Dear Editor;

Various quantities and units related to ionizing radiation have been introduced and defined by ICRU and its precursor since 1928, when the first international unit of X-radiation, roentgen, was adopted at ICR. The latest definitions of fundamental quantities were given in ICRU Report 60 (1998), and those of quantities used in radiation protection were in ICRU Report 51 (1993) and Report 57 (1998).

Kazuaki Katoh of Ibaraki Prefectural University of Health Sciences and I have studied the history of dosimetric quantities. Most of them were introduced to meet primarily pragmatic needs, rather than requirements of the law of fundamental physics. As a result, their concepts and definitions had to be revised repeatedly to evolve into more sophisticated ones. Nonetheless, in our views there still remain uncertainties or irrationalities in the current definitions of some dosimetric quantities. This letter is intended to raise thought for refining the concepts and definitions of such quantities.

1) Dosimetric quantity as macroscopic quantity

The non-stochastic dosimetric quantities are macroscopic quantities, though the explicit expression can only be seen in their definition of the absorbed dose; i.e., the expression “$d_{\langle \varepsilon \rangle}$ is the mean energy imparted” can be interpreted as an ensemble mean of a stochastic quantity. It is understood that exposure, kerma, and cema have similar meanings implicitly.

Macroscopic physical quantities should be inherently consistent with thermodynamics. However, it is neither self-evident nor easily provable whether dosimetric quantities are consistent with (either equilibrium or non-equilibrium) thermodynamics. It is difficult for me to see how the energies appearing in the definition of dosimetric quantities relate to the thermodynamic quantities, e.g., to free energy production or entropy production in an electron-phonon system.

The circumstance that dosimetric quantities were not derived from the principles of fundamental physics may have caused such a difficulty. I have seen no article that developed dosimetric quantities from a fundamental description of the physics of the radiation-material system. W. C. Roesch expressed the absorbed dose using a transport equation of ionizing particles, however, it was not a theoretical derivation of the quantity but a restatement of the ICRU’s definition (Roesch 1968).

Hundred years have passed since Holzknecht proposed the first (at least one of the earliest) unit “H” of a dosimetric quantity based on his dosimeter named Chromoradiometer (Holzknecht 1902, 1905). Time is ripe for reconsidering what macroscopic dosimetric quantities are from a fundamental point of view.

I regret I have no complete solution of this issue yet. In the following I point out problems that are seen in the current definitions of the quantities and units and propose some improvements.
2) On the definition of the mass energy transfer coefficient

In Report 60, ICRP defined the mass energy transport coefficient as follows:

“The mass energy transfer coefficient, $\mu_t/\rho$, of a material, for uncharged particles, is the quotient of $dR_{tr}/R$ by $\rho dl$, where $dR_{tr}/R$ is the fraction of incident radiant energy that is transferred to kinetic energy of charged particles by interactions, in traversing a distance $dl$ in the material of density $\rho$, thus

$$\mu_t/\rho = (1/\rho dl)(dR_{tr}/R).$$

This statement has a deficiency, because the energy transferred to kinetic energy of charged particles is not a fraction of incident radiant energy. It is the fraction of the sum of incident radiant energy and the rest energy released from nuclear- and elementary-particle interactions by the incident uncharged particle. Thus, the current definition gives an incorrect value of the kinetic energy of secondary charged particles, especially in the case where incident thermal neutrons cause nuclear fission. As a result, one cannot correctly evaluate kerma, $K$, from the currently defined mass energy transport coefficient.

The interaction of radiation with matter is stochastic. Thus, the above-mentioned fraction is a stochastic quantity. Hence it is necessary to refer to the quotient $dR_{tr}/R$ appearing in the definition as an ensemble mean.

In the old Reports (from Report 10a (1962) to Report 33 (1980)), the mass energy transfer coefficient for photons of energies where nuclear reactions do not occur was also expressed as mass attenuation coefficients of photoelectric effect, Compton scattering, and pair production as follows:

“For x rays and gamma rays, the separate components of $\mu_t/\rho$ are not usually expressed in terms of cross section; instead, the following notation is used,

$$\mu_t/\rho = \tau/\rho + \sigma_{ca}/\rho + \kappa_a/\rho,$$

where the component mass energy transfer coefficients refer to those for the photoelectric effect, Compton effect, and pair production, respectively, and

$$\tau/\rho = (\tau/\rho)(1 - \delta/h\nu),$$

where $\tau/\rho$ is the photoelectric mass attenuation coefficient ($\delta$ is defined as the average energy emitted as fluorescent radiation per photon absorbed in the preceding paragraphs),

$$\sigma_{ca}/\rho = (\sigma_c/\rho)(E_c/h\nu),$$

where $\sigma_c/\rho$ is the Compton mass attenuation coefficient, $E_c$ is the average energy of the Compton recoil electron, and

$$\kappa/a/\rho = (\kappa/a/\rho)(1 - 2mc^2/h\nu),$$

where $\kappa/a/\rho$ is the mass attenuation coefficient for pair production.” (ICRU Report 33)

This expression has disappeared from the latest Report, though it is useful to understand the nature of the quantity. From an educational viewpoint I propose its revival. However, the following improvement is necessary in its revival.
The fraction of incident photon energy transferred to secondary electrons is not $E_e/h\nu$, since kinetic energy of Auger electrons should also be taken into account. Thus it should be expressed as $(E_e + (\langle I \rangle - \delta'))/h\nu$, where $\langle I \rangle$ is the mean excitation energy of target atom and $\delta'$ is the mean energy emitted as fluorescent radiation per photon scattered. Here I have used a symbol $\delta'$ different from the mean energy of fluorescent radiation from the target atom excited in a photoelectric effect, $\delta$, since the mean excitation energy of the target atom is different between these two processes.

3) On the definition of kerma

ICRU defines the kerma in Report 60 as follows:

“The kerma, $K$, is the quotient of $dE_{\text{ir}}$ by $dm$, where $dE_{\text{ir}}$ is the sum of the initial kinetic energies of all the charged particles liberated by uncharged particles in a mass $dm$ of material, thus

\[ K = \frac{dE_{\text{ir}}}{dm}. \]

As mentioned in Section 1, it would be better to express the quantity $dE_{\text{ir}}$ as an ensemble mean, since the kerma is a macroscopic quantity. It should be noted that the contradicting requirement on the size of mass, $dm$, shown below (for example), becomes unnecessary if one uses the idea of an ensemble mean.

“An elementary volume in the medium which on the one hand is so small that a further reduction in the size would not appreciably change the measured value of the quotient and on the other hand is still large enough to contain many interactions and be traversed by many particles. (ICRU Report 10)"

There is one serious uncertainty in the current definition of kerma. The definition does not clarify to what extent of emissions of charged particles should be taken into account. The emission of Auger electrons is explicitly assigned as the contributing process. The emission of Coster-Kronig electrons should also be included, but it is not explicitly stated. However, it remains unclear to what extent of delayed emissions of charged particles by the nuclear inelastic scattering, e.g., photo-nuclear reaction, neutron capture and so on should be explained. Setting an objective elapsed time as a threshold seems difficult for me.

Let us move on a rather pragmatic issue. The following expression seen in older ICRU Reports:

“Since $dE_{\text{ir}}$ is the sum of the initial kinetic energies of the charged ionizing particles liberated by the uncharged ionizing particles, it also includes the energy that these charged particles radiate in bremsstrahlung.” (ICRU report 33)

sometimes led students to a misunderstanding about the nature of kerma such that “the energy relating to the kerma consists of that expend in ionization and excitation and that radiate in bremsstrahlung”. On the other hand, the kerma being often used as an approximation of the absorbed dose, the concept termed “collision kerma”, probably first used by F. H. Attix, is practically useful. I would propose to
employ this terminology, and to define the kerma more clearly (Attix 1979).

4) On the definition of exposure

In the early ICRU Reports, the air that secondary electrons ionize is clearly stated as “dry air” (e.g., ICRU 1959). The specification has disappeared since Report 10, though it is essential. I propose to revive the specification, “dry air”, since the value of “mean energy expended in air per ion pair formed” depends on the humidity.

The concept of exposure has evolved toward a more abstract idea so that it can be applied to the point of interest where air is absent. However, such a change in concept is not clearly seen in the definition itself. I often encounter those who believe that exposure could only be used in air, despite of the supplemental explanation given in ICRU Report. Thus, I would propose to modify the statement as follows:

“The exposure, \( X \), is the quotient of \( d<Q> \) by \( dm \), where \( d<Q> \) is the absolute expectation value of the total charge of the ions of one sign which would be produced in dry air when all the electrons and positrons which would be liberated or created by photons in air of mass \( dm \) at the point of interest are reduced their kinetic energy to that less than minimum ionization energy of air in dry air, thus

\[
X = \frac{d<Q>}{dm}.
\]

5) On the energy imparted

The expression of the energy imparted, and of the absorbed dose as a result, using the energy balance in a small volume element of the material, enables one to define the quantity independent of the mechanism of imparting (or depositing) energies. The definition, however, makes unclear the nature of the quantity, i.e., what the physical state of the material where energy is imparted by ionizing radiation is. This makes it difficult to understand the physics of the quantity.

In the early Reports of ICRU, processes that contribute to the energy imparted are listed up, though in a not sophisticated way. I believe that certain expression about the nature and the physics of the quantity is necessary.

6) On the names and the symbols of units

Three different dosimetric quantities, kerma, cema and absorbed dose, use the same special unit name “gray” and its symbol Gy. These quantities are not simply additive to each other; hence using the same unit name/symbol will cause unnecessary confusion. I would propose to use distinct unit names/symbols such as “kerma-gray” (Gy\(_K\)) and “cema-gray” (Gy\(_C\)).

Similar but (socially) more serious situation occurs in the unit of doses used for radiation protection. The value of the effective dose becomes smaller than that of equivalent dose when one’s body is exposed partly to the ionizing radiation. Most people will regard it a “trick” when two different values of “sievert” are reported to the same exposure. Thus I strongly propose to use Sv only for effective dose and introduce another unit for equivalent dose, such as Ty (Taylor) or Mo (Morgan),
or something else appropriate.

7) On the operational quantities

Many operational quantities have been introduced since Report 39 of 1985 (practically Report 19 of 1971). Among them there are almost obsolete quantities such as dose equivalent indices and individual dose equivalents. There also exist quantities such as directional dose equivalents whose definition have been modified again and again. Disuse of unnecessary quantities as well as changes in the definition, however, have never explicitly declared yet. As a result, I sometimes find that even specialists of radiation protection discuss different quantities under the same name.

The operational quantities are in effect a prescription of the calibration standard for dosimeters that are used for practical measurement in radiation safety. However, as many operational quantities exist, there appears a curious hierarchy among them, which ICRU might not have intended.

To clear the situation, it is necessary to choose a single operational quantity and declaring disuse of the others. The choice is apparent: it is nothing but the utmost quantity in above-mentioned hierarchy, i.e., the effective dose calculated with an anthropomorphic phantom in anterio-posterior geometry (ICRU Report 57). Dosimeters used for environmental monitoring shall be calibrated to the unique operational quantity in free air, and dosimeters used for individual monitoring shall be calibrated on that phantom.

8) References


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