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***"Considerations of Beta and Electron Transport in
Internal Dose Calculations"***

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Task 1 - Pediatric Models & their Applications to Radiation Dose Calculations

Task Summary

The goal of this particular task is to consider, for the first time, the explicit transport of beta particles and photon-generated electrons in the series of six phantoms developed by Cristy and Eckerman (1987) at the Oak Ridge National Laboratory. In their report, ORNL/TM-8381, specific absorbed fractions of energy are reported for phantoms representing the newborn (3.4 kg), the one-year-old (9.8 kg), the five-year-old (19 kg), the ten-year-old (32 kg), the fifteen-year-old/adult female (55-58 kg), and the adult male (70 kg). Radiation transport calculations were performed with the Monte Carlo code ALGAMP which allows photon transport only. In subsequent calculations of radionuclide S values as is done in the MIRDOSE2 computer program (Stabin et al. 1984), electron absorbed fractions are thus considered to be either unity or zero depending upon whether the source region does or does not equal the target region, respectively.

Previous work performed in this research has indicated that this assumption can lead to large errors in calculated S values for adult-phantom organs with either walls or large surface-to-volume ratios. Clearly, these errors will increase in magnitude as one looks at the smaller phantoms in the series. In this work, the Cristy and Eckerman phantoms are being coupled to the electron-photon transport code EGS4 with the ultimate goal of generating a complete set of electron absorbed fractions of energy for all relevant source-target combinations in each of the six phantoms. This data set will then be used to produce a revised set of S values for publication through the MIRD committee and for use by the nuclear medicine community.

Progress Report

Head Region

The original plan for coding the phantoms was to start at the top of the head of the phantom and work down to the legs. The head has therefore been coded successfully, including an elliptical and cylindrical section of the head, the skin covering the outer head region, the elliptical brain surrounded by the elliptical cranium, the concentric cylinder facial skeleton, the cylindrical section of the spine and the thyroid.

Initial efforts were directed to verify the new FORTRAN coding by comparing values calculated with EGS4 to those published by ORNL. Figs. 1 and 2 show the comparison of SAF values for photon sources contained within the thyroid and brain of the adult male phantom. All values calculated with EGS4 fall within 8% of the data published by ORNL. Fig. 3 shows a comparison of SAF values where the target is not the same as the source. All of the EGS4 values shown in Figure 3 fall within the error bars produced with the coefficient of variation of the ORNL data.

Fig. 1. Comparison of photon specific absorbed fractions using the thyroid as the source and target region.

Fig. 2. Comparison of photon specific absorbed fractions using the brain as the source and target region.

Fig. 3. Comparison of photon specific absorbed fractions using the thyroid as the source region and the brain as the target region.

All values previously shown were calculated without considering the explicit transport of the secondary particles. In this case, once an electron is created in a photon interaction, it is assumed to deposit all its initial kinetic energy at the interaction site. An additional set of calculations with EGS4 which included charged particle transport revealed a decrease in the SAF for both the thyroid and brain regions. The decrease in SAF values may be attributed to electrons that escape the source region prior to complete deposition of their kinetic energy.

The thyroid and brain regions were also used to demonstrate deviations from the traditional assumption of full energy deposition by electron sources in the source region. Figs. 4 and 5 show the percent decrease in the SAF values calculated with EGS4 as compared to SAF values assuming an AF of unity. This deviation can again be attributed to the escape of electrons from the source/target region without total energy deposition in that region. The deviation increases for higher energy electron sources and lower phantom ages (as average organ size decreases with decreasing age). The complexity of the shape of the source/target region may also contribute to the decrease in SAF values. For example, the brain is a larger, ellipsoidal shape, while the thyroid is a smaller, oddly shaped region.

Fig. 4. Percent decrease in the specific absorbed fraction for electron sources in the thyroid when electron transport is explicitly considered.

Fig. 5. Percent decrease in the specific absorbed fraction for electron sources in the brain when electron transport is explicitly considered.

Trunk Region

The outer elliptical region of the trunk has been coded and was included in the geometry when calculating the SAF values for the brain and thyroid. Within the trunk region, only a few organs remain to be coded. The coding of the GI tract was accomplished as a separate PhD project and is currently being written up for publication.

Much like the stomach contents and walls, several other organs contained within the trunk region are ellipsoidal in shape. The ellipsoidal regions within the trunk include the urinary bladder contents and walls, spleen, thymus, testes and the ovaries. Additional comparisons of photon SAF values to ORNL data for the urinary bladder walls and the ovaries are shown in Figs. 6 and 7. All values calculated with EGS4 fall within 5% of the ORNL values.

As shown in values calculated for the head regions, Fig. 8 shows the deviation of AF values using electron sources in various ellipsoidal regions. The largest deviation from the unity AF is shown for the ovaries, which are the smallest regions in the comparison. As the size of the ellipsoidal region increases and the energy of the electrons decreases, the AF value does indeed approach unity. Electron sources were also used to calculate AF values shown in Fig. 9 for the urinary bladder walls. Previous dose estimates assume that the specific absorbed fraction of the bladder is given as $1 / (2 m_{\text{contents}})$; consequently, the absorbed fraction to the wall for electron source must be simply the ratio of the wall mass to the contents mass. For the adult male phantom, this ratio is 0.226. Fig. 9 shows a large deviations from this assumption, particularly at the lower electron energies.

Coding of the remainder of the organs within the trunk regions is simplified by the macro routines (much like a FORTRAN subroutine) already developed for the work performed to date. The following is a list of regions to be coded in the near future:

- Skeleton (arm bones, pelvis, spine, rib cage, clavicles and scapulae)
- Adrenals
- Breasts
- Gall Bladder
- Heart
- Kidneys
- Liver
- Lungs
- Pancreas
- Uterus

Legs and Gonad Regions

The conical leg sections have already been coded into the phantoms. The gonads will be added easily by utilizing the previously mentioned macros.

Fig. 6. Comparison of photon specific absorbed fractions with the urinary bladder contents as the source region and the bladder wall as the target region.

Fig. 7. Comparison of photon specific absorbed fractions for the ovaries as both a source and target region.

Fig. 8. Electron absorbed fractions for various ellipsoidal source regions as compared to the assumed value of unity traditionally used in internal dosimetry calculations.

Fig. 9. Electron absorbed fractions for the urinary bladder wall from electron sources in the bladder contents.

Current Status and Research Direction

At the present time, Task 1 is proceeding on schedule with no changes in the originally proposed direction of research. Progress reports have been given regularly to the MIRD committee through the MIRD Task Group on Dosimetric Models for Pediatric Phantoms of which the PI serves as Task Group Leader. It is anticipated that the full coding of the entire family of phantoms will be complete prior to the March 1995 meeting of the committee at which time production runs will have been underway. At the committee's suggestion, the electron absorbed fraction data base will be generated first for the adult male phantom. Production of a full set for all phantoms is expected to be completed sometime within the first half of the third year of the project. When complete, the project team will compile a full set of revised S values for subsequent publication as a MIRD monograph.

References

Cristy, M.; Eckerman, K. F.; Specific absorbed fractions of energy at various ages from internal photon sources. I. Methods. Oak Ridge National Laboratory, ORNL/NUREG/TM-8381; Vol. 1; 1987.

Stabin, M.G.; Watson, E. E.; and Bolch, W. E.; MIRDOSE2 computer program. Radiation Internal Dose Information Center, Oak Ridge Associated Universities, 1984.

Task 2 - An Improved Dosimetric Model of the Head and Brain

Task Summary

The goal of this research task is to develop an improved and more detailed dosimetric model of the brain coupled with an improved model of the head region as developed previously by the MIRD committee. Nuclear medicine imaging of the brain via PET and SPECT has expanded tremendously over the past several years. As the localization of the agents within the brain becomes more and more specific to the metabolic or physiological functions being investigated, the dosimetry of the brain and surrounding organs in the head become increasingly outdated. Brain models previously developed by Eckerman et al. (1980) and Poston (1984) have improved brain dosimetry only in regard to a differentiation of gray and white matter. It is the goal of this research to develop an improved model of the brain which further differentiates the basal ganglia, the ventricle systems, and the cerebellum.

Progress Report

We are pleased to report that the work in this task has been accelerated and that the development and calculations for the improved head and brain model for the 70-kg phantom is essentially complete (approximately one year ahead of schedule). As described below, we will use this opportunity to extend this work and develop a complimentary series of improved head and brain phantoms for the remaining five phantoms of the Cristy and Eckerman series.

Fig. 10 gives a graphical display of the improved brain model. In green are shown the interior ventricular systems of the brain. The two lateral ventricles are modeled as two right circular cylinders 5-cm in length. The third ventricle is modeled as a narrow elliptical cylinder situated below and between the lateral ventricles. Upon the advice from the MIRD committee, the basal ganglia have been subdivided into the caudate nuclei (shown in red) and the lentiform nuclei (shown in blue). Each caudate nucleus is modeled as the combination of a right circular cylinder 3.55-cm in length and a sphere 0.75-cm in radius representing the head of each caudate nucleus. The lentiform nuclei (putamen plus the globus pallidus) are modeled as two ellipsoids minus the intersecting regions of the caudate nucleus and the thalamus (shown in yellow). The (x,y,z) coordinate axes of each ellipsoid are 1.0, 1.9, and 1.5 cm, respectively. The thalamus is also modeled as two ellipsoids, one in each cerebral hemisphere. The (x,y,z) coordinate axes of these ellipsoids are 0.65, 1.0, and 1.0 cm, respectively.

The cerebral cortex is modeled as a 1.0-cm thick layer of gray matter defined by two half ellipsoids. The bottom ellipsoid is cut by an inclined plane allowing for improved modeling of the upper facial skeleton. The cerebellum (shown in blue) is thus formed as a "shelf" lying in the lower anterior portion of the brain. A 1.0-cm layer of the gray matter covers the cerebellum. In addition, two adjoining 1.0-cm layers of gray matter are shown penetrate the interior of the brain at the longitudinal cerebral fissure. The white matter region is considered to be the total region bounded by the gray matter region, minus the interior structures.

Fig. 10. View of the interior structures of the brain model.

Combined views of both the improved brain and head models are shown in Fig. 11 (lateral view) and Fig. 12 (frontal view). The spine includes three regions: an outer vertebral bone region (magenta), a region of cerebrospinal fluid (green), an interior spinal tissue region (pink). Below the cranium (light brown) is a CSF region of the subarachnoid space (not shown) which surrounds the cerebral cortex. Table 1 lists all source/target regions of the head and brain model along with their total volumes.

Table 1
List of the regions within the head and brain model

Region	Volume (cm ³)
Brain	1467.6
Caudate Nucleus	10.50
Cerebellum	139.14
Cerebral Cortex	622.36
CSF in Skull	56.90
Eyes	15.2
Head	4032.71
Lateral Ventricles	20.10
Lentiform Nucleus	19.44
Mandibles	170.5
Neck	567.37
Skin	280.13
Skull	364.57
Spinal Column	14.92
Spinal CSF	6.75
Spinal Skeleton	111.77
Teeth	31.17
Thalamus	6.45
Third Ventricle	1.244
Thyroid	19.89
Upper Face Region	265.54
White Matter	648.36

Electron and photon transport has been performed within the head and brain model for particles in the energy range 10 keV to 4 MeV. Tables of absorbed fractions, specific absorbed fractions, and their coefficients of variation have been generated for all source-target combinations. Figs. 13 and 14 display calculated values self-absorbed fractions for various source regions in the brain containing photon and electron sources, respectively. The latter figure clearly indicates that the traditional assumption of an AF of unity for electron sources in the source region become invalid at energies of only a few 100 keV and lead to large errors for higher energy electrons exceeding 1 MeV. Figs. 15 and 16 show corresponding data for other source regions within the head model.

Fig. 11. Lateral view of the head and brain model.

Fig. 12. Frontal view of the head and brain model.

Finally, S values have been generated for the following radionuclides and source regions:

Radionuclides for source regions within the brain:

^{11}C , ^{13}N , ^{15}O , ^{18}F , ^{57}Cu , ^{62}Cu , ^{64}Cu , ^{67}Cu , ^{76}Br , ^{82}Rb , ^{85}Kr , $^{99\text{m}}\text{Tc}$, ^{122}I , ^{123}I , ^{133}Xe , ^{197}Hg , and ^{203}Hg

Radionuclides for sources regions in the skull and spinal skeleton:

^{32}P , ^{33}P , ^{89}Sr , ^{90}Sr , ^{90}Y , $^{99\text{m}}\text{Tc}$, ^{131}Cs , ^{131}I , ^{153}Sm , ^{186}Re , ^{188}Re , and ^{226}Ra

Radionuclides for the thyroid as the source region:

$^{99\text{m}}\text{Tc}$, ^{122}I , ^{123}I , ^{125}I , ^{126}I , ^{129}I , ^{130}I , ^{131}I , ^{132}I , $^{132\text{m}}\text{I}$, ^{133}I

Fig. 13. Self-absorbed fractions for photon sources located within the brain.

Current Status and Research Direction

At the present time, photon and electron transport calculations are complete and positron transport calculations are in progress. In the evaluation of S values for positron emitters (e.g., ^{11}C , ^{13}N , ^{15}O , ^{18}F , and ^{82}Rb), positron absorbed fractions were assumed to equal those of equivalent-energy beta particles with additional consideration of the 511-keV annihilation photon contributions. This assumption may not be valid for the smaller structures of the brain in that photon absorbed fractions for 511-keV photons created at sites of annihilation may differ from that assuming a uniform distribution of 511-keV photon emissions in the source

Fig. 13. Self-absorbed fractions for electron sources located within the brain.

Fig. 15. Self-absorbed fractions for photon sources located within the head.

Fig. 16. Self-absorbed fractions for electrons sources located within the head.

region. Comparisons between these two sets of absorbed fractions will be made once the transport calculations are complete. If differences are noted, we will propose to treat positrons separately from beta particles in calculations of radionuclide S values.

With accelerated progress in this particular task, opportunities now exist to extend the adult head and brain model to the remaining five pediatric phantoms in the Cristy and Eckerman series. Beginning this spring, research contacts at the University of Florida's College of Medicine will be established for the purpose of collecting MRI and CT head and brain images of younger patients. These images will then be used to scale and/or modify the adult head and brain model in the development of head and brain models for the pediatric series of phantoms.

References

- Cristy, M.; Eckerman, K. F., and Warner, G. G.; Dosimetric evaluation of brain scanning agents. Proceedings of the Third International Radiopharmaceutical Dosimetry Symposium; October 1980.
- Poston, J. W.; Research on the experimental verification of dosimetry calculations. Research Progress Report. DOE Report DE-AS05-790EV10248; June 1984.

Task 3 - An Improved Dosimetric Model of Trabecular Bone

Task Summary

Assessment of electron absorbed fractions of energy in trabecular bone is one of the more difficult, yet important, areas of internal dosimetry. In this task, a spherical shell model of trabecular bone has been developed based upon the marrow cavity and trabeculae chord length distributions as measured by Spiers and his colleagues (Beddoe et al. 1976). Using the electron transport code EGS4, electrons are born within one of three source regions: marrow, bone surface, or bone volume. Cavity sets of random created during electron transport where each consists of a sphere of marrow (whose size is selected from the Spiers marrow distributions), a 10- μ m layer of endosteum, and a sphere of bone matrix (whose size is selected from the Spiers trabeculae distributions). Transport calculations are performed for each of nine sites within the skeleton; consequently, this data should be of importance in performing site specific dosimetry as part of bone pain radionuclide therapy. Realistic skeletal averages of marrow and bone surface dose can also be realized using improved S values generated with these new AF data.

Progress Report

At the present time, Task 3 is approximately 3-4 months ahead of the originally proposed schedule. Electron transport simulations are complete and revised S values have been calculated for the following list of radionuclides:

^{32}P , ^{33}P , ^{45}Ca , ^{49}Sc , ^{89}Sr , ^{90}Sr , ^{90}Y , $^{115\text{m}}\text{Cd}$, and ^{143}Pr .

Photon transport in this model has yet to be initiated; consequently, this preliminary list is restricted to only those radionuclides of interest in bone dosimetry which have no or relatively small photon emissions.

Model estimates of electron absorbed fractions of energy in trabecular bone are shown in Figs. 17 - 22 for the electron sources in the marrow, bone surface, and bone volume, and for marrow and endosteum as target regions. Figs. 18 and 19 both show that the ICRP 30 method of assessing electron absorbed fraction of energy to the marrow for both surface and volume sources, respectively, greatly overestimates the dose to marrow for electrons of small initial energies at all skeletal sites. At high electron energies, the ICRP 30 method underestimates the dose to marrow for those skeletal sites with relatively large cavity size distributions (e.g., sacrum and thoracic vertebrae). Nevertheless, it continues to overestimate dose to marrow for skeletal sites with small cavity size distributions (e.g., parietal bone). Figs. 21 and 22 indicate that the ICRP 30 methodology generally underestimates the absorbed fraction of energy to endosteum for electron sources on the bone surface and in the bone volume, respectively. ICRP 30 does not consider marrow sources and thus no comparisons can be made in this case.

(Fig. 17)

Absorbed Fractions in the Marrow for Marrow Sources

(Fig. 18)

Absorbed Fractions in the Marrow for Surface Sources

(Fig. 19)

Absorbed Fractions in the Marrow for Volume Sources

(Fig. 20)

Absorbed Fractions in the Endosteum for Marrow Sources

(Fig. 21)

Absorbed Fractions in the Endosteum for Surface Sources

(Fig. 22)

Absorbed Fractions in the Endosteum for Volume Sources

Current Status and Research Direction

Since early summer of 1994, we have been collaborating with Dr. Keith Eckerman at ORNL who has been kind enough to give us the original cavity size distributions of Spiers. It is our understanding that the Dr. Eckerman has been looking at this problem since the early 1980's and has recently completed a revision to one-dimensional model of electron energy loss originally performed by Spiers. He has been very supportive of this research task. Our immediate plans are to first publish this work in the Journal of Nuclear Medicine, followed by a detailed comparison of our three-dimensional electron transport estimates of electron AF values in trabecular bone with those of Dr. Eckerman's one-dimensional, CSDA estimates. This comparison is also of extreme interest to the MIRD Committee and its Task Group on Trabecular Bone Dosimetry of which the PI currently serves as Task Group Leader.

Two major extensions of this work will be pursued over the remaining two years of the grant. First, contacts within the medical bone research community will be made to see if newer data on cavity size distributions within the skeleton and for various pediatric ages are available. It must be remembered that the distributions used in this and other dosimetry studies are solely based upon the single sets of measurements made by Spiers and his students in the late 1960's. Second, the photon transport within the spherical shell model will be initiated. At this point, however, the microscopic shell model must be coupled within the macroscopic skeleton model of the Cristy and Eckerman phantoms. This coupling of the pediatric phantom work of Task 1 with the shell model of Task 3 is essential to correctly estimate absorbed fractions to marrow and endosteum, not only from photon sources within trabecular bone, but from photon source elsewhere in the body.

References

Beddoe, A. H.; Darley, P.J.; Spiers, F. W. Measurement of trabecular bone structure in man. *Phys. in Med. and Biol.* 21 (4): 589-607; 1976.

Task 4 - Experimental Determination of Organ Absorbed-Dose Distributions

Task Summary

This task represents the experimental component of the project in which tissue-equivalent materials are investigated for the source of experimentally verifying calculational estimates of photon absorbed fractions for internal sources. In a letter to Dean Cole dated February 1, 1994, we had indicated the awarding of our 3-year proposal at funding levels below that originally requested would require us to discontinue both Tasks 4 and 6 within our project commitment to DOE. Fortunately, a graduate student funded through DOE's Applied Health Physics Fellowship program had agreed to pursue this line of research. Consequently, we are pleased to report limited progress in this area.

Progress Report

The development of a volumetric dosimeter has proceeded consisting of a 100 mL sphere comprised of 90% water and 10% gelatin by mass. Dose information from the sphere is gathered by a 0.1%-0.5% mass of TLD-100 powder (93% ^6Li and 7% ^7Li). Use of this powder provides a linear response over a wide range of photon energies while maintaining the tissue-equivalency of the gelatin mixture. A source sphere of an identical geometry will provide for energy deposition in the target mold. Both the source and target molds will be placed into a large polyethylene container filled with distilled water for a five-day exposure period.

Preliminary assessments have been performed in the following areas prior to creating an actual dosimeter. These assessments have included:

(1) A homogeneity check of the TLD/gelatin mass throughout the sphere.

The homogeneity results have been encouraging, with the TLD/gelatin ratio varying by only $\pm 0.15\%$ throughout the target mold.

(2) An evaluation of the procedures employed by Spence (1993).

The majority of the methods employed in the feasibility study work very well; however, improvements have been made in the methods used to establish TLD mass in the target mold and molding techniques. Although much of the work done by Spence (1993) could be directly applied to the development of a spherical volumetric dosimeter, some important topics were not addressed in this master's thesis. These include:

(3) Developing a procedure for employing the gelatin mixture in an enclosed volume.

This work was vital because the mold created by Spence (1993) was an open 100 mL beaker. If the gelatin was to be used as a volumetric dosimeter, the mixture had to be capable of being formed into any desired shape. A procedure has been developed that makes this possible.

(4) Developing a procedure for constructing a spherical source volume.

The source volume will be created in the same way as the target; however, distilled water used in the target will be replaced with an equal volume of ^{137}Cs solution for absorbed fraction measurements and ^{90}Sr for dose profile information. Since the geometry being investigated is a separate source/target configuration, no TLD-100 powder will be placed into the source organ.

(5) Improving the TLD recovery procedure.

Spence (1993) utilized an Erlenmeyer flask assembly that resulted in losses due to crystal deposition. A new vacuum filtration system is being employed to eliminate these losses and improve the recovery of TLD crystals.

(6) Investigating methods of minimizing TLD losses during dosimeter preparation, molding, and recovery.

The main focus of this work has been to identify a suitable substitute for water as an agent for dissolving the gelatin during recovery. The procedure employed by Spence (1993) used hot water for this purpose which probably resulted in a loss of some recorded dose information (lithium fluoride has a solubility of 0.27 g per 100 mL of water). Since lithium fluoride is insoluble in alcohol, this liquid seemed to be the obvious choice for a dissolving agent; however, a pure alcohol cannot be used because it reacts with the gelatin. A 60%/40% mixture of water to alcohol by volume eliminated the reaction problem while providing an improvement over the use of pure water.

(6) Producing a calibration curve that will equate the amount of charge collected by the TLD to an absorbed dose.

This curve is necessary to establish the response of the TLD powder. Until this calibration has been accomplished, no useful dose information can be obtained for photons or charged particles.

The graduate student is currently in the process of procuring the necessary ^{137}Cs and ^{90}Sr for use in the source volume. While he is waiting for the source material, he will be concentrating on developing the photon and beta calibration curves and gaining proficiency on the TLD reader. Following the construction of the source volume, he will begin taking measurements with target spheres at varying distances. The gelatin-based volumetric dosimeter shows great promise for future uses, including verification of Monte Carlo dose estimates and the construction of phantoms to perform internal dose assessments and external beam measurements.

Current Status and Research Direction

At the present time, the target sphere irradiations using a ^{137}Cs gelatin-source sphere have been performed at source-to-target distances of 1.0, 2.0, 5.0, and 15.0 cm. Total photon absorbed fractions, as measured by the LiF power have

shown very good agreement with those calculated in EGS4 photon simulations. Statistical analysis of the data is in progress and thus a quantitative statements of the agreement cannot as yet be made. Future work in this area should include: (1) assessment of target region dose contours via the LiF TLD powder measurements of gelatin slices; (2) measurement of self-absorbed fractions for source regions containing pure beta-emitting radionuclides; and (3) investigations of gelatin-tissue-equivalent materials in the fabrication of physical phantoms of the Cristy and Eckerman pediatric series. These investigations, however, will only be pursued to the extent that additional sources of funding or student support are available.

References

Spence, J. L.; Development of a Tissue Equivalent Phantom Material. Master's Thesis, Texas A&M University, 1993.

Task 5 - Microdosimetry of Beta Emitters in Radioimmunotherapy

Task Summary

The goal of this particular task is the develop, for the first time, a microdosimetry scheme for assessing distributions of absorbed dose to subcellular targets irradiated by electrons and beta particles. At the present time, microdosimetry studies of internal emitters have been limited to looking at only alpha particles; no comprehensive microdosimetric studies of internal beta-particle sources has been pursued. Specific applications of this work have been directed toward radioimmunotherapy, although the techniques are valid and useful for assessing dose distribution within any source region containing a nonuniform distribution of beta emitters.

Progress Report

Task 4A: Monoenergetic Single Event Densities

Calculations of single event densities have been completed for discrete parametric values of electron energy and target distance from a point electron source. The discrete values for electron energies are 25 keV, 50 keV, 100 keV, 200 keV, 500 keV, 1 MeV, 2 MeV and 2.5 MeV. The discrete values for target distance include 0.5 mm and every one-tenth of the nominal CSDA range corresponding to the electron energy (i.e., 0.1 to 1.2 times of the CSDA range). In a previous progress report, the shift of the most probable specific energy toward higher values was observed as the target is located farther from the source point. In addition, the extent of the shift has been observed to decrease with the electron energy.

Task 4B: Monoenergetic Specific Energy Distributions

The calculations of specific energy distribution have been completed for the same parametric combinations of electron energy and the target distance as for the single event density calculations. The convolutions to generate the multiple event density functions from single event density functions were carried out by generic method, shown as in Eq. (1), rather than by applying Fourier transformation. The Poisson distribution in Eq. (2) was assumed for the probability function of the number events; the specific energy distributions are the results of overall contributions as described in Eq. (3).

$$f_n(z,r,E) = f_1(z,r,E) * f_{n-1}(z,r,E) = \int_0^z f_1(z-z',r,E) f_{n-1}(z',r,E) dz' \quad (1)$$

$$P_n(r,E) = \frac{e^{-M(r,E)} M(r,E)^n}{n!} \quad (2)$$

$$f(z,r,E) = \sum_{n=0}^{\infty} P_n(r,E) f_n(z,r,E) \quad (3)$$

A common trend has been observed in the specific energy distributions for 8 discrete energies and up to 12 scaled distances for each energy. The specific energy distributions for 25-keV electrons are shown in Figs. 1 and 2. The fact that the specific energy distribution becomes narrower with greater source intensity is reasonable. At high source intensities, specific energy distributions in semi-logarithmic scale appear as Poisson distributions. The geometric mean of the specific energy increases by the same order of magnitude as the increase in source intensity beyond certain ranges of specific energy.

Fig. 23. Specific energy distributions for 10^3 emissions of 25-keV electrons.

Fig. 24. Specific energy distributions at $0.1R_{csda}$ for 25-keV electrons.

Task 4C: Beta-Particle Specific Energy Distributions

Analytic equations have been generated for monoenergetic point kernels in the form of a specific energy distribution as a function of electron energy E , target distance r , and the mean number of events $M(r,E)$ [i.e., $f(z,r,E;M)$]. The event probability, $w(r,E)$, also has been analytically described. By applying the analytic equations in calculating monoenergetic point kernels based on the spectral distribution of electron energy in the beta spectra, beta point kernels for ^{131}I and ^{90}Y have been generated. The relations described in Eqs. (4) to (6) are applied in this procedure. The effect of source intensity on the distribution has also been evaluated.

$$N(r,E) = g(E) A(r) \quad (4)$$

$$M(r,E) = \omega(r,E) N(E) \quad (5)$$

$$f[z,r;A(r)] = f[z,r,E_1;M(r,E_1)] * f[z,r,E_2;M(r,E_2)] * \dots * f[z,r,E_{imax};M(r,E_{imax})] \quad (6)$$

Examples of beta point kernels are shown in Figs. 25 to 28 for ^{131}I and for ^{90}Y .

Fig. 25. Specific energy distributions at various target distances for 10^6 emissions of ^{131}I .

Fig. 26. Specific energy distributions at various target distances for 10^9 emissions of ^{90}Y .

Fig. 26. Specific energy distributions at a target distance of 200 mm for ^{131}I at various values of cumulated activities ($\tilde{A}$).

Fig. 28. Specific energy distributions at a target distance 4000 mm for ^{90}Y at various values of cumulated activities ($\tilde{A}$).

Task 4D: Applications of Beta Point Kernels to Distributed Source Problems

A spherical model of tumor and surrounding normal tissue as shown in Fig. 29 was used to describe distributed source problems. The contributions of discrete source volumes to the dose of a target are combined by convolutions:

$$f(z) = f(z, x_1; A_1) * f(z, x_2; A_2) * \dots * f(z, x_n; A_n), \quad (7)$$

where A_i is the cumulated activity at a discrete source volume around the distance x_i from the target.

Fig. 29. A spherical model of tumor and surrounding normal tissues.

Both uniform and exponentially decreasing (surface-to-center) source distributions in model tumors were considered. Fig. 30 shows the mean specific energy from the specific energy distribution at various target locations for ^{131}I and ^{90}Y ; the total cumulated activity in 1-cm diameter tumor is 10^{10} transformations. The difference due to tumor size in the spatial distribution of mean specific energy also has been investigated with a 0.1-cm diameter tumor as shown in Fig. 31.

Fig. 30. The mean specific energy at various target locations for 10^{10} transformations within 1-cm diameter tumor.

Fig. 31. The mean specific energy at various target locations for 10^7 total transformations within a 0.1-cm diameter tumor.

Current Status and Research Direction

Based upon the originally proposed schedule of activities, Task 5 is shown to be proceeding approximately nine months ahead of schedule. The entire calculational scheme is projected to be completed within the first half of the second year of the grant with two to three papers being submitted for publication prior to that time. The remainder of the grant period will be used to investigate coupling this calculational method with autoradiography data from animal studies of antibody uptake and distribution. This portion of the research will be performed in collaboration with Dr. Barry Wessels of George Washington University through his membership on the MIRD Committee.

While autoradiography represents a data source for which the microdosimetric method can be directed applied (~ 50- μ m source resolution), the more immediate need in clinical nuclear medicine studies has been the rapid application of the MIRD schema to SPECT data (~ 4-6 mm resolution). To address this need, it is proposed that EGS4 electron and low-energy photon transport calculations be initiated under Task 5 for a cubical array of tissue-equivalent target cubes 4-6 mm on a side with a centrally located source cube. Data generated from these simulations will be used to report AFs, SAFs and subsequently S values for various radionuclides which can then be coupled with SPECT imaging data on cumulated activity at the same level of resolution. Dose distributions could then be generated easily through a simply matrix multiplication of S values and $\bar{A}$ values. This extension of Task 5 will be performed in collaboration with members of the MIRD Task Group on Nonuniform Dosimetry.

Task 6 - Mechanisms of Radiation Damage to DNA

Task Summary

The research proposed in this task represents an innovative approach to evaluating currently suggested mechanisms of radiation damage to DNA from the indirect action of charged particles. State-of-the-art Monte Carlo computer codes are used to simulate the formation, diffusion, and chemical reaction of various free radical species within electron and alpha-particle tracks produced in the vicinity of simple DNA molecules. Reactions describing free radical attack at specific sites on the DNA molecule are incorporated into the computer model. This computational capability enables the simulation of specific irradiation experiments on a nanometer spatial scale and on a nanosecond temporal scale. Comparisons between calculated yields and reported measured yields of DNA damage products provide a unique and independent test for these reactions schemes. In addition, the computer model, once developed, will enable investigations of the dependence of DNA damage upon changes in irradiation conditions (dose rate and charged-particle track structure), and the DNA's chemical environment (presence of dissolved oxygen and free radical scavengers). The effects of such changes are relevant to our understanding of the oxygen effect, threshold doses, and the effectiveness of radioprotectors.

Progress Report

As with Task 4, developments in this particular research task have been slowed as a result of award levels approved below those originally requested. Modeling efforts have proceeded at modest levels slightly behind the proposed schedule of activities. At present, a preliminary model of single-stranded polyuridylic acid [poly(U)] has been developed which will be used to simulate the experimental work of von Sonntag and Schulte-Frohlinde (von Sonntag 1987). Additional models are to be developed for single-stranded poly(dT) and double-stranded poly(dT)-poly(dA) for comparison with data measured by Karam et al. (1986, 1988).

Current Status and Research Direction

No specific changes are proposed in the research direction of this task.

References

- Karam, L. R. Effects of Ionizing Radiation on Polydeoxythymidylic Acid and Polydeoxyadenylic Acid•polydeoxythymidylic Acid as Models for DNA Damage. Ph.D dissertation, American University, Washington D.C.; 1988.
- Karam, L. R.; Simic, M. G.; Dizdaroglu, M. Free radical-induced cross-linking of polydeoxythymidylic acid in deoxygenated aqueous solution. *Int. J. Radiat. Biol.* 49(1):67-75:1986.
- von Sonntag, C., *The Chemical Basis of Radiation Biology*, Taylor & Francis, New York, 1987.

PROJECT OUTPUT

Refereed Technical Journals (published)

- R. H. Ritchie and Wesley E. Bolch, "Aloof-Trajectory Interactions of Low-Energy Electrons with Condensed Matter," *Radiat. Prot. Dosim.* **52**, 135-138 (1994)
- Wesley E. Bolch and Eun-Hee Kim, "Calculations of Electron Single-Event Distributions for Use in Internal Beta Microdosimetry," *Radiat. Prot. Dosim.* **52**, 77-80 (1994).
- M. G. Stabin, J. E. Turner, R. N. Hamm, and W. E. Bolch, "Track Structure Simulation and Determination of Product Yields in the Radiolysis of Water Containing Various Solutes," *Radiat. Prot. Dosim.* **52**, 255-258 (1994).

Refereed Technical Journals (submitted)

- O. R. Hernandez, W. E. Bolch, and J. W. Poston, Sr., "A Linear Time-Varying Simulation of the Respiratory Tract for the Inhalation of Radioactive Aerosols," (submitted to Health Physics).

Refereed Technical Journals (in development)

- L. S. Bouchet, W. E. Bolch, D. A. Weber, H. L. Atkins, and J. W. Poston, Sr., "An Improved Dosimetric Model of the Adult Head and Brain," (for submission to the J. Nucl. Med.).
- J. W. Poston, Jr., K. A. Kodimer, W. E. Bolch, and J. W. Poston, Sr., "A Revised Dosimetric Model of the Gastrointestinal Tract", (for submission to the J. Nucl. Med.).
- R. A. Parry, W. E. Bolch, and J. W. Poston, Sr., "Monte Carlo Estimates of S-Values for Bone-Seeking Beta Emitters", (for submission to the J. Nucl. Med.).
- E. H. Kim, W. E. Bolch, W. D. Reece, and J. W. Poston, Sr., "A Microscopic Approach in Cellular Dose Calculations for Electron Sources," (for submission to Med. Phys.).
- S. Calvo, K. F. Eckerman, and W. E. Bolch, "Estimates of Electron Absorbed Fractions of Energy for the Upper Respiratory Tract," (for submission to the J. Nucl. Med.).

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C. Contact (Person knowledgeable of content)

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Phone 409-845-4138

Position Principal Investigator

Organization TAMU

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