=N-(N/2)*2
    IF(K.NE.0) GO TO 122
    IF(Z(NP).GT.67.3) GO TO 122
121 IR(NP)=31
    JO=78
    RETURN
122 IF((X(NP)+2.)*2/9.+4.*(Y(NP)+6.)*2+(Z(NP)-60.5
1 )**2/16..GT.1.)GO TO 123
    IR(NP)=41
    JO=107
    RETURN
123 IF(Z(NP).LT.69.8) GO TO 601
    IF(XX/46.24+CNV.GE.1.) GO TO 13
601 IF(Z(NP).GT.44.8) GO TO 14
    IF(Z(NP).LT.43.0) GO TO 2
602 IF(XX+YY.GT.6.25) GO TO 14
    IR(NP)=48
    JO=107
    RETURN
C LIVER, STOMACH, KIDNEYS, SPLEEN, AND RIBS ,AORTA & VC
2 IF(XX/272.25+YY/64..GT.1.) GO TO 201

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      IF(X(NP)/35.+Y(NP)/45.-Z(NP)/43..GT.-1.) GO TO 201
      IR(NP)=17
      JO=107
      RETURN
201  XP=(X(NP)-8.)**2
      YP=(Y(NP)+4)**2
      ZP=(Z(NP)-35.)**2
      IF(XP/16.+YP/9.+ZP/64..GT.1.) GO TO 203
      IF(XP/11.471769+YP/5.697769+ZP/54.567769.LE.1.) GO TO 202
      IR(NP)=6
      JO=107
      RETURN
202  IR(NP)=7
      JO=107
      RETURN
203  TA2=(Y(NP)-6.)**2/2.25+(Z(NP)-32.5)**2/30.25
      IF((X(NP)+6.)**2/20.25+TA2.GT.1.) GO TO 204
      IF(X(NP).GT.-3.) GO TO 205
      IR(NP)=16
      JO=18
      RETURN
204  IF((X(NP)-6.)**2/20.25+TA2.GT.1.) GO TO 205
      IF(X(NP).LT.3.) GO TO 205
      IR(NP)=15
      JO=18
      RETURN
205  IF((X(NP)-11.)**2/12.25+(Y(NP)-3.)**2/4.+(Z(NP)-37.)
1    **2/36..GT.1.)GO TO 206
      IR(NP)=38
      JO=107
      RETURN
206  IF(XX/272.25+YY/86.49.LT.1.) GO TO 21
      IF(XX/289.+YY/96.04.GT.1.) GO TO 14
      IF(Z(NP).LT.35.1) GO TO 21
      NN=(Z(NP)-35.1)/1.4
      KK=NN-(NN/2)*2
      IF(KK.EQ.0) GO TO 121
C  PANCREAS AND ADRENALS
21  IF(XX/225.+YY+(Z(NP)-37.)**2/9..GT.1.) GO TO 213
      IF(X(NP).LT.0.) GO TO 213
      IF(Z(NP).LT.37.) GO TO 212
211  IR(NP)=52
      JO=107
      RETURN
212  IF(X(NP).LE.3.) GO TO 211
213  TA3=4.*(Y(NP)-6.5)**2+(Z(NP)-38.)**2/25.
      IF((X(NP)+4.5)**2/2.25+TA3.GT.1.) GO TO 214
      IF(Z(NP).LT.38.) GO TO 602
      IR(NP)=2
      JO=3
      RETURN
214  IF((X(NP)-4.5)**2/2.25+TA3.GT.1.) GO TO 602
      IF(Z(NP).LT.38.) GO TO 602
      IR(NP)=1
      JO=3
      RETURN
C  PELVIS, ULI(ASC), AND LLI(DEC)

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```

3 IF(XX+(Y(NP)+3.)*2.GT.144.) GO TO 702
  IF(XX+(Y(NP)+3.8)*2.LT.127.69) GO TO 33
  IF(Y(NP).LT.-3.) GO TO 702
  IF(Z(NP).GT.14.) GO TO 302
  IF(Y(NP).GT.5.) GO TO 702
301 IR(NP)=30
  JO=78
  RETURN
302 IF(Z(NP).LE.22.) GO TO 301
  GO TO 701
303 XP=(X(NP)+8.5)**2
  YP=(Y(NP)+2.36)**2
  IF(XP+YP.GT.6.25) GO TO 304
  IF(Z(NP).LT.14.45) GO TO 32
  IF(Z(NP).GT.24.) GO TO 31
  IF(XP+YP.LT.3.20947225) GO TO 333
  IR(NP)=8
  JO=107
  RETURN
333 IR(NP)=9
  JO=107
  RETURN
304 XP=(X(NP)-((Z(NP)-24.)*.28/15.28)-9.)*2
  YP=(Y(NP)-((8.72-Z(NP))*2.5/15.28))*2
  IF(XP/3.5344+YP/4.5369.GT.1.) GO TO 305
  IF(Z(NP).LT. 8.72) GO TO 32
  IF(Z(NP).GT.24.) GO TO 31
  IF(XP/2.4964+YP/1.7956.LT.1.) GO TO 334
  IR(NP)=10
  JO=107
  RETURN
334 IR(NP)=11
  JO=107
  RETURN
305 IF(Z(NP).LT.17.) GO TO 32
  IF(Y(NP).GT.2.2) GO TO 701
  IF(Y(NP).LT.-4.86) GO TO 701
ULI(TRV), S.I., BLADDER, LLI(TRV), AND BLADDER
31 YP=(Y(NP)+2.36)**2
  ZP=(Z(NP)-25.5)**2
  IF(YP/6.25+ZP/2.25.GT.1.) GO TO 311
  IF(X(NP).LT.-10.5.OR.X(NP).GT.10.5) GO TO 311
  IF(YP/3.892729+ZP/.946729.LT.1.) GO TO 333
  IR(NP)=8
  JO=107
  RETURN
311 IR(NP)=12
  JO=107
  RETURN
32 YP=(Y(NP)+4.5)**2
  ZP=(Z(NP)-8.)*2
  IF(XX/24.581764+YP/11.957764+ZP/11.957764.GT.1.) GO TO 322
  IF(XX/22.146436+YP/10.278436+ZP/10.278436.LT.1.) GO TO 321
  IR(NP)=3
  JO=107
  RETURN
321 IR(NP)=4

```

```

      JO=107
      RETURN
322 IF(X(NP).LT.3.) GO TO 323
      IF(X(NP).GT.10.29) GO TO 325
      P=(SQRT ((X(NP)-3.)**2+(Z(NP)-8.72)**2)-5.72)**2
      IF(P+YY.GT.2.4649) GO TO 325
      IF(Z(NP).GT.8.72) GO TO 325
      IF(P+YY.LE..8281) GO TO 334
      GO TO 324
323 IF(X(NP).LT.-1.57) GO TO 325
      P=(SQRT((X(NP)-3.)**2+ZZ)-3.)**2
      IF(P+YY.GT.2.4649) GO TO 325
      IF(P+YY.LE..8281) GO TO 334
324 IR(NP)=10
      JO=107
      RETURN
325 IF(XX/6.25+(Y(NP)+2.)**2/25.+(Z(NP)-14.)**2/2.25.GT.1.) GO TO 701
      IF(Y(NP).LT.-4.5) GO TO 701
      IR(NP)=14
      JO=107
      RETURN
701 IF(Z(NP).LT.15.5) GO TO 702
      IF(XX+YY.GT.6.25) GO TO 702
      IR(NP)=48
      JO=107
      RETURN
702 IR(NP)=13
      JO=107
      RETURN
C OVARIES
  33 TA4=YY*4.+(Z(NP)-15.)**2*.25
      IF((X(NP)+6.)**2+TA4.GT.1.) GO TO 331
      IR(NP)=23
      JO=66
      RETURN
331 IF((X(NP)-6.)**2+TA4.GT.1.) GO TO 303
      IR(NP)=22
      JO=66
      RETURN
      END
C
C *****
C SUBROUTINE LEGS
      COMMON/STACK/E(40),X(40),Y(40),Z(40),U(40),V(40),W(40),W
      *T(40),IQ(40),IR(40),NP,JO
      DOUBLE PRECISION E
C JB = 103
C JS = 101
      IF(JO.EQ.67) GO TO 28
      IF(Z(NP).GT.-79.8) GO TO 6
C SKIN
  3 IR(NP)=36
      JO = 82
      RETURN
C RIGHT & LEFT BLOOD TUBES
  6 IF((X(NP)+(6.0+0.06892*Z(NP))**2+Y(NP)*Y(NP).GT.0.25) GO TO 5
  20 IR(NP)=50

```

```

      JO=107
      RETURN
      5 IF((X(NP)-(6.0+0.06892*Z(NP))**2+Y(NP)*Y(NP).GT.0.25) GO TO 10
      GO TO 20
      10 TRM1=Z(NP)/10.+10.
      TRM2=(TRM1-.2)**2
      IF(X(NP))8,3,18
      8 IF((X(NP)+TRM1)**2+Y(NP)*Y(NP).GT.TRM2) GO TO 3
      TA=Z(NP)*.1002506265 + X(NP)+ 10.
      TY=Z(NP)*.0313283208 + 3.5
      IF(TA*TA.GT.TY*TY-Y(NP)*Y(NP)) GO TO 15
C   R.LEG BONE
      IR(NP)=29
      JO = 78
      RETURN
C   TISSUE
      15 IR(NP)=44
      JO = 92
      RETURN
      18 IF((X(NP)-TRM1)**2+Y(NP)*Y(NP).GT.TRM2) GO TO 3
      TA=Z(NP)*.1002506265 - X(NP)+ 10.
      TY=Z(NP)*.0313283208 + 3.5
      IF(TA*TA.GT.TY*TY-Y(NP)*Y(NP)) GO TO 15
C   L.LEG BONE
      IR(NP)=28
      JO = 78
      RETURN
      28 IF(X(NP)) 29,37,33
      29 IF((X(NP)+1.3)**2/1.69+(Y(NP)+8.)**2/2.25+(Z(NP)+2.3)
      1 **2/5.29.GT.1.)GO TO 37
C   R.TESTE
      IR(NP)=40
      JO = 86
      RETURN
      33 IF((X(NP)-1.3)**2/1.69+(Y(NP)+8.)**2/2.25+(Z(NP)+2.3)
      1 **2/5.29.GT.1.)GO TO 37
C   L.TESTE
      IR(NP)=39
      JO = 86
      RETURN
C   GENITALIA
      37 IR(NP)=24
      JO = 107
      RETURN
      END
C
C *****
C
C   SUBROUTINE HEAD
      COMMON/STACK/E(40),X(40),Y(40),Z(40),U(40),V(40),W(40),W
      *T(40),IQ(40),IR(40),NP,JO
      DOUBLE PRECISION E
      XX=X(NP)*X(NP)
      YY=Y(NP)*Y(NP)
      IF(XX/36.+YY/81.+(Z(NP)-86.5)**2/42.25.GT.1.) GO TO 8
C   BRAIN
      IR(NP)=5

```

```

      JO = 107
      RETURN
      8 IF (XX/46.24+YY/96.04+(Z(NP)-85.5)**2/68.89.GT.1.) GO TO 12
C   SKULL
      IR(NP)=33
      JO = 78
      RETURN
      12 IF (Z(NP).LT.85.5) GO TO 16
C   SKIN
      13 IR(NP)=37
      JO = 82
      RETURN
      16 IF (XX/46.24+YY/96.04.GT.1.) GO TO 13
      IF (Y(NP))23.53.18
      18 IF (Z(NP).GT.78.5) GO TO 53
      IF (XX/4.+(Y(NP)-5.5)**2/6.25.GT.1.) GO TO 53
C   SPINE
      IR(NP)=34
      JO = 78
      RETURN
      23 IF (Z(NP).GT.79.5) GO TO 53
      IF (Z(NP).LT.76.) GO TO 38
      IF (Y(NP).GT.-2.936) GO TO 53
      IF ((Y(NP)+6.436)**2+(Z(NP)-76.)**2.GT.12.25) GO TO 53
      IF (X(NP).LT.-.625) GO TO 53
      IF (X(NP).GT.-.375) GO TO 32
C   NARES
      29 IR(NP)=21
      JO = 63
      RETURN
      32 IF (X(NP).GT.-.375) GO TO 36
C   SEPTUM
      IR(NP)=20
      JO = 63
      RETURN
      36 IF (X(NP).GT.-.625) GO TO 53
      GO TO 29
      38 YC=Y(NP)+6.
      YC2=YC*YC
      CYX=XX+YC2
      IF (CYX.GT.4.84) GO TO 53
      IF (CYX.LT.1.) GO TO 53
      IF (YC.GT.0.) GO TO 53
      IF (Z(NP).GT.75.) GO TO 53
      IF (Z(NP).GT.71.25) GO TO 48
      TA=-(Z(NP)*.2343144)+17.402008
      GO TO 49
      48 TA=Z(NP)*.0781048-4.85786
      49 IF ((YC-ABS(X(NP)))**2.LT.CYX*TA*TA*2.) GO TO 53
C   THYROID
      IR(NP)=42
      JO = 107
      RETURN
C   FACE
      53 IF ((Y(NP).GE.-6.32).OR.(Z(NP).GT.85.5)) GO TO 17
CC
      IF ((Z(NP).LT.82.98)) GO TO 111

```

```

        if((x(np).lt.0.).and.((x(np)+3.4)**2+(z(np)-84.2)**2+(y(np)+
1 7.5)**2).lt.1.4884)then
c right eye
        ir(np)=53
        jo=107
        else
            if((x(np).gt.0.).and.((x(np)-3.4)**2+(z(np)-84.2)**2+(
1 y(np)+7.5)**2).lt.1.4884)then
c left eye
            ir(np)=53
            jo=107
            endif
            endif
111  IR(NP)=51
        JO=107
        RETURN
C  TISSUE
17  IR(NP)=45
    JO = 92
    RETURN
END
C
C *****

```

APPENDIX B
LISTING OF RADIATION SOURCE SUBROUTINES

```

C *****
C
C      SUBROUTINE ovaries(XI,YI,ZI,UI,VI,WI,IRI)
C      UNIFORM IN ovaries
C      2 X=RAN(1XX)
C        Y=RAN(1XX)-0.5
C        Z=RAN(1XX)*4.-2.0
C        IF(X*X+Y*Y/0.25+Z*Z/4.GT.1.) GO TO 2
C        IF(RAN(1XX).GT.0.5)GOTO 10
cc     left ovary
C        XI=X+6.
C        YI=Y
C        ZI=Z+15
C        IRI=22
C        GOTO 20
cc     right ovary
C      10 XI=X-6.
C        YI=Y
C        ZI=Z+15.
C        IRI=23
C      20 CALL GTISO(UI,VI,WI)
C        RETURN
C        END
C *****
C
C      SUBROUTINE STOMACH(XI,YI,ZI,UI,VI,WI,IRI)
C      UNIFORM IN STOMACH CONTENTS
C      2 X=RAN(1XX)*8.-4.
C        Y=RAN(1XX)*6.-3.
C        Z=RAN(1XX)*16.-8.
C        IF((X/3.387)**2+(Y/2.387)**2+(Z/7.387)**2.GT.1.) GO TO 2
C        XI=X+8.
C        YI=Y-4.
C        ZI=Z+35.
C        IRI=7
C        CALL GTISO(UI,VI,WI)
C        WGT=1.
C        RETURN
C        END
C *****
C
C      SUBROUTINE BLADDER(XI,YI,ZI,UI,VI,WI,IRI)
C      UNIFORM IN BLADDER CONTENTS
C      2 X=RAN(1XX)*9.916-4.958
C        Y=RAN(1XX)*6.816-3.458
C        Z=RAN(1XX)*6.816-3.458
C        IF((X/4.706)**2+(Y/3.206)**2+(Z/3.206)**2.GT.1.) GO TO 2
C        XI=X
C        YI=Y-4.5
C        ZI=Z+8.
C        IRI=4
C        CALL GTISO(UI,VI,WI)
C        WGT=1.
C        RETURN
C        END

```

```

C *****
C      SUBROUTINE KIDNEY(XI,YI,ZI,UI,VI,WI,IRI)
C      MONOENERGETIC
C      UNIFORM IN BOTH KIDNEYS
C
C      IF(RAN(1XX).LE..5) GO TO 8
C RIGHT KIDNEY
C      2 X=RAN(1XX)*7.5-4.5
C      Y=RAN(1XX)*3. - 1.5
C      Z=RAN(1XX)*11.- 5.5
C      IF(X*X/20.25+Y*Y/2.25+Z*Z/30.25.GT.1.) GO TO 2
C      6 XI=X-6.
C      IRI=16
C      GO TO 13
C LEFT KIDNEY
C      8 X=RAN(1XX)*7.5-3.
C      Y=RAN(1XX)*3. -1.5
C      Z=RAN(1XX)*11.-5.5
C      IF(X*X/20.25+Y*Y/2.25+Z*Z/30.25.GT.1.) GO TO 8
C      12 XI=X+6.
C      IRI=15
C      13 YI=Y+6.
C      ZI=Z+32.5
C      CALL GTISO(UI,VI,WI)
C      WGT = 1.
C      RETURN
C      END
C
C *****
C
C      SUBROUTINE testes(XI,YI,ZI,UI,VI,WI,IRI)
C      UNIFORM IN testes
C      2 X=RAN(1XX)*2.6-1.3
C      Y=RAN(1XX)*3.-1.5
C      Z=RAN(1XX)*4.6-2.3
C      IF(X*X/1.69+Y*Y/2.25+Z*Z/5.29.GT.1.) GO TO 2
C      IF(RAN(1XX).GT.0.5)goto 10
C cc left teste
C      XI=X+1.3
C      YI=Y-8.
C      ZI=Z-2.3
C      IRI=39
C      goto 20
C cc right teste
C      10 xi=x-1.3
C      yi= y-8.
C      zi= z-2.3
C      iri=40
C      20 CALL GTISO(UI,VI,WI)
C      RETURN
C      END
C

```

```

      SUBROUTINE LUNGS(XI,YI,ZI,UI,VI,WI,IRI)
C     UNIFORM IN LUNGS
      2 X=RAN(IXX)*10.-5.
        Y=RAN(IXX)*15.-7.5
        Z=RAN(IXX)*24.
        IF((X/5.)**2+(Y/7.5)**2+(Z/24.)**2.GT.1.) GO TO 2
        IF(RAN(IXX).LE..5) GO TO 6
C     LEFT LUNG
C     IF(Y.GT.0.) GO TO 7
C     IF(Z.GT.11.5)GO TO 7
C     IF(((X+6.)/5.)**2+(Y/7.5)**2+(Z/24.)**2.LT.1.) GO TO 2
C     IF(Y.GE.1.)GO TO 7
C     IF(X.LT.-0.5)GO TO 2
      7 XI=X+8.5
        ZI=Z+43.5
        YI=Y
        IRI=18
        GO TO 9
C     RIGHT LUNG
C     6 IF(Y.GT.0.) GO TO 8
C     6 IF(Z.LT.2.5.OR.Z.GT.10.5)GOTO 8
C     IF(((X-6.)/5.)**2+(Y/7.5)**2+(Z/24.)**2.LT.1.) GO TO 2
C     IF(Y.GE.1.5)GOTO 8
C     IF(X.GT.3.1)GOTO 2
      8 XI=X-8.5
        ZI=Z+43.5
        YI=Y
        IRI=19
      9 CALL GTISO(UI,VI,WI)
        WGT=1.
        RETURN
      END

C
C *****
C
      SUBROUTINE HEART(XI,YI,ZI,UI,VI,WI,IRI)
C     UNIFORM IN HEART
      2 X=RAN(IXX)*13.-5.
        Y=RAN(IXX)*10.-5.
        Z=RAN(IXX)*10.-5.
        IF(X**2/64.+Y**2/25.+Z**2/25..GT.1.) GO TO 2
        IF(X.GE.0.) GO TO 7
        IF(X**2+Y**2+Z**2.GT.25.) GO TO 2
        IF(X/3.+Z/5..LT.-1.) GO TO 2
      7 XI=X*.694272044-Y*.3237443709-Z*.6427876097
        YI=X*.4226182617+Y*.906307787
        ZI=X*.5825634161-Y*.2716537823+Z*.76604444
        XI=XI-1.
        YI=YI-3.
        ZI=ZI+51.
        CALL GTISO(UI,VI,WI)
        WGT=1.
        IRI=47
        RETURN
      END

```

```

C      *****
C      SUBROUTINE SPLEEN(XI,YI,ZI,UI,VI,WI,IRI)
C      UNIFORM IN SPLEEN
2     X=RAN(1XX)*7.-3.5
      Y=RAN(1XX)*4.-2.
      Z=RAN(1XX)*12.-6.
      IF(X*X/12.25+Y*Y/4.+Z*Z/36..GT.1.) GO TO 2
      XI=X+11.
      YI=Y+3.
      ZI=Z+37.
      CALL GTISO(UI,VI,WI)
      WGT=1.
      IRI=38
      RETURN
      END

C      SUBROUTINE THYRIOD(XI,YI,ZI,UI,VI,WI,IRI)
C      UNIFORM IN THYRIOD
2     Z=RAN(1XX)*5.+70.
      IF (Z.LE.71.25) THEN
        TA=-(Z*0.2343144)+17.402008
      ELSE
C      TA=.6094757-.0781049*(Z-70.)
        TA=Z*0.0781048-4.85786
      ENDIF
3     X=2.2*(RAN(1XX)*2-1)
      Y=-(RAN(1XX)*2.2)
      IF((X**2+Y**2).GT.4.84) GO TO 3
      IF((X**2+Y**2).LT.1.) GOTO 3
      IF((Y-ABS(X))**2-2*TA**2*(X**2+Y**2).LT.0.) GO TO 2
      IRI=42
      XI=X
      YI=Y-6
      ZI=Z
      CALL GTISO(UI,VI,WI)
      WGT=1.
      RETURN
      END

```

```

      SUBROUTINE LIVER(XI,YI,ZI,UI,VI,WI,IRI)
C     UNIFORM IN LIVER
2    X=RAN(IXX)*33.-16.5
      Y=RAN(IXX)*16.-8.
      Z=RAN(IXX)*16. + 27.
      IF((X/16.5)**2+(Y/8.)**2.GT.1.) GO TO 2
      IF(X/35.+Y/45.-Z/43..GT.-1.) GO TO 2
      XI=X
      YI=Y
      ZI=Z
      IRI=17
      CALL GTISO(UI,VI,WI)
      WGT=1.
      RETURN
      END

C
C *****
C
      SUBROUTINE UTERUS(XI,YI,ZI,UI,VI,WI,IRI)
C     UNIFORM IN UTERUS
2    X=RAN(IXX)*5.-2.5
      Z=RAN(IXX)*3.-1.5
3    Y=RAN(IXX)*10.-5.
      IF(Y.LT.-2.5)GOTO 3
      IF((X/2.5)**2+(Y/5.)**2+(Z/1.5)**2.GT.1.) GO TO 2
      XI=X
      YI=Y-2.
      ZI=Z+14.
      IRI=14
      CALL GTISO(UI,VI,WI)
      WGT=1.
      RETURN
      END

C
C *****

```

VITA

Bamikole Williams Jimba, the son of Solomon and Comfort Jimba, was born in September 2, 1954, in Kabba, Nigeria. He completed his secondary and higher school education at Government College, Keffi, Nigeria. He attended Ahmadu Bello University, Zaria, Nigeria, where he received a Bachelor of Science degree in Physics and University of Washington, Seattle, where he received a Master of Science degree in Nuclear Engineering. He worked for the Physics Department, Ahmadu Bello University, Zaria, before enrolling at Texas A&M University, in the Health Physics program of the Nuclear Engineering Department.

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