ENVIRONMENTAL RADIATION DOSIMETRY WITH IONIZATION CHAMBERS AND THERMOLUMINESCENCE DOSIMETERS

Wayne M. Lowder

Health and Safety Laboratory
U. S. Energy Research and Development Administration
New York, New York 10014

1. INTRODUCTION

Measurements of environmental radiation fields are carried out with many types of radiation detectors. Two applications of such measurements are directed toward the assessment of absorbed dose to man from externally-incident environmental radiation. First, the absorbed doses to various organs from the natural background radiation may be of direct interest on their own merits or to provide perspective in evaluating dose from other sources. This assessment requires an analysis of detector response in terms of radiation field quantities that can be related to the desired doses. Second, the assessment of organ doses from manmade sources may be desired, which requires a knowledge of detector response to the natural background radiation so that the response to the superimposed radiation may be inferred. Because of its relevance to these applications, we will consider here some of the general aspects of the dosimetric interpretation of radiation detector response to the natural background components. The methods for calibrating two widely-used detectors, the ionization chamber and the thermoluminescence dosimeter (TLD), in such radiation fields is discussed, to exemplify both the problems of analyzing detector response and the methods for arriving at reliable dose inferences. Such methods are contrasted with the recommendations of the ICRU and the areas of applicability of each are indicated.

The subject matter of this paper will be limited to the determination of absorbed dose rate or long-term dose to human organs at a particular location in the environment. The determination of dose to real individuals moving through the environment from a set of field measurements or from dosimeters worn on the body is considered in reference (1).

2. GENERAL METHODOLOGY OF DOSE ASSESSMENT

The general aspects of inferring dose to man from externally-incident environmental radiation have been discussed in two recent papers (1,2). The problem can be briefly described in the following manner. A radiation field within a small spatial volume is completely defined by specifying the flux density, $\Phi_i(E,\Omega)$, as a function of energy and angle for each of the i components (particle types). In the environment, we are usually interested in the radiation field in air at some distance above the air-ground interface, often one meter. If we then introduce a mass of material, our "detector", into this volume and perhaps surround it with additional matter of the same or different composition, this modifies the flux densities within the volume, i.e., $\Phi_i \rightarrow \Phi_i'$. Any response, R_i, of this detector to the i^{th} component can be related to these flux densities via a calibration factor, k_i, as follows:

$$R_i = \iint k_i'(E,\Omega)\ \Phi_i'(E,\Omega)\ dE\ d\Omega \qquad (1a)$$

$$= \iint k_i(E,\Omega)\ \Phi_i(E,\Omega)\ dE\ d\Omega \qquad (1b)$$

Equation 1b is more useful since it relates detector response to a quantity, Φ_i, that is independent of the presence and the properties of the particular detector. Let us now consider two such detectors, our measuring instrument and a human organ. The ΣR_i for the former can be a counting rate, an electric current, or another type of signal, while the ΣR_i of interest for the latter is mean absorbed dose over the organ mass. It is clear that the relationship between these two sets of responses is both complicated and dependent on a knowledge of each of the flux densities. Our problem is to find a method that will enable us to infer the ΣR_i for the human organ when we have determined the response of our measuring instrument to the incident radiation. In practice, we must usually do this without detailed knowledge of either the k_i or the Φ_i.

The key to the solution of this problem for natural environmental radiation fields is the fact that the energy and angular distributions of the flux densities of the important components, namely cosmic-ray muons and electrons and terrestrial photons, have fairly constant shapes from place to place (2). For example, Beck (3) has shown that the terrestrial photon energy spectrum at one meter above the ground is not sensitive to the relative soil concentrations of potassium, uranium, and thorium. As a consequence, the responses, R_i, of any detector are approximately proportional to the amplitudes of the total flux densities ($= \iint \Phi_i(E,\Omega)\ dE\ d\Omega$). They may be calibrated against these amplitudes or any other quantity proportional to them, such as ionization rate or absorbed dose rate in air (since charged particle equilibrium approximately holds in free air) or kerma or exposure rate for photons. For example, equation 1b can be modified to

$$R_i = k_i \dot{D}_i \qquad (2)$$

where the absorbed dose rate, $\dot{D}_i$, is

$$\dot{D}_i = \iint q_i(E)\ \Phi_i(E,\Omega)\ dE\ d\Omega = q_i \Phi_i$$

with q_i being the collision stopping power for charged particles and the product of the energy and the mass energy transfer coefficient for photons.

Although many environmental radiation measurements are reported in terms of these quantities, this is but an intermediate step on the road to human dose assessment. The measurement defines the radiation field in the absence of the human body, i.e., the irradiation conditions. However, this is all the information that is needed to calculate the absorbed dose to human organs in the presence of the human body. Such calculations have been performed and reported by O'Brien and McLaughlin (4) and O'Brien and Sanna (5) for cosmic-ray particles and terrestrial photons, respectively. These data can be used to derive a calibration equation of the same form as equation (2) for each organ dose rate, to an accuracy of the order of ± 10 percent.

In the following two sections, we illustrate this methodology of calibration with two very different types of detector.

3. IONIZATION CHAMBER CALIBRATION

Our standard ionization chambers for environmental radiation measurements are 25-cm diameter steel spheres with walls of 2.6 g cm^{-2} thickness containing 25 atm of argon. The walls absorb any external alpha and beta radiation, and cosmic-ray neutrons lose very little energy in collisions with the argon atoms. This discrimination is useful since the terrestrial photons and cosmic-ray charged particles that produce most of the response are also the main contributors to dose to man (2).

The calibration of these chambers has been discussed in detail by DeCampo et al. (6). The gamma-ray response per unit flux density, exposure rate, or absorbed dose rate in free air is determined in the laboratory at various photon energies, and these data are used to infer the response to a typical spectrum of energies in the environment. The response to cosmic-ray charged particles is more difficult to determine in the absence of standard fields of known properties. Initially, we inferred the cosmic-ray response as a function of altitude by field measurements at various altitudes along with simultaneous determinations of the exposure rate by means of a gamma-ray spectrometer system (7). The inferred gamma response of the ion chamber was then subtracted from the total to yield the desired response. At later dates, we have performed theoretical analyses of the response to cosmic-ray muons and electrons (6,8) using published particle energy spectra (2,9). These yielded values for the response per unit flux density, ionization rate, or absorbed dose rate in free air in close agreement with the inferred experimental values when the sea-level ionization rate was taken to be 2.1 ion pairs cm^{-3} s^{-1} (7).

The relation between the total instrument response to terrestrial photons and cosmic-ray charged particles and quantities such as the absorbed dose rates in free air ($\dot{D}_i$) from these two components of the total field can be expressed as

$$R = R_\gamma + R_c = k_\gamma \dot{D}_\gamma + k_c \dot{D}_c$$

where k_γ and k_c are the calibration factors derived as described above for the two components. As it stands, this equation is inadequate to define the field with a single measurement, R, since it contains two unknowns, $\dot{D}_\gamma$ and $\dot{D}_c$. However, $\dot{D}_c$ is known as a function of pressure-altitude to an accuracy of about ± 5 percent (7,9). Thus, a determination of barometric pressure at the time of measurement will permit the inference of $\dot{D}_c$, and equation 3 can then be used to infer $\dot{D}_\gamma$. These two parameters can be used to obtain organ dose by applying the appropriate conversion factors from references (4) and (5).

4. TLD CALIBRATION

The procedure for calibrating thermoluminescence dosimeters (TLDs) in environmental radiation fields is similar to that for the ionization chambers, but involves several different problems. Both the ionization chamber and TLD responses are approximately proportional to absorbed dose in the detector medium, but the stored energy in the TLD is gradually accumulated over the time of exposure. Many of the special problems in the use of TLDs in environmental applications have been discussed by Burke (10).

Our TLD packages for environmental radiation measurement consist of five LiF (TLD-700) ribbon dosimeters (3.2 × 3.2 × 0.9 mm) mounted in a lucite

container providing at least 0.37 g cm^{-2} thickness around the ribbons. This thickness is sufficient to provide electronic equilibrium during calibration and to shield against external alpha and beta radiation. The gamma calibration is accomplished in a ^{137}Cs beam in the laboratory and expressed in thermoluminescent response (integrated counts) per unit exposure. Studies of the response of such dosimeter packages as a function of photon energy and angle indicate that this calibration is also applicable (to within a few percent) to exposure in environmental photon fields.

The calibration of the response of these dosimeters to cosmic radiation is a more difficult undertaking. In late 1974, we exposed bare ribbon dosimeters to an 8 GeV muon beam of the Alternating Gradient Synchrotron at Brookhaven National Laboratory. This experiment (8) established that the thermoluminescent response per unit absorbed dose in the ribbon for such muons equals that for 0.662 MeV photons, and that simple cavity theory using restricted stopping powers yields a correct value for absorbed dose in the dosimeter. This theory was then applied at other muon energies, and the results were weighted according to the shape of the cosmic-ray muon spectrum. The net result was a calculated response to these muons per unit absorbed dose in air that is 15 percent lower than the analogous value for environmental photons. We would expect that the response to high-energy electrons in the cosmic radiation would be comparable to that for the muons. However, the theoretical considerations here are more complex, and it appears that the usual cavity theories do not yield accurate results (11). This point is of some relevance to medical dosimetry.

The gamma and cosmic radiation calibration factors obtained as described above are inserted into equation 3 to infer $\dot{D}_\gamma$, the mean absorbed dose rate in air from terrestrial photons over the period of exposure. The quantity, $\dot{D}_c$, is determined from an estimate of the mean barometric pressure over the period of exposure. The interpretation of TLD response in terms of dose to man is identical to the interpretation of ion chamber response, once $\dot{D}_\gamma$ is determined.

The validity of these calibration factors has been checked by comparing four-week integrated exposure data at several field sites obtained with both our TLDs and a continuously monitoring ionization chamber. The inferred values for exposure or absorbed dose in free air from photons generally agree to within 5 percent. Another comparison between the two detectors has been made in a three-month exposure within the HASL whole body counter shield, where the bulk of the field consists of cosmic-ray muons and associated collision electrons. The ratio of the response of the TLDs to the absorbed dose in air inferred from the ionization chamber data agreed to within the uncertainties of measurement with our theoretically-derived cosmic ray calibration factor for the TLDs.

5. DISCUSSION

The consistency checks on our detector response calibration factors discussed above are indicative of an accuracy in our direct interpretations in terms of radiation field quantities of about ± 5 percent (s.d.). Taking account of the additional uncertainties in the analytical calculations of human organ dose and of the idealizations of the human body that are inherent in such calculations, we estimate the accuracy of the organ dose estimates to be about ± 10 percent (s.d.). It is indeed remarkable that certain regularities in the characteristics of natural environmental radiation fields permit the achievement of such a degree of accuracy in dose assessment from a single measurement or limited set of measurements.

The same considerations mentioned here for these two detectors also apply to other detectors. Studies of the energy and angle dependences of detector response to gamma radiation can usually be carried out in the laboratory, and a calibration factor derived for typical environmental photon fields (3). The evaluation of the cosmic ray response is more complicated. However, the availability of considerable information on the composition, differential flux densities, and ionization rates of the cosmic-ray components (2,9) does make possible a calculational approach to this problem when the detector geometry is relatively simple.

The effectiveness of the general methodology of dose assessment discussed here depends on the availability of information that is independent of the particular measurement process. The generation of much of this information for natural radiation fields has been carried out with this particular goal in mind. The listed references provide guidance to the sources of such information.

The application of this methodology in other radiation fields requires the generation of similar types of information so that appropriate detector calibrations can be derived. This is often the role of gamma spectrometry in the measurement of photon fields. The field-quantity-to-organ-dose conversion factors given by O'Brien and Sanna (5) are available for any photon field. Analogous calculations are in progress for charged particles.

In recent years, the ICRU (12,13) has defined a quantity called absorbed dose index at a point, which is "the maximum absorbed dose within a 30 cm diameter sphere centered at this point and consisting of material equivalent to soft tissue with a density of 1 g cm^{-3}". This quantity, and the related dose equivalent index, is presumed "to meet the need for the characterization of ambient radiation levels at any location for purposes of radiation protection". Although the ICRU reports indicate both explicitly and implicitly that the index quantities are appropriate for radiation protection applications, these quantities might also be used uncritically for the type of dose assessment discussed in this paper. However, this approach involves measurement problems of a significant nature that have not yet been sufficiently studied, and yields only an upper-limit dose estimate that may be quite different from the actual organ doses. In the absence of any information on the ambient radiation field, the index quantity approach may be the only one available. Since this is not the case for natural environmental radiation, the approach to dose assessment via the determination of field quantities yields more realistic and more informative estimates. This is particularly important when the ultimate purpose of dose assessment is the correlation of dose with biological response.

ACKNOWLEDGEMENT

This paper relies strongly on the published and unpublished work of several associates in the Radiation Physics Division, notably, Harold Beck, Gail de Planque Burke and Keran O'Brien, and on the support of James McLaughlin.

REFERENCES

(1) LOWDER, W. M., Methods of external radiation dose assessment, An. Acad. Bras. Cienc. (to be published, 1977)

(2) LOWDER, W. M., Basic aspects of environmental radiation measurements, Proc. Tenth Midyear Symp., Health Phys. Soc., Saratoga Springs, NY (1976)

(3) BECK, H. L. "The physics of environmental gamma radiation fields", The Natural Radiation Environment II (ADAMS, J. A. S., LOWDER, W. M., GESELL, T. F., Eds), USERDA Report CONF-720805-P1 (1972) 101

(4) O'BRIEN, K., McLAUGHLIN, J. E., The radiation dose to man from galactic cosmic rays, Health Physics 22 (1972) 225

(5) O'BRIEN, K., SANNA, R. S., The distribution of absorbed dose rates in humans from exposure to environmental gamma rays, Health Physics 30 (1976) 71

(6) DeCAMPO, J. A., BECK, H. L., RAFT, P. D., "High pressure argon ionization chamber system for the measurement of environmental exposure rates", USAEC Report HASL-260 (1972)

(7) LOWDER, W. M., BECK, H. L., Cosmic-ray ionization in the lower atmosphere, J. Geophys. Res. 71 (1966) 4661

(8) LOWDER, W. M., BURKE, G. de P. "The cosmic ray response of LiF TL dosimeters", USERDA Report HASL-313 (to be published, 1977)

(9) NCRP "Natural background radiation in the United States", NCRP Report 45, Washington, DC (1976)

(10) BURKE, G. de P., Thermoluminescence dosimetry: environmental monitoring near nuclear reactor sites, IEEE Trans. Nucl. Sci. NS-23 (1976) 1224

(11) O'BRIEN, K., Monte-Carlo calculations of the energy response of lithium fluoride dosemeters to high-energy electrons (< 30 MeV), Phys. Med. Biol. (to be published, 1977)

(12) ICRU "Radiation quantities and units", ICRU Report 19, Washington, DC (1971)

(13) ICRU "Conceptual basis for the determination of dose equivalent", ICRU Report 25, Washington, DC (1976)