RADIATION DOSIMETRY

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INTRODUCTION

Radiation dosimetry depends on the accumulated knowledge in nuclear science in general and in nuclear and radio chemistry in particular. The latter is concerned with the study of the inner workings of radioactive atomic nuclei and their interaction with inert and biological matter.

Earlier on, nuclear and radio chemistry was involved with the understanding of the behavior of fission and fusion products, and the protection against radiation in the design of nuclear weapons. This evolved into research in the service of the nuclear power industry, maintaining the nuclear stockpile and the applications of radiotherapy and nuclear medicine.

NEW MODALITIES

Fascinating new directions are taking shape for the future. New molecules are being tagged with radioactive isotopes to deliver deadly radiation straight to cancer cells that may have metastasized or spread throughout the body.

Conventional radiation beam therapy works well in the case of well localized cancer, but he use of Synthetic High affinity Ligands (SHALs) and monoclonal antibodies, promises the reaching of the Holy Grail of cancer treatment in the form of a magic or silver bullet directly delivered to the sites of tumors.

The same compounds targeting the tumors can also be used with imaging techniques to identify the locations of tumors in the body. New detectors are being designed to use the radioisotope tagged molecules to reveal the locations of cancer cells.

New mass spectroscopy techniques are observing how isotopes interact with human cells.

Radiation transport methodologies such as Monte Carlo methods are being linked to nuclear data libraries in for planning radiation beam therapy.

Programs in safeguards, nonproliferation and homeland security are evolving to meet the demands of a changing world. Scientists are called to detect minute amounts of radiation and to manage the consequences of radiological events. In this regard, radiological detectors large and small, permanently installed and hand held are being developed. New technologies for detecting gamma radiation and neutron emissions are under development.

Another promising area of endeavor involves the measurement of the ways the human body responds to small doses of radiation. With a better understanding of the effects of radiation on living tissue, medical personnel will be able to measure the dose received and intervene before the treated individuals become sick and die. The objective is to treat the human body as a walking dosimeter. If the concept of radiation preconditioning or even the controversial radiation hormesis idea are understood or become realities, thousands of lives could be saved, in what is the prime national and international health issue of cancer prevention and treatment.

SCOPE OF RADIATION DOSIMETRY

In radiation dosimetry we are concerned with the transport and interaction of ionizing radiation in matter. We start with a radiation source S, and consider a material M interposed between it and a detector D. The radiation from the source interacts with the interposing material before arriving at the detector.

The material M could be inert. In that case it is treated as a shield, and the objective is to design it in such a way so as to shape the radiation field before its arrival at the detector D. The material could be biological in nature, and the task becomes the assessment of the biological effects in the intervening material and how the radiation would affect the detector D, which could be a lesion or a tumor.

Attenuation and absorption are important in shielding and in radiotherapy and radiation processing where the aim is to deliver a precise amount of dose of radiation to a sample or tumor.

Radiation can be in the form electromagnetic radiation as x rays or gamma rays. It could also be in the form of neutral particles such as neutrons, or in the form of charged particles such as electrons, protons or alpha particles. Their effects and penetration in various materials, including the human body and its different constituents must be considered.

The damaging or beneficial potential of radiation of ionizing radiation is what is designated as dosimetry. The biological effect of radiation is related to the energy deposited by ionization in a mass of tissue, or the absorbed dose. This is modified by several factors including:

1. The microscopic spatial distribution of the ionizations,
2. The concentration of oxygen, described by the oxygen enhancement ratio, OER,
3. The rate of energy deposition,
4. The type of radiation,
5. The response of the biological material to the ionization created in it.

Neutrons damage in metals is related to the displacements per atom (dpa) and vacancies created by neutron collisions with the nuclei. It also creates transmutations by nuclear reactions leading to activation of the materials. Hydrogen and helium nuclei can be generated in the lattice, leading to volumetric deformation and swelling. Embrittlement of steel correlates with the neutron fluence with neutron energies above 1 MeV, which is a major consideration in designing future breeder or fusion reactors.

In experimental and theoretical investigations, the energy spectrum of the particles is obtained and then convoluted with an energy dependent response function to get estimates of different reaction rates. Thus the dosimetry task involves both the methods of calculating the spectrum and of calculating the response function or dose.

DOSIMETRY PROBLEM

Several steps are involved in a dosimetry problem:

1. **Source specification**, including its strength, energy spectrum, angular distribution, spatial distribution and time distribution.
2. **Specification of geometry** of the source, intervening medium and detector. This includes material compositions and densities. Simplified geometrical configurations are adequate for most applications. In detailed studies detailed models or phantoms are used to account for heterogeneity of the human body or the designed shield. Phantoms are artificial bodies, approximately the size, shape and density of a human body, used for calibrating counters, or for numerical computations. The experimental phantoms are designed so that the radioisotopes they contain have a similar distribution as the isotopes expected in the real body. Figures 1-3 show different phantom configurations.

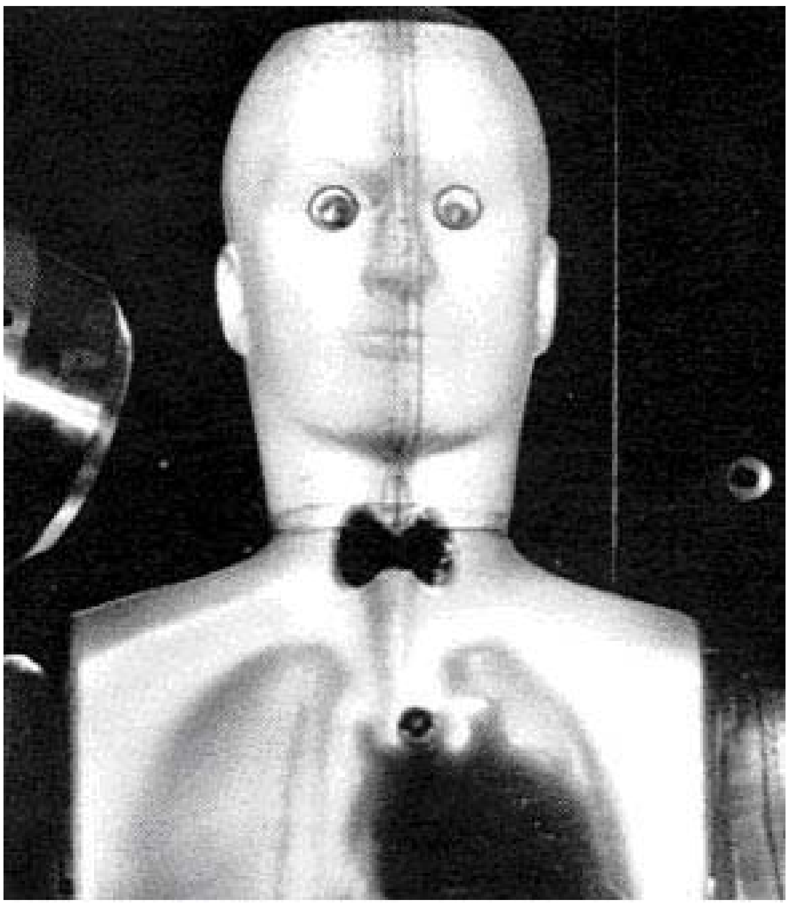

Fig. 1: Human phantom used to study I^{131} in the thyroid gland.

3. **Data mine for the cross sections** for the different interactions from a data warehouse. These could include attenuation coefficients, secondary radiation production, activation cross sections, response functions, and multigroup or point cross sections. The data that is obtained may need to be reduced to a form suitable for the particle transport calculations.

4. **Specify the detectors** locations energy and angular responses according to the purpose of the calculation. Response functions for the calculation of the dose at different locations that are of interest are obtained. Point, surface or volume detectors can be used.
5. **Choose a calculation methodology** analytical, numerical or statistical and an associated computer program to be used in solving the problem based on its complexity and the accuracy desired in the result. A new computer program can be written for the considered problem, or an existing one modified to suit the purpose at hand. The transport of particle is carried out from the source through the intervening materials and at each of the detectors.

Figure 1 is an experimental phantom used to study the radiation spectrum from the thyroid gland area in the neck. The radiation field is determined by a sodium iodide (NaI) scintillation detector from I^{131} in the thyroid used to treat thyroid nodules or Graves syndrome.

In the calculation geometrical model of Fig. 3, the human trunk is modeled by an elliptical cylinder:

$$\left(\frac{x}{20}\right)^2+\left(\frac{y}{10}\right)^2 \leq 1,\ 0 \leq z \leq 70, \tag{1}$$

the head is modeled as;

$$\left(\frac{x}{7}\right)^2+\left(\frac{y}{10}\right)^2 \leq 1,\ 70 \leq z \leq 94, \tag{2}$$

and the legs are modeled as truncated elliptical cone;

$$\left(\frac{x}{20}\right)^2+\left(\frac{y}{10}\right)^2 \leq \left(\frac{z+100}{100}\right)^2 1,\ -80 \leq z < 0. \tag{3}$$

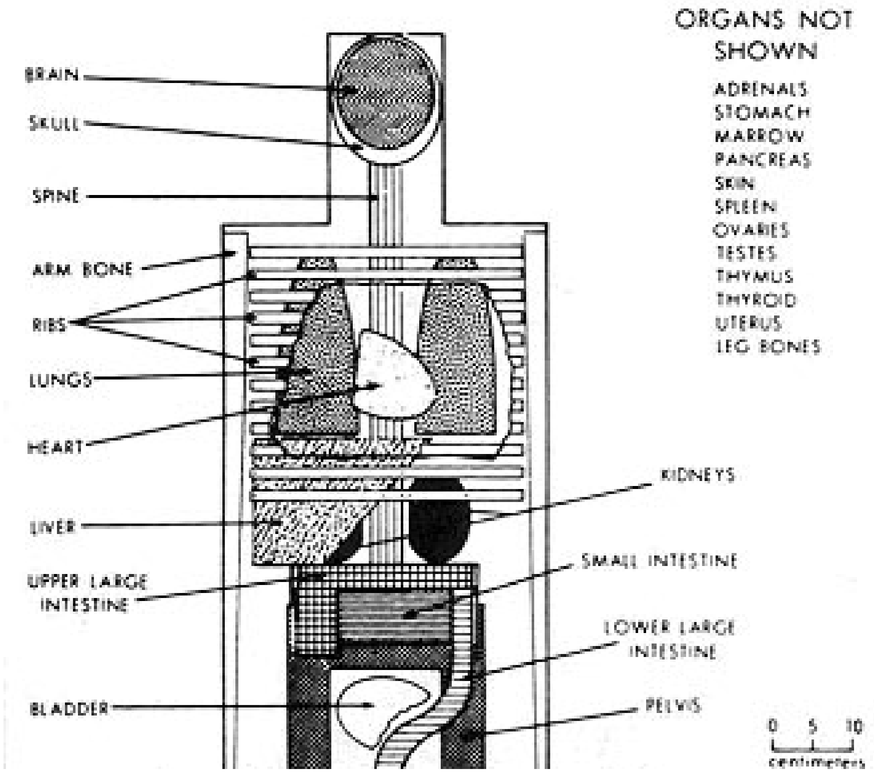

Fig. 2: Anterior view of the principal organs in the head and trunk of human phantom used in the calculation of dose to an organ from radionuclides deposited in another organ.

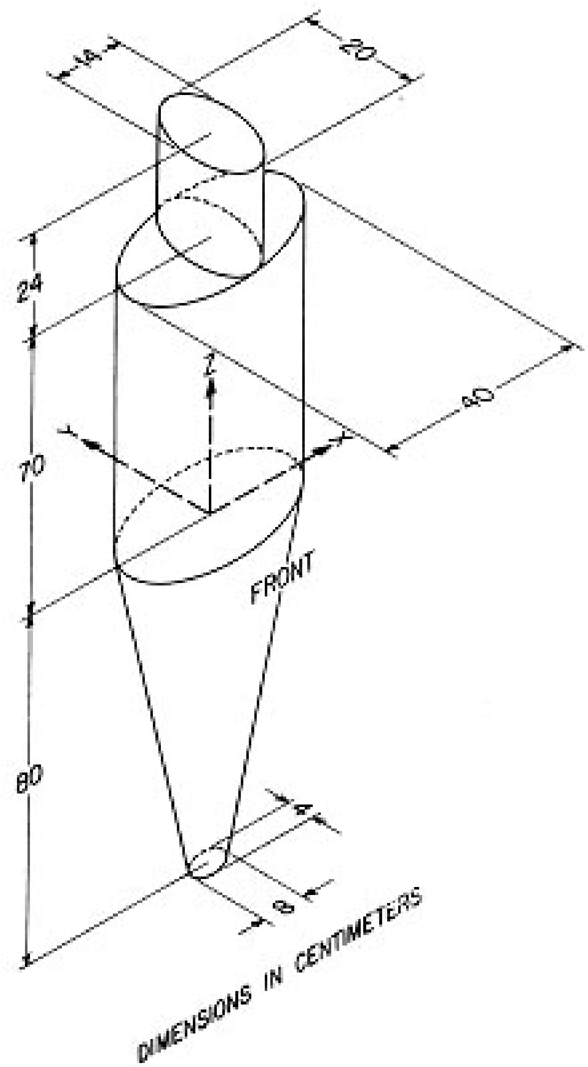

Fig. 3: Adult human phantom geometrical model.

6. **Comparison of calculated response** to the limiting criteria of the problem. This includes maximum allowable doses or regulatory criteria. If necessary modify thre geometries, the design, substitute other materials, and iterate until a satisfactory response is obtained.
7. **Estimation of cost** and other constraints may have to be taken into consideration. The procedure or the shield may have to be optimized. Interplay between the safety of the procedure or shield design and its cost may require modification of the surrounding structures or their shapes. In aerospace and naval applications, space and weight become paramount criteria.
8. **Performance verification** must be undertaken of the dose within the body or the within the shield. Actual measurements may be needed, or the measurements are made in a mockup or a phantom representing the body

NEUMANN SERIES SOLUTION OF THE TRANSPORT EQUATION

Using matrix notation and considering the transport operator T and collision operator C as matrix operators the particle transport equation can be written in terms of the ingoing collision density ψ as:

$$\begin{aligned} \psi &= S_c + H\psi, \\ \psi - H\psi &= S_c, \\ [I - H]\psi &= S_c \end{aligned} \tag{4}$$

where: I is a unit matrix operator,
H=TC is the transport operator,
$S_c = TS$ is the once transported source,
S is the physical source.

Premultiplying by the inverse in Eqn. 4 we get:

$$\begin{aligned} [I-H]^{-1}.[I-H]\psi &= [I-H]^{-1}.S_c \\ I.\psi &= \frac{I}{I-H}.S_c \end{aligned} \tag{5}$$

Using the expansion:

$$\frac{1}{1-x} = 1 + x^2 + x^3 + \ldots \quad , \quad \forall x < 1, \tag{6}$$

Eqn. 5 yields the Neumann series expansion for the ingoing collision density:

$$\begin{aligned} \psi &= [I + H + H^2 + \ldots \ ].S_c \\ &= S_c + (TC)S_c + (TC)^2 S_c + \ldots \quad , \quad \forall \ \rho(TC) < 1. \end{aligned} \tag{7}$$

where the spectral radius of (H = TC) is less than unity.

RESPONSE FUNCTIONS

The accuracy of the dose determination depends on the problem at hand. In radiation therapy an accuracy of 10 percent or better is needed to achieve the required therapeutic response. This is necessary to avoid damaging the intervening tissue between source and detector. In shield calculation a relaxed requirement on the accuracy of 30 percent may be adequate.

The dose or other response function is normally computed as the integral quantity:

$$D = \iint \Sigma_r(\overline{r}, E)\psi(\overline{r}, E) d\overline{r} dE \tag{4}$$

where: D is the dose,

$\psi(\bar{r}, E)$ is the collision density describing the radiation field,
$\Sigma_r(\bar{r}, E)$ is the spacially and energy dependent response function.

Computational methods benefit today from the availability of a multitude of platforms from desktops to supercomputers making radiation transport in realistic three dimensional geometries possible.

DISCUSSION

Doses of radiation to workers and the public are regulated by state and federal agencies and it becomes a matter of professionalism and ethics for the radiation practitioner to abide by these laws and rules.

The recommendations and guidelines of national and international professional groups such as the National Council on Radiation Protection and Measusements (NCRP) and the International Commission on Radiological Protection (ICRP) must be taken into account. Protection of one self, coworkers and the public is a matter of public service and requires the highest level of professionalism and ethics.

EXERCISE

1. Obtain the Neumann series solution of the Transport Equation in terms of the outgoing collision density as:

$$\chi = S + (CT)\chi$$

Compare the solution to that for the ingoing collision density:

$$\psi = S_c + TC\psi, S_c = TS \ .$$

REFERENCES

1. Tomas Diaz de la Rubia, "Calling All Nuclear Scientists," Science and Technology Review, National Nuclear Security Administration, Lawrence Livermore National Laboratory, July/August, 2003.
2. A. Edward Profio, "Radiation Shielding and Dosimetry," Wiley-Interscience, 1979.
3. W. S. Snyder, H. L. Fisher, Jr., M. R. Ford, and G. G. Warner, "Estimates of absorbed dose fractions for monoenergetic photon sources uniformly distributed in various organs of a heterogeneous phantom," Society of Nuclear Medicine, Medical Internal Radiation Dose (MIRD) Pamphlet 5, J. Nucl. Med. Supple. 3, August 1969.
4. John H. Woodburn and Frederick W. Lengemann, "Whole Body Counters," Division of Technical Information, USAEC, 1967.