



On the definition of absorbed dose



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HIGHLIGHTS

- A stringent definition of absorbed dose is given.
- This requires the definition of an irradiation and a suitable probability space.
- A stringent definition is important for an understanding of the concept absorbed dose.

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ABSTRACT

Purpose: The quantity absorbed dose is used extensively in all areas concerning the interaction of ionizing radiation with biological organisms, as well as with matter in general. The most recent and authoritative definition of absorbed dose is given by the International Commission on Radiation Units and Measurements (ICRU) in ICRU Report 85. However, that definition is incomplete. The purpose of the present work is to give a rigorous definition of absorbed dose.

Methods: Absorbed dose is defined in terms of the random variable specific energy imparted. A random variable is a mathematical function, and it cannot be defined without specifying its domain of definition which is a probability space. This is not done in report 85 by the ICRU, mentioned above.

Results: In the present work a definition of a suitable probability space is given, so that a rigorous definition of absorbed dose is possible. This necessarily includes the specification of the experiment which the probability space describes. In this case this is an irradiation, which is specified by the initial particles released and by the material objects which can interact with the radiation.

Some consequences are discussed. Specific energy imparted is defined for a volume, and the definition of absorbed dose as a point function involves the specific energy imparted for a small mass contained in a volume surrounding the point. A possible more precise definition of this volume is suggested and discussed.

Conclusions: The importance of absorbed dose motivates a proper definition, and one is given in the present work. No rigorous definition has been presented before.

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1. Introduction

The quantity absorbed dose is ubiquitous in radiation therapy, radiation biology, medical physics, radiation protection, nuclear medicine, diagnostic radiology, etc. Therefore a stringent definition is important.

In ICRU Report 85 (Seltzer, 2011) specific energy imparted is defined. Absorbed dose is then defined as the expected value of specific energy imparted. This implies that specific energy imparted is regarded as a random variable, which is a real-valued function defined on a probability space (Chung, 2001; Gut, 2009). The definition of specific energy imparted as a random variable,

therefore, must specify a suitable probability space. This is not done in Seltzer (2011). As a probability space is a mathematical description of the situation being considered, in this case an irradiation with ionizing radiation, the definition of the probability space must include the exact conditions of the situation that is described. In the present case this includes a definition of what is meant by an irradiation, and how it is repeated.

Having defined specific energy imparted as a random variable, absorbed dose at a point is defined as the expected value of the specific energy imparted to a volume surrounding the point and containing a small mass. Because of the atomic nature of matter, this volume cannot be arbitrarily small. In fact, it cannot be small compared to interatomic or intermolecular distances in the object. In accordance with Seltzer (2011), but somewhat more explicit, a definition of absorbed dose at a point involving a small volume

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which is large compared to the intermolecular distances is given. The volume thus defined is small compared to the spatial distribution of energy depositions by ionizing radiation.

2. Theory

Probability theory is used to give a mathematical description of experiments (or processes) that can, at least in theory, be repeated, and which give some observable result which will vary randomly for each repetition of the experiment. One important aspect in formulating the theoretical model is that it requires a description of the experiment, and how it is repeated.

In the present case the experiment consists of an irradiation. To formulate a mathematical model it is necessary to give an unambiguous description of what is meant by an irradiation. Loosely speaking an irradiation consists of subjecting a material object to ionizing particles.

For the present purpose a more accurate description is needed. A starting point is to define the particles used to irradiate the object. These will be called initial particles in the present work. During the irradiation the initial particles will give rise to new particles, second, third, etc. generation particles. These higher generation particles are not part of the definition of an irradiation. Due to interaction probabilities they will not be identical even if the initial particles are the same. A parallel can be drawn to a Monte Carlo calculation where the initial particles are given, and other particles are created by interactions with the irradiated object.

A repetition of an irradiation is then to let exactly the same initial particles irradiate the same object. Because of the random nature of the interactions of the particles the energy depositions in the object will not be the same.

In contrast to a Monte Carlo calculation, it is in a real world experiment in general impossible to generate an identical set of initial particles, as the creation of ionizing particles in most cases is of a random nature, such as radioactive decay, or the generation of electrons from a glow discharge. However, this does not prevent the formulation of a mathematical model.

The initial particles are thus defined by their particle type, energy, position at creation, time of creation, direction and energy at creation.

For example, in the treatment of a patient with a radioactive source, such as in brachytherapy, the initial particles would be all particles emitted by the source during the treatment.

It is also necessary to define the environment in which the irradiation takes place. This consists of all materials that could possibly interact with the initial particles or any secondary particle that could be created. In this work this is called the geometry of the irradiation. The geometry can be a function of time. This aspect of the definition is not mentioned in Seltzer (2011).

This motivates the following definition, which is crucial for the definition of absorbed dose:

An irradiation is defined by

1. A set of initial particles and their properties, regarding particle type and energy, position at creation, time of creation, initial direction and
2. A description of the geometry of the irradiation, specifying all materials that could interact with the initial particles or any secondary particles that could be created, and their changes as a function of time.

Absorbed dose is defined using the expected value of the random variable specific energy imparted. The domain of definition of a random variable is a sample space belonging to a probability

space, designed to describe the real-world process we are considering (Gut, 2009), in this case the transfer of energy from ionizing radiation to matter. Therefore, to give a meaningful definition of specific energy imparted as a random variable it is necessary to define a suitable probability space.

3. Results

Using the definition of an irradiation given in the previous section, a probability space describing an irradiation with ionizing radiation can now be defined. It is assumed that the geometry consists of N_A atoms, numbered from 1 to N_A , and that atom j experiences n_j interactions. An outcome is defined by the energy transfers of these interactions. A more complete treatment is given in the appendix.

Before defining absorbed dose, the quantities used in the definition, namely energy imparted and specific energy imparted to the matter in a volume, must be defined. In the following, “energy imparted to a volume” will be short for “energy imparted to the matter in a volume”.

3.1. Energy deposit

The energy deposit, $\epsilon_{j,i}$, is the energy deposited in a single interaction, interaction i of atom j say, as defined in the appendix.

3.2. Energy imparted to a volume V

The energy imparted to a volume V , $\epsilon(V)$, as defined in Seltzer (2011) is

$$\epsilon(V) = \sum_{j,i} \epsilon_{j,i} \quad (1)$$

where the summation is performed over all energy deposits, $\epsilon_{j,i}$, where atom j is in the volume V , and $1 \leq i \leq n_j$

3.3. Specific energy imparted to a volume

The specific energy imparted to the volume V , $z(V)$, is then defined as

$$z(V) = \epsilon(V)/m(V) \quad (2)$$

where

$$m(V) = \sum_j m_j \quad (3)$$

where m_j is the mass of atom j and the sum is extended over all atoms in V .

From the definition of the probability space in the appendix it is clear that the energy imparted, and the specific energy imparted to the volume V are random variables defined on that probability space.

3.4. Definition of absorbed dose

With specific energy imparted defined it is now possible to define absorbed dose. Following Seltzer (2011), absorbed dose is defined as a point function, $D(x)$, where x is a point in the geometry of the irradiation:

$$D(x) = \frac{E(\epsilon(V_{small}(x)))}{m(V_{small}(x))} \quad (4)$$

where $E(\epsilon(V_{small}(x)))$ is the expected value of $\epsilon(V_{small}(x))$ (this is called “mean” in Section 5.2.5 of Seltzer, 2011) and $m(V_{small}(x))$ is

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