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WHAT ARE THE CURRENT NEEDS?

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HEALTH PHYSICS INSTRUMENTS: WHAT ARE THE CURRENT NEEDS?

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Summary

Health Physics instruments are used to measure the risk which may be incurred by an individual exposed to a given radiation field. The response of the instrument sensors will differ markedly from actual human risk factors for a variety of reasons, and this requires the use of instrument modifications and conversion factors. The values of these conversion factors continue to be updated and will likely change in the future. To accommodate the effects of different types of radiation and new conversion and usage factors, new instruments should be able to determine the type, energy distribution, and direction of incoming radiation and then apply the proper weighting factors to determine relative human risk. Such instrumentation will need to utilize modern sensor elements and microprocessor electronics.

Introduction

The health risks associated with individual exposures to ionizing radiation are reasonably well-known. The assessment of this risk depends on both the instrumentation needed to quantitate the radiation and a proper interpretation of the indicated results.

Ideally, an instrument would give an indicated response which is directly proportional to the health risks associated with a given radiation exposure. In practice, radiation is detected with a sensor element whose response can differ markedly from living tissue. To further compound the problem, sensitivity of the tissue to radiation effects depends on its location in the body, bodily function, chemical composition, the rate of linear energy transfer of a given radiation, and the relative probabilities for somatic, carcinogenic, or hereditary effects in the given tissue. The variables involved in relating sensor response to human health risk factors are indicated in equation 1:

$$\text{Health Risk} = M \cdot K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \quad (1)$$

where: M = Instrument Reading
K₁ = Detector Response Calibration
K₂ = Energy Deposition in Detector ÷ Detector Response
K₃ = Energy in Tissue ÷ Energy in Detector
K₄ = Probability of Health Effects ÷ Energy in Tissue
K₅ = Radiobiological Effectiveness Factor

The problems associated with the energy and radiation response characteristics of the sensor element can be partially accommodated by calibration techniques designed for specific applications. In addition, some of the biological response considerations can be accommodated by the use of scattering and absorbing materials which alter the sensor energy response in the desired direction. In practice, however, this approach is limited in the number of applications for which it can be used and is generally not suitable for use in mixed radiation fields.

In general, instrumentation for beta, gamma, or neutron fields differs significantly in operation and interpretation. The detection of beta radiation can readily be accomplished using ionization sensitive detectors with a sufficiently thin entry window. Gamma ray detectors require a larger detection volume and are most useful when the ionization sensor mimics tissue absorption characteristics. Neutron detection requires the use of sensor elements with large nuclear neutron capture cross-sections (usually in the thermal range) or which effectively absorb energy by direct knock-on energy transfer from the neutron.

Gamma Ray Instrumentation Problems

The future needs for instrumentation can best be illustrated by considering the specific needs for gamma ray instruments. The principal gamma ray instruments use sensor elements such as ionization chambers, geiger-mueller tubes, scintillators, thermoluminescent insulators, and semiconductors. While some of these sensors may be made using tissue-equivalent gases or scintillator materials, exact matching of the body's response to radiation and mass distribution is difficult to achieve.

One approach which has been developed and which remains in use today is to quantify radiation in terms of exposure as measured by the equilibrium ionization rate in air at standard conditions. This parameter is relatively easy to measure and provides a convenient standard for specifying instrument performance and for calibration. Actual dose to the body then depends on the use of energy-dependent correction factors which relate air exposure measurements to body dose.

The determination of the correct conversion factors is not straightforward. Dose within a body depends on the elemental composition and densities of the body components, the relative location of those components, and scatter and buildup in the body tissue as a function of energy. Direct instrumentation at depth in an actual body is difficult and has been done only on rare occasions. Most determinations have been made using instrumented phantoms or theoretical computational approaches.

Various computational models and phantom measurements are being actively pursued.¹⁻¹⁰ Recently, the ICRU proposed the use of a 30 cm tissue sphere as the proper simulation of the human body and defined a term, the dose equivalent index (or DEI), as the maximum dose rate which can occur at any point in the sphere as a result of a given exposure.⁸ Numerous calculations, with supporting measurements, have been made of the DEI.¹⁻⁵ Our own DEI calculations support those of Dimbylow and Francis. Additional calculations, which we have made for a 30 cm slab model of the human torso, do not differ significantly from the DEI calculations. This is important since some of the recent confirmatory measurements have been performed using a slab model.⁵

Figure 1 shows two of the more recent calculations by Dimbylow and Francis³ and Kramer and

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Drexel.² The data points represent phantom measurements by Francis and Morris⁴ and Yoder⁵. While the agreement isn't exact, good qualitative agreement is apparent - especially when compared to earlier conversion factor standards as indicated by the 1977 ANSI standard.⁹

Figure 1

Dose Equivalent Index Conversion Factors for Gamma Rays as a Function of Photon Energy

Once a standard conversion factor is adopted, instrument developers can select sensor materials and various absorber and scattering materials to tailor the instrument for the desired response. In addition, clever electronics can be designed to alter the instrument output so that the net result is an instrument which reads in terms of dose equivalent. However, before this ambitious task is undertaken, it would be appropriate to consider the potential shortcomings of the dose equivalent index approach.

The DEI assumes that an individual remains stationary while he is exposed to a parallel beam source of monoenergetic gamma rays. In practice, radiation is distributed in energy and, due to scatter, rarely appears as a parallel beam. In addition, individuals rarely remain stationary (except for situations such as glove box workers) so that their movement tends to average the radiation direction. These factors create problems for the DEI approach since the DEI is not additive with energy (since the DEI for different energies occurs at different depths in the body) and is not additive with respect to radiation direction (due to the shielding effects of the body). However, an instrument, operating in the free-field mode, tends to be additive with respect to both radiation energy and direction. As a result, use of the DEI conversion factors shown in Figure 1 can result in dose estimate (and hence risk) errors of up to a factor of $\times 5$.⁶

An alternative approach to the DEI would be to base dose calculations on a more realistic exposure model which considers dose at specified depths and which allows for the averaging of radiation direction. The special exposure conditions which result in higher dose rates are usually known and could readily be treated as special cases. While such an approach may result in a better assessment of actual dose for a given radiation exposure, it does not take into account the differences in radio-sensitivity of different body organs or of the differences in energy absorption due to differences in chemical composition.

To address this issue, the ICRP has proposed a series of weighting factors for the risks associated with the uniform exposure of different organs as shown in Table 1.¹⁰

TABLE I

Recommended ICRP Risk-Weighting Factors

Tissue	Weighting Factor
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remaining organs	0.30*
	1.00

*A risk factor of 0.06 is to be applied to any 5 additional organs receiving the highest dose equivalents.

These factors take into account the relative likelihood of carcinogenic or hereditary effects as a result of radiation exposure and represent the primary stochastic risks resulting from low levels of radiation exposure. Such problems are of primary concern for gamma ray exposure in most health physics applications.

The development of conversion factors which are more directly related to risk can be done using calculational means to assess the dose levels affecting each of the critical organs for a given exposure and then applying the appropriate weighting factors. We have made an estimate of such a conversion factor based on our calculations and on data from Kerr.¹¹ The composite conversion factor is shown as the ICRP-26 weighted curve in Figure 2 and is compared with the proposed 10 CFR 20.12, ¹³ conversion factors for DEI at 1 cm which is similar to Figure 1. The ICRP-26 weighted risk factor curve which we have calculated correlates well with a similar calculation performed by Kramer using the MIRD phantom.¹³

Figure 2

Gamma Ray Conversion Factors as a Function of Energy

As may be seen from Figure 2, the two conversion factor curves may differ by up to a factor of four, depending on energy. While the DEI curve shown in Figure 2 represents the current standard, it is possible that the problems associated with the DEI and a desire for a more accurate estimate of risk

factors for exposed individuals may result in future changes to this standard. If so, an instrument which was developed to match present DEI-based conversion factors would then be inaccurate. This has obvious implications for future instrument development.

Beta Ray Instrumentation Problems

Thus far, we have only considered gamma ray measurements. Beta ray measurements have perhaps even greater problems. Beta rays do not have the penetration capability of gamma rays and hence tend to affect the body surface. Betas with energies at the body surface of less than 70 keV do not penetrate the dead layer of the skin and are of no consequence. Betas above this energy which penetrate to the basal epidermal layer can cause somatic effects at high exposure levels. At energies in excess of 700 keV, sufficient penetration is possible to cause corneal damage to the eye, again of a somatic nature. Energies above about 2 MeV are required before exposure to deeper-lying radiosensitive organs occurs which ultimately limits the dose which can be tolerated.

The beta dosimetry problem is further complicated by the absorption of energy in the air. As an example of this problem, a measurement made at chest level of the dose effects of a beta emitter spill on the floor will significantly underestimate the dose to the lower extremities. In general, an effective beta measurement must be made at the point of concern. In addition, it must evaluate the beta energy distribution to determine the relative hazards associated with exposure to that portion of the body.

Neutron Instrumentation Problems

Neutron detectors have a different set of dosimetry problems. The sensor elements respond to thermal neutrons (neutron absorption) or to higher energy neutrons (knock-on energy transfer). Detection of higher energy neutrons can also be accomplished using scattering material in conjunction with a thermal neutron detector.

Neutrons have a higher radiobiological effectiveness factor due to the higher density of knock-on ionization than do gamma and beta rays. This additional effectiveness factor is a function of energy and can range up to a factor of x 20 at higher energies. The most common way to include this factor during measurements is to use a combination of scattering and absorbing materials in conjunction with a thermal neutron detector to tailor the total instrument response to the rem response curve of the human body. Recent calculations based on the definition of the dose equivalent index¹ have not resulted in significant changes in the rem response curve.

The main drawback with remmeters is their bulk. In addition, the rem response over the full energy range is not perfect and some questions remain concerning the proper shape of the rem response curve at medium neutron energies.¹⁴ Smaller and lighter sensors which depend on knock-on energy transfer do not respond to neutron energies less than several hundred keV and cause additional error when used in radiation fields containing significant quantities of thermal neutrons.

Mixed Radiation Field Instrumentation Problems

The difficulties in determining health effects in single radiation fields are significantly com-

pounded in the mixed radiation fields commonly found in nuclear fuel reprocessing facilities and operating nuclear power reactors. The problems involved in monitoring mixed gamma and beta ray fields will be used to illustrate the problem.

Many instruments are designed to detect both beta and gamma rays since the sensors respond to the ionizing properties of both of these radiations. Normally, an entry window equivalent to the outer body skin thickness is used to filter out low-energy beta and gamma rays. A semi-quantitative determination of the relative beta and gamma components is then made using an additional movable absorber to block the less penetrating beta rays. However, this alters the instrument gamma ray response characteristics and does not give a good quantitative estimate of the beta ray health risk effects.

An instrument which is sensitive to both beta and gamma rays can result in significant measurement error if used by an operator unskilled in determining the relative effects and hazards of both beta and gamma radiation. As an example, consider a radiation field composed of background gamma radiation and a ¹³⁷N beta ray source. Table 2 shows the measurement results in terms of indicated dose assuming only gamma radiation for fields which are respectively 100% gamma ray, 50% gamma and 50% beta ray, and 100% beta ray. The principal error is due to the differences in health risks of the two radiations compared to the amount of ionization which they can produce in a given sensor.

TABLE 2

Relative Effective Risk Levels
Indicated by an Instrument Used
in a Mixed Beta-Gamma Radiation Field

Gamma Radiation: Distributed Background Spectrum			
Beta Radiation: ¹³⁷ N			
	100% Gamma Ray 0% Beta Ray	50% Gamma Ray 50% Beta Ray	0% Gamma Ray 100% Beta Ray
Instrument Reading	1.0	1.0	1.0
Relative Risk Level	1.0	0.56	0.11

Desired Instrument Characteristics

The preceding examples illustrate the following points:

- 1) The health risk effects of ionizing radiation are not simply related to the outputs from representative sensors;
- 2) The health risk effects depend strongly on the mode of individual exposure and on the energy and direction of the radiation field; and
- 3) The affected body areas and magnitude of the health effects differ depending on the type of radiation.

If an ideal, multi-purpose instrument were to be developed, it should have the following attributes:

- 1) It should be able to differentiate between

the different radiation types and quantitate each type separately;

- 2) It should be able to measure the energy distribution of each radiation type with sufficient accuracy to apply energy-dependent dose factors;
- 3) It should be able to evaluate the relative degree of directionality of each type of radiation while responding to radiation from all directions;
- 4) It should be able to apply calibration factors to each of the radiation types and energy and directional distributions;
- 5) It should have provisions for application to special exposure conditions such as the stationary worker when desired; and
- 6) It should provide an output in a form which is indicative of the level of risk in easily understood units such as the effective whole-body dose rate.

In practice, such an instrument may be difficult to develop and may be prohibitively expensive for many applications. However, many of these requirements may be met with a less sophisticated instrument by using sensors which can discriminate among radiation types and which are capable of measuring the energy spectrum of the desired radiations.

The ability to apply various weighting factors and worker exposure conditions can then be easily accomplished using present microelectronics capabilities. Such an instrument has the potential of providing a much more accurate indication of health risks due to a given radiation field. This improvement in accuracy would be especially pronounced in cases where the instrument is being used by a minimally trained individual.

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