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Validity of the Concept of Absorbed Dose as a Physical Quantity

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ABSTRACT

The concept of the "absorbed dose" of ionizing radiation is scrutinized from physical point of view. It is shown that the concept and definition of the quantity in the ICRU system is disqualified as a physical quantity and the absorbed dose can not always be a "measure of cause" in describing causality relation between radiation and effects on matter. The current absorbed dose depends even on the energy that have already been brought out from the matter, contrary to the intention of introducing the quantity. Trials to remove these difficulties are made. However, it is also shown there still exists an essential problem that cannot be solved by improving the formulation.

KEYWORDS

metrology, ionizing radiation, radiation dose, radiation dosimetry, absorbed dose, energy imparted, physical quantity, ICRU, energy conservation.

§1. Introduction

The absorbed dose is considered to be the most important physical quantity in the present system of radiation dosimetry. Radiation dosimetry is a common basis for all sciences treating the effects of ionizing radiation on matters. As the uses of ionizing radiation have been increased in many field of sciences, radiation dosimetry becomes more and more important. Hence, it becomes even more substantial to consolidate the foundation of the radiation dosimetry.

The concept of "dose" of ionizing radiation was introduced on earth as a "measure of cause" in describing causality relation between radiation and effects. The dosimetric quantities in the terminology of the International Commission on Radiation Units and Measurements (ICRU) are nothing but doses from this point of view. Among these doses, the absorbed dose is considered to be the most fundamental one, with at least two reasons. First, the concept of the absorbed dose has the widest range of applicability; it can be applied to any kind of radiation and of material. Secondly, it was simply and naively believed that energy is the ultimate source of changes in matter, since most changes of matter accompany changes of its internal energy.

Considering the purpose of introducing the quantity, "dose", it is most desirable to make it hold a property that the same amount of effect is produced from the same amount of dose for any kind of radiation and for any kind of effects, independently. However, such an ideal quantity has not been found and it seems quite sure that such a quantity does not exist. The second best of the strategy is to find a dose which holds the same property for any kind of radiation as far as the type of effect is fixed.

As a result, various kind of doses were proposed and used in various fields of science and engineering. As a matter of fact, most of them are derived from the absorbed dose and expressed as weighted doses. Thus, the absorbed dose is given a role of the most basic quantity in the present system of radiation dosimetry. Therefore, it is important to investigate rigor of the concept and physical meaning of the absorbed dose.

Today, the so-called standard system of radiation dosimetry is based on the one recommended by the ICRU and has been widely used in the world. It was 1928 when the ICRU first introduced a system of radiation dosimetry,[1] and since then the ICRU revised it repeatedly[2-7] upon increased knowledge of related sciences.

The definition of the absorbed dose in the most recent version of the recommendation[7] is given as follows:

"The absorbed dose, D, is the quotient of $d\langle\varepsilon\rangle_{av}$ *by* dm, *where* $d\langle\varepsilon\rangle_{av}$ *is the mean energy imparted by ionizing radiation to matter of mass* dm, *thus*

$$D = d\langle\varepsilon\rangle_{av}/dm.$$

The energy imparted, ε, *by ionizing radiation to matter in a volume, is:*

$$\varepsilon = R_{in} - R_{out} + \Sigma Q,$$

where

R_{in} *is the radiant energy incident on the volume, i.e., the sum of the energies (excluding rest energies) of all those charged and uncharged ionizing particles which enter the volume,*

R_{out} *is the radiant energy emerging from the volume, i.e., the sum of the energies (excluding rest energies) of all those charged and uncharged ionizing particles which leave the volume,*

and ΣQ *is the sum of all changes (decreases: positive sign; increases: negative sign) of the rest mass energy* (sic) *of nuclei and elementary particles in any interactions which occur in the volume."*

The term "ionizing particles" seen in this definition implies the entities of ionizing radiation, and the ICRU claims[6] that "*ionizing radiation consists of charged particles and/or uncharged particles capable of causing ionization by primary or secondary processes.*" Here, the term "ionization" is used to mean "*a process in which one or more electrons are liberated from a parent atom or molecule or other bound state.*"[6]

The absorbed dose being the basic dose, it should be well-defined as a physical quantity. Here, the term physical quantity is used to mean "*a property of a physical object or phenomenon that can be quantified by measurement and by calculation*" following the ICRU.[7] Thus, if the absorbed dose is a physical quantity at all, at least (1) physics characterizing the quantity should be clear, and (2) numerical specification of the quantity should be rigorous. In this paper, properties of the absorbed dose are scrutinized from these two points of view, and are discussed in detail in §2 and 3, respectively.

Independent of the problem whether the absorbed dose is a well-defined physical quantity or not, it is also important to investigate the adaptability of the concept to the purpose of introducing the dose. This will be discussed in §4.

§2. Physics of Energy Transfer Related to the Absorbed Dose

In the current system of radiation dosimetry introduced by the ICRU, the absorbed dose is defined as the mass density of the "mean energy imparted" in the ICRU terminology.[7] It is recognized that the energy imparted was introduced considering gross energy balance to the matter of mass, dm (Fig. 1), but (1) the process of energy transfer from radiation to matter and (2) existing forms of the energy transferred are not clear. These cause some ambiguity in interpreting the quantity.

2.1 *Treatment of Energy in the Definition of the Absorbed Dose*

In the definition of the absorbed dose quoted above, only kinetic energy is considered concerning the energy of ionizing particles, which leads lack of rationality in evaluating the energy imparted in some cases, or the law of energy conservation will be violated. Concretely, nuclear reactions accompanying change of mass number are the case. Changes in rest energy of nuclei due to increase/decrease in mass numbers are not usually considered to contribute to radiation effects. Thus, they need

not be taken into the dose. However, they cannot be excluded from the evaluation of the energy imparted without violating the law of energy conservation.

For example, in the case of an (n,γ) reaction induced by a thermal neutron, R_{IN} is the kinetic energy of the thermal neutron (say 0.025 *eV*), R_{OUT} is the total energy of emerging prompt gamma-rays (say 8 *MeV* in total) and ΣQ is the change in rest energy due to increase of mass number by one (-932 *MeV*). The outcome of the calculation of the energy imparted with these values, shows most of the contribution to the quantity comes from ΣQ, which cannot be the cause of radiation effects. From physical point of view, the cause of radiation effects in this case is not thus evaluated energy but energy transferred from prompt gamma rays to the matter, which the ICRU presumably intended to use. To obtain such desirable result the change of rest energy due to change in mass number should be excluded, but it leads violation of the law of energy conservation.

The ICRU has not adequately considered the law of energy conservation in defining the energy imparted. This is one of the reasons why currently defined energy imparted cannot express the quantity that causes radiation effects without violating the law of energy conservation in some cases. Thus, it is necessary to change the definition of energy imparted so as to include rest energy of ionizing particles related. Hence, the authors propose to amend the definition of the energy imparted as follows.

R_{in} *is the energy of ionizing particles incident on the volume,* *i.e., the sum of the kineic* ***and rest*** *energies of all those charged and uncharged ionizing particles which enter the volume,*

R_{out} *is the energy of ionizing particles emerging from the volume, i.e., the sum of the kinetic* ***and rest*** *energies of all those charged and uncharged ionizing particles which leave the volume,*

and ΣQ *is the sum of all changes (decreases: positive sign; increases: negative sign) of the rest energy of nuclei and elementary particles in any interactions (****including addition and removal of nuclei and elementary particles****) which occur in the volume.*

Hereafter, the authors employ this amended definition of the energy imparted in this paper.

2.2 *The Physical State Where Energy Is "Imparted"*

In general, when some energy is imparted to a matter, its state of motion and/or its internal state change. The change in internal energy of the matter at a specified time after irradiation is the sum of changes in both kinetic and binding energy of all the constituents (excluding the change in kinetic energy of translational and rotational motion of the matter). Some part of this internal energy will be brought out from the matter in future either in the form of ionizing radiation or in the form of non-ionizing radiation. In this article, the term "non-ionizing radiation (nIR)" is used to mean the flow of energy whose entities are other than ionizing particles. Fig. 2 illustrates this phenomenon schematically.

In the figure, an amount of energy, ε_0, is deposited in a matter of mass, d*m*, at the time, $t = t_0$, instantaneously. This brings an increase in internal energy of the matter by an amount ε_0 at $t = t_0$. Line D shows the total loss of this deposited energy with time. Some portion of this energy lost is carried out by nIR, and it is represented with line C. The difference between lines D and C corresponds to the energy carried out in the form of ionizing particles, which is nothing but the (mean) radiant energy, R_{out}. Thus *the mean energy imparted*, $\langle\varepsilon\rangle_{av}$, changes with time as shown with line E, while the increment of internal energy of the matter of mass, dm, varies with line B.

As seen in the figure, the mean energy imparted, $\langle\varepsilon\rangle_{av}$, is a time dependent quantity, and it is denoted by $\langle\varepsilon_{IMP.}\rangle_{av}(t)$ in this paper for the convenience in later discussion. This quantity can be expressed with the sum of the increment of internal energy of the matter at the time;

$$\Delta U_{INT.}(t) \equiv U_{INT.}(t) - \lim_{t \to t_0 - 0} U_{INT.}(t),$$

and the energy *which have already been brought out from the matter* by nIR, $\int_{t_0}^{t} d\tau \oint_{dm} \mathbf{ds} \cdot \boldsymbol{\psi}_{nIR.}(\tau)$;

$$\langle\varepsilon_{IMP.}\rangle_{av}(t) = \Delta U_{INT.}(t) + \int_{t_0}^{t} d\tau \oint_{dm} \mathbf{ds} \cdot \boldsymbol{\psi}_{nIR.}(\tau),$$

where t_0 is the time when the irradiation started, $\boldsymbol{\psi}_{nIR.}(t)$ is the vectorial energy fluence rate[8] of nIR *generated in the mass*, surface element **ds** is taken as outward normal, and the integral is to be done over the entire surface of the mass element, d*m*.

It is apparent that the energy brought out from the mass,

dm, by nIR, $\int_{t_0}^{t} d\tau \oint_{dm} \mathbf{ds} \cdot \boldsymbol{\psi}_{nIR.}(\tau)$, is not dependent on the internal state of the matter at the time, t. In other words, $\int_{t_0}^{t} d\tau \oint_{dm} \mathbf{ds} \cdot \boldsymbol{\psi}_{nIR.}(\tau)$ cannot have a definite value, even though the energy imparted to the mass element, $\langle \varepsilon_{IMP.} \rangle_{av}(t)$, is strictly given. Consequently, it is not possible to specify the macroscopic state of the matter corresponding to the ICRU quantity, $\langle \varepsilon_{IMP.} \rangle_{av}(t)$.

§3. Quantification of the Absorbed Dose

It seems that the concept of absorbed dose was introduced on the premise that the value of the dose is to be fixed immediately after the irradiation, while energy impartation do not always occur instantaneously. In case intermediate metastable states of the matter are formed in the processes, energy transfer lasts till these metastable states have disappeared completely. Thus, values of the absorbed dose cannot be fixed till a sufficiently long time has passed. Processes that accompanies production of radioactive nuclei are the typical cases.

Here, an extreme example is shown to clarify the problem. Suppose there is a mass of cobalt-59 irradiated with thermal neutrons instantaneously. Immediately after the irradiation, prompt gamma rays are emitted, which give contribution to the dose. However, one beta ray and two gamma rays (by primary decay scheme) are emitted from the product nucleus (cobalt-60) in future, and they also contribute to the dose (Fig. 3). In this case, the contribution of the latter reaches as much as one third of the former.

Thus, the absorbed dose is, in reality, a function of time, even if the matter is exposed to radiation in infinitesimally short time interval. In addition, the physical entity of the quantity changes time to time, when formation of intermediate metastable states are involved. As a result, different physical entities can provide same value of the absorbed dose, though they may be different each other as a cause of radiation effect. Only the quantity whose value is assigned by the expectation value in the infinite future can characterize a common physical phenomenon among processes with intermediate states of various half lives. The property of the quantity, however, does not fit the purpose of introducing doses.

It should also be noted that the absorbed dose at a point of interest in the matter changes when configurations of matters surrounding the point are altered. Since, ionizing radiation produced by interactions occurring outside the mass, dm, is possible in principle to interact with the matter inside the mass. More generally, values of the absorbed dose are dependent on matters existing in whole space.[9]

§4. Adaptability of the Absorbed Dose

In addition to aptitude tests of the absorbed dose as a physical quantity discussed in the preceding sections, performance analysis of the quantity to the purpose of introduction is also necessary.

The name "absorbed dose" implies the mass density of *mean energy absorbed* by the matter, but it **IS** defined as the mass density of *mean energy imparted* to the matter. The difference in these two quantities is the mean energy brought out from the matter per unit mass, in the form of nIR, i.e.,

$$\int_{t_0}^{t} d\tau \oint_{dm} \mathbf{ds} \cdot \langle \boldsymbol{\psi}_{nIR.} \rangle_{av}(\tau)/dm.$$

The energy brought out from the matter prior to the time, t, whether its carriers are ionizing particles or not, cannot cause effects to the matter at the time, t, in principle.

Hence, it is illogical to use the concept of the absorbed dose as a measure of cause unconditionally. The absorbed dose could be a "good" measure of cause in quantitative description of causal relation between radiation and effects, if and only if the mean energy imparted, $\langle \varepsilon_{IMP.} \rangle_{av}(t)$, is proportional to the mean energy absorbed, i.e., the mean of the change in internal energy of the matter of mass, $\langle \Delta U_{INT.} \rangle_{av}(t)$. However, the difference in these two quantities, $\int_{t_0}^{t} d\tau \oint_{dm} \mathbf{ds} \cdot \langle \boldsymbol{\psi}_{nIR.} \rangle_{av}(\tau)$, depends not only on radiation and matter but also on the size of mass element, dm. The size of the mass element cannot be chosen arbitrarily, since the value of the absorbed dose depends on the size of mass element due to the stochastic nature of interactions between radiation and matter.[10] Thus a statement that "the absorbed dose is a measure of cause in describing causality relation between radiation and effects" does not always hold.

§5. Conclusion

In this paper, the concept of the "absorbed dose" was analyzed from physical point of view, and it turned out that the concept and definition of the quantity is disqualified as a physical quantity. In the ICRU system, (1) the definition of the absorbed dose is not always consistent with the law of energy conservation, and (2) physics or physical phenomena characterizing the quantity is not clear enough. The latter makes impossible to discuss the limit of applicability of the quantity. The authors have shown the way to amend the flaw of the definition. However, even if the definition is corrected, problems on the physical phenomena characterizing the quantity still remains. Thus, the authors could not help concluding that the statement that "the absorbed dose is a well-defined physical quantity" is dubious.

Looking back on the processes of introducing the concept of the absorbed dose, discussions on the applicability of the quantity seem to have been insufficient. It also seems the concept of the quantity is made upon the premise that it can be used without restriction on the types and energy of radiation as well as kind of materials. However, as discussed in §2 and 3, *the absorbed dose is intrinsically dependent both on the types and energy of radiation and on the kind of material*. Thus, the range of applicability of the absorbed dose turned out not so wide as expected.

It is also concluded that the absorbed dose can not always serve a proper quantity as a "measure of cause" in describing causality relation between radiation and effects. Since it depends even on the energy that have already bean brought out from the matter by nIR which by no means affect the matter.

A possible solution to remove this flaw of the concept of the absorbed dose is to amend its definition by replacing "the mass density of the mean energy imparted" with "the mass density of the mean energy absorbed", though this amendment makes the quantity time-dependent. Our proposal of re-defining the absorbed dose can be expressed as follows:

The absorbed dose, $D(t)$, is,

$$D(t) = d\langle \varepsilon_{ABS.} \rangle_{av}(t)/dm,$$

where $d\langle \varepsilon_{ABS.} \rangle_{av}(t)$ *is the mean energy absorbed by ionizing radiation to the matter of mass dm at a specified time, t.*

Here, $\langle \varepsilon_{ABS.} \rangle_{av}(t)$ *is defined as;*

$$\langle \varepsilon_{ABS.} \rangle_{av}(t) = \langle \varepsilon_{IMP.} \rangle_{av}(t) - \int_{t_0}^{t} d\tau \oint_{dm} d\mathbf{s} \cdot \langle \boldsymbol{\psi}_{nIR.} \rangle_{av}(\tau).$$

Numerical values of this quantity is much smaller than that of the currently defined absorbed dose. However, magnitude and performance of the quantity are not related each other. Thus, it cannot be a reason to the claim that this quantity is not adequate as a dose. It is a matter of technology of measurement or evaluation utilizing computer simulation.

There is no clear criterion to classify radiation into ionizing and non-ionizing. In spite of efforts[8,11,12)] to find out the criterion, none of them has been sucsessful to the present. This is "a crying for the moon", since ionization depends on the

kind and state of material. On the other hand, it is not necessary introduce the quantity of dose separately for ionizing radiation and non-ionizing radiation. Our proposal of specifing the "absorbed dose" with the "absorbed energy density", discussed above, meets this requirement.

Quantities generically named dose of ionizing radiation still contains some conceptual ambiguity, though they have been used in many sciences as measures of cause in describing causal relation of radiation effects. The authors would like to emphasize the necessity of further investigations in this field.

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FIGURE CAPTIONS:

Figure 1

The concept of "the energy imparted" in the ICRU terminology. Flow of energy is that of kinetic energy of ionizing particles, and source of energy is the change of rest energy occurring in the matter.

Figure 2

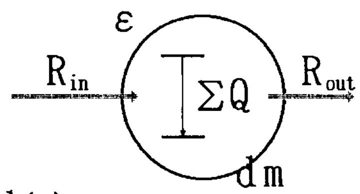
Physical entity of "the energy imparted" is shown schematically. Energy is deposited to the matter instantaneously at time t_0. Line A denotes the amount of initially deposited energy, line B shows internal energy of the matter of mass dm, line D which is complementary of line B represents total energy lost and line E is "the energy imparted" in the ICRU terminology. The difference between line A and line E is the amount of energy having left the mass in the form of ionizing radiation, and the difference between line E and line B corresponds to the amount of energy having left the mass in the form of nIR (line C).

Figure 3

An extreme case where the value of *the absorbed dose* induced by an instantaneous irradiation becomes strongly dependent on time. A mass of ^{59}Co is irradiated instantaneously with thermal neutrons at $t = 0$. (a) During fast deexcitation of the compound nuclei (*i.e.*, excited states of ^{60}Co), many photons (spontaneous gamma-rays) whose total energy is about 7.5 *MeV*/nucleus are emitted. Succeedingly, one beta-ray, one neutrino and two gamma-

rays (their total kinetic energy is about 2.8 *MeV*/nucleus in average) are emitted with half life of 5.27 years. (b) If the volume of the irradiated matter is so large that most gamma-rays will not escape from the volume, the contribution of beta- and gamma-rays of ^{60}Co to *the absorbed dose* reaches as much as one third of the spontaneous gamma-rays' contribution.

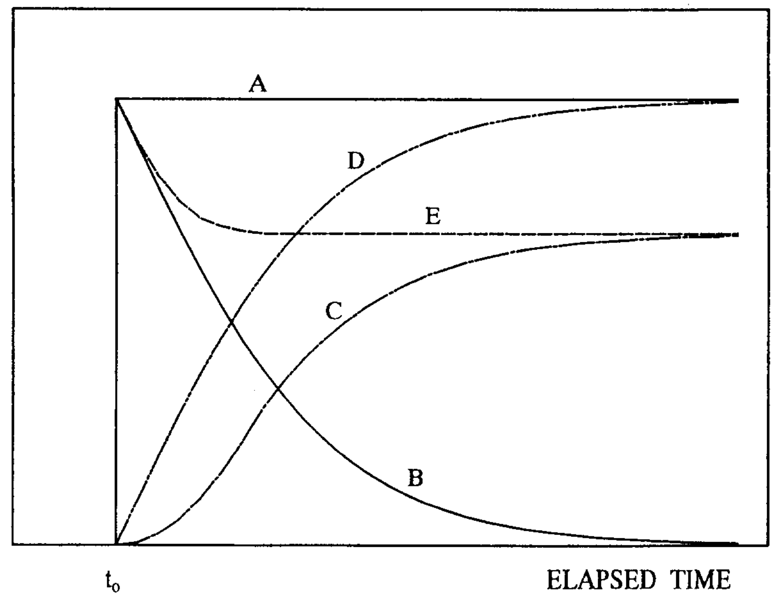
Figure 1



$$D = \frac{d\langle\varepsilon\rangle_{av}}{dm}$$

Figure 2

PHYSICAL ENTITY OF "THE ENERGY IMPARTED"



A: Initial Energy Deposit
B: Increment of Internal Energy
C: Non–Ionizing Radiation Loss
D: Total Energy Loss
E: The Energy Imparted (= B + C)
(A – E = D – C is Ionizing Radiation Loss)

Figure 3a

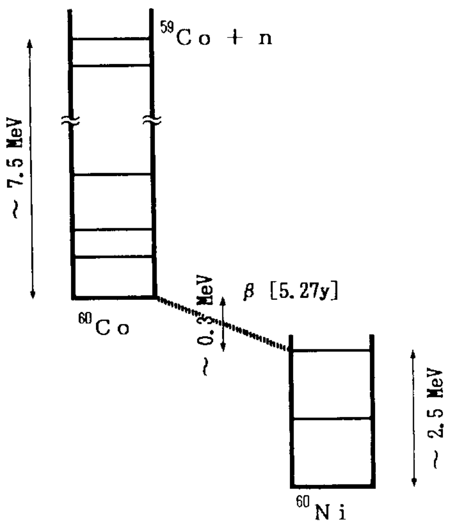


Figure 3b