The measuring of the absorbed dose in human tissue that underwent irradiation with ionizing radiation

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Abstract. Ionizing radiations are radiations of atomic origin (X) or nuclear origin (α, β, γ). They are composed of either subatomic particles (α, β) or electromagnetic waves (X, γ) which possess enough energy to remove electrons from the atoms and molecules of the medium with which particles interact. They thus generate ionizing processes. The effects that are produced by the interaction of the ionizing radiations with a particular medium (which could be human tissue) have different intensities depending on the nature of the incident radiations, on the rate in which these radiations release energy to the medium and on the total amount of energy released to the medium. For this reason, the energy released by a particular type of ionizing radiations to a particular type of medium has become of great interest both for researchers and for specialists who deal with using ionizing radiations in different fields, such as the biomedical one. The aim of the present paper is to briefly present some of the aspects connected to the way certain quantities are defined, quantities which are specific to the interaction of ionizing particles with the medium they pass through and which are also connected to the energy released in the medium. The paper also describes methods of measuring these quantities.

1. Introduction

Ionizing radiations are radiations of atomic origin (X) or nuclear origin (α, β, γ). They are composed of either subatomic particles (α, β) or electromagnetic waves (X, γ) which possess enough energy to remove electrons from the atoms and molecules of the medium with which particles interact. They thus generate ionizing processes. The ionizing processes that appear as a result of radiations giving up a certain amount of energy to the medium they pass through, also allow to measure (in given specified conditions), this released energy. From the point of view of the present paper, it is important that the ionizing radiations partially or totally give up energy to the medium with which they interact (the interaction medium); this energy has various effects in the medium. These effects can be used in order to detect the ionizing radiations and to measure various characteristic quantities either of the radiations themselves, or of their interaction with a certain medium.

The effects that are produced by the interaction of the ionizing radiations with a particular medium (which could be human tissue) have different intensities depending on the nature of the incident radiations, on the rate in which these radiations release energy to the medium and on the total amount of energy released to the medium. For this reason, the energy released by a particular type of ionizing
radiations to a particular type of medium has become of great interest both for researchers and for specialists who deal with using ionizing radiations in different fields, such as the biomedical one. In the biomedical field, the ionizing radiations are, in present, more and more used, either for the radiodiagnostic and radiotherapy. But, it is well known that their positive effects are accompanied by negative effects. That is why it is very necessary to have adequate and accurate measurement methods for the energy released by these radiations in tissues.

The aim of the present paper is to briefly present some of the aspects connected to the way certain quantities are defined, quantities which are specific to the interaction of ionizing particles with the medium they pass through and which are also connected to the energy released in the medium. The paper also describes methods of measuring these quantities. The paper also describes methods for measuring these quantities and presents a special type of detector, dedicated to the absolute measurement of the absorbed dose, as the quantity which expresses the absorbed energy per mass unit in the interaction medium.

This detector was specially designed, according to the requirements of the theory (the cavity-theory) and needed a complete characterisation. The first step in this characterisation was to verify if it’s way of operating fulfils the requirements of the theory.

2. The absorbed dose – the quantity describing the energy absorption in a medium

The absorbed dose

The absorbed dose, $D$, is a measure of the energy deposited in a medium by ionizing radiation. It is equal to the energy deposited per unit mass of medium, and, so, has the unit $J/kg$, which is given the special name Gray (Gy) [1].

The absorbed dose is the quantity of main interest to the clinician, for both beta and gamma radiations. It is the quotient of $dE$ by $dm$, that is, the differential energy absorbed in the differential mass in the medium. [1]

The photons and the electrons present in different types of ionizing radiation ionize the water molecules, producing free radicals (OH radicals) which, in turn, ionize the molecules and atoms present in the DNA molecules. That is why it is very important, for the radiological protection as well as the medical applications of the ionizing radiation, to know the absorbed dose to water, that is, the energy deposited per unit mass of water, by different radiations [2], [4].

The absorbed dose measurement

The measurement of the energy absorbed in tissues, namely, the measurement of the absorbed dose, is performed by measuring other quantities which are specific to the effects produced by this energy in tissues. The main effects of the ionizing radiation interaction with matter are:

- electrical effect;
- chemical effect;
- thermal effect.

Among these, the most widely used is the electrical effect, which consists of the ionization of the atoms and molecules of a gas submitted to irradiation; the most frequently used gas for this aim is air.

The measurement of the ionization produced in air by the photons (X and gamma radiations) lead to the definition of a quantity named exposure ($X$).

$$X = \frac{\Delta Q}{dm} \tag{1}$$

where $\Delta Q$ is the total ionization electrical charge produced by ionization in the $dm$ mass of dry air. But this quantity does not offer any information concerning the energy deposited by the ionizing radiation in matter. That is why the physicists considered it necessary to define a new quantity related to the energy deposited in matter, and this quantity was the absorbed dose in a given medium.
The measurement of the absorbed dose by measuring the ionization electrical charge or current is very widely used due to several advantages: the electrical measurements are very easy to perform and are also very precise. They make it possible to obtain very low uncertainties regarding the results of the measurements.

The ionometric method for the measurement of the absorbed energy in different media

Heavy charged particles (protons and those heavier) penetrating a material in which nuclear interactions are disregarding show a dose-vs- in depth distribution in the shape of the classical Bragg curve. This means that if a particle spends the first half of its initial kinetic energy along a path length \(x\), the remaining half of the energy will be spent in a distance equal to approximately \(x/3\), this crowding the partial rate of energy expenditure toward the end of the track. The dose decreases from its maximum as the particles run out of the energy and stop. This decreasing limb of the Bragg curve roughly coincides with the corresponding curve of the particles vs. depth.

The highly ionized dose maximum shown in Figure 1 [3] suggested the possible usefulness of such a beam for delivery of therapeutic doses of ionizing radiation to tumors at some depth in the body, while minimizing the dose to overlying human tissue. This possibility was discussed by Raju et al (1969). They pointed out that the Bragg peak of heavy particles is too located, and needs to be “smeared out” in depth if tumors even 1 cm in diameter are to be uniform dosed.

The Bragg-Gray cavity theory can be applied whether the field of charged particles enters from outside the vicinity of the cavity, as in the case of a beam of high-energy particles, or is generated in medium \(W\) through interactions by indirectly ionized radiation. In the latter case it is also assumed that no such interactions occur in gas \((g)\).

If the medium \(g\), occupying the cavity, is a gas \((g)\) in which a charge \(Q\) (of either sign) is produced by the radiation, \(D_g\) can be expressed (in grays) in terms of that charge as

\[
D_g = \frac{Q}{m} \left( \frac{\bar{W}}{e} \right)
\]

(2)

where \(Q\) is expressed in coulombs, \(m\) is the mass \((kg)\) of gas in which \(Q\) is produced and \(\frac{\bar{W}}{e}\) is the mean energy spent per unit charge produced \((J/C)\). Using equation (1), the Bragg-Gray equation is obtained, in terms of cavity ionization [5].

\[
D_m = \frac{Q}{m} \left( \frac{\bar{W}}{e} \right)_n S_g
\]

(3)

The most complex elaboration of the cavity theory for \(\beta\)-particles was presented by Böhm [5]; he also designed a cavity chamber with variable volume (the extrapolation chamber). It was intended for the absolute measurement of the energy released (that is, the absorbed dose) in a particular medium for \(\beta\)-radiation.
This equation allows one to calculate the absorbed dose in the medium immediately surrounding a Bragg-Gray cavity, on the basis of the charged particles produced in the cavity gas, provided that the appropriate values of $\frac{W}{e}$ and $\bar{S}_g^w$ are known.

The medium $w$ surrounding the cavity of an ionization chamber is ordinarily just the solid chamber wall itself, and one often refers to the Bragg-Gray theory as providing a relation between the doses in the gas and in the wall [3], [6].

Such a type of ionization chamber (extrapolation chamber) was also designed and built in the Radiation Metrology Testing and Dosimetry Team (CMRID) of the “Horia - Hulubei” National Institute for Research and Development in Physics and Nuclear Engineering (IFIN-HH).

3. Experimental characterisation of the ionization chamber

3.1 Description of the extrapolation ionization chamber built in IFIN-HH

The ionization chamber has a cylinder shape with plane-parallel electrodes (Figure 2). The voltage electrode (polarization electrode) is made up of an electroconducting layer (an aluminium layer a few microns thick), which is placed on one of the sides of a very thin sheet of mylar (7 mg/cm²); this electrode is also the input window of the detector. The collecting electrode is made up of a graphite layer placed on a polyester block. This graphite layer is electrically isolated from the guard electrode (guard ring). The latter consists of a circular layer of graphite. The guard ring is connected to the detector’s ground and is intended to define the sensitive volume of the detector from an electrical point of view [7].
The sensitive volume of the detector can be modified mechanically, by varying the distance between the polarization electrode and the collecting electrode, with a micrometric screw, in the range of 0.5-16 mm [7].

Figure 3 shows the size and shape of the electrodes.

3.2 Experiments

Figure 4 presents the electrical circuit used for measuring the ionization charge (or current) of the ionization chamber [7], [8].
As previously shown, in order to calculate the rate of the absorbed dose (the rate of the energy absorption in a given medium) particular forms of equation (3) were used. So, for the β-ray, the relation for the absorbed dose rate is:

\[
\dot{D} = k \left( \frac{\bar{W}}{e} \right) \frac{mS_w}{A\rho} \left( \frac{dI}{dx} \right)_{x=0}
\]

where:
- \(K\) = constant which takes into account the unit of measure
- \(\bar{W}/e\) = the average energy required to generate an ion pair in air
- \(e\) = the elementary electronic charge
- \(A\) = the area of the collecting electrode
- \(mS_w\) = the ratio of the mass stopping powers in the wall and the gas of the chamber
- \(\rho\) = the air density in the sensitive volume of the ionization chamber

In order to see to what extent the ionization chamber made by IFIN-HH acts accordingly to the cavity theory, referring to β and α radiation, the following experiments were made [8].

The experimental lifting of the curves \(I=I(U)\) for a given source of β and α radiation, in a well-defined geometry. The geometry corresponds to various distances between the voltage electrode and the collecting electrode (the collector), \(x\), and also allowed to establish the range within which the detector is working at saturation.

Choosing a value for the polarisation voltage that lies within the saturation range for all the values of the distance between the electrodes, \(x\), the graphic representation of the curve that gives the ionization current, \(I\), versus the distance between the electrodes of the chamber, is determined experimentally.

For the value of the polarization voltage, \(U=15\) V, inside the saturation range of the \(I=I(U)\) curve, we made also measurements of the ionization current and so, we obtained the curve, that expresses the ionization current versus the distance between the electrodes, \(x\), respectively the sensitive volume of the detector \((V = A)\).

### 4. Results

The measurement of the ionization current

The ionization current was generated by the detector in the presence of a source of α-ray, in a fixed geometry. The ionization current was measured with a Keithley 617 electrometer.

In order to identify the saturation range of the polarisation voltage, we measured the ionization current \(I\), versus the polarisation voltage, \(U\), for three values of the distance between the electrodes. The results of these measurements are given in Table 1.
Table 1. The average values of the ionization current $I$, for different values of the polarization voltage, $U$, considering three given values for $x$.

| $U$ (V) | $I(A) \cdot 10^{12}$ | $s_n$ | $I(A) \cdot 10^{12}$ | $s_n$ | $I(A) \cdot 10^{12}$ | $s_n$ |
|--------|----------------------|-------|----------------------|-------|----------------------|-------|
| 0      | 0.9562               | 0.0689| 1.3015               | 0.0720| 0.2280               | 0.00937|
| 0.1    | 0.9149               | 0.0056| 0.9008               | 0.0105| -0.1689              | 0.08783|
| 0.2    | 0.7831               | 0.0075| 0.4981               | 0.0055| -0.2463              | 0.00338|
| 0.3    | 0.6781               | 0.0042| 0.1961               | 0.0045| -0.3016              | 0.00369|
| 0.4    | 0.5147               | 0.0040| -0.0083              | 0.0006| -0.4289              | 0.0012 |
| 0.5    | 0.3569               | 0.0044| -0.1558              | 0.0749| -0.4775              | 0.00354|
| 0.6    | 0.2266               | 0.0025| -0.2707              | 0.0049| -0.5232              | 0.0015 |
| 0.7    | 0.1173               | 0.0030| -0.3866              | 0.0010| -0.6658              | 0.17079|
| 0.8    | -0.0103              | 0.0007| -0.4498              | 0.0035| -0.6970              | 0.00451|
| 0.9    | -0.2214              | 0.0030| -0.5420              | 0.0025| -0.7821              | 0.00481|
| 1      | -0.2097              | 0.0041| -0.6054              | 0.0035| -0.8231              | 0.00561|
| 1.1    | -0.3385              | 0.0037| -0.6331              | 0.0010| -0.9535              | 0.01032|
| 1.2    | -0.4842              | 0.0046| -0.6753              | 0.0053| -1.1163              | 0.0109 |
| 1.3    | -0.6296              | 0.0062| -0.7574              | 0.0069| -1.1316              | 0.01392|
| 1.4    | -0.6747              | 0.0088| -0.7906              | 0.0057| -1.1429              | 0.10211|
| 1.5    | -0.7835              | 0.0089| -0.8000              | 0.0076| -1.3976              | 0.01178|
| 1.6    | -0.9372              | 0.0080| -0.8269              | 0.0051| -1.4437              | 0.00997|
| 1.7    | -0.9951              | 0.0065| -0.9205              | 0.0055| -1.5508              | 0.01679|
| 1.8    | -1.0525              | 0.0059| -0.9639              | 0.0049| -1.7373              | 0.01422|
| 1.9    | -1.1389              | 0.0103| -1.2585              | 0.0085| -1.7860              | 0.01198|
| 2      | -1.1231              | 0.0080| -1.2666              | 0.0092| -1.5118              | 0.36604|
| 2.5    | -1.4284              | 0.0115| -1.4584              | 0.0182| -2.0908              | 0.02444|
| 3      | -1.5745              | 0.0307| -1.6113              | 0.0228| -2.2369              | 0.0164 |
| 10     | -2.0935              | 0.0187| -2.6550              | 0.0231| -3.1186              | 0.02122|
| 30     | -2.3699              | 0.0241| -3.1101              | 0.0335| -3.5970              | 0.04656|

Table 1.
The average values of the ionization current $I$, for different values of the polarization voltage, $U$, considering three given values for $x$.

where $s_n$ is the standard deviation of the average value of $I$.
The curve $I=I(U)$ for the three values of $x$, corresponding to the data from Table 1 are presented in Fig. 5.
Choosing a value of 15 V for the polarization voltage that lies within the saturation range for all the values of the distance between the electrodes, x, the graphic representation of the curve that gives the ionization current, I, versus the distance between the electrodes of the chamber (the sensitive volume of the detector), is determined experimentally.

From the analysis of the experimental data, the first important observation is that for U=0, in the presence of the radioactive source, the ionization chamber presented a positive current, whose values depend on the value of the distance between the electrodes of the chamber. That means that, in the calculation of the absorbed dose rate, an appropriate correction must be done.

The analysis of the results obtained regarding the $I=I(U)$ characteristics of the ionization chamber in the presence of an $\alpha$-radiation field, as above presented (Fig. 5), shows that in this case, the detector has a typical behavior. The ionization current reaches the saturation value fairly quickly for the three values of the distance between the electrodes. Other experiments have shown that the detector has the same behavior for the values of $x$ in the range (0.5 .. 15)mm.

The ionization current reaches the saturation value fairly quickly for all the possible values of the distance between the electrodes.

In saturation conditions, we have concluded that the $I=I(x)$ curve also has a typical behavior for this type of detector, respectively, for $x \to 0$, the ionization current is proportional to the distance between the electrodes, $x$, that is to the sensitive volume of the chamber. [9]
6. Conclusions

The analysis of the experimental data obtained using our ionization chamber with variable volume, lead to some important conclusions:

The \( I=I(U) \) curves, obtained for \( \alpha \)-ray irradiation of the detector, (Figure 5) indicate that the ionization chamber reached the saturation for all the values of the distance between the electrodes (i.e. for all the values of the sensitive volume). In this case, we can be sure that the collecting of the ionization charges produced in the sensitive volume of the detector is complete and so, the chamber is working at saturation. In this case, it was possible to choose a value of the polarising voltage corresponding to the saturation, for all the values of \( x \).

For the values of the polarising voltage, selected according the criteria mentioned abose (\( U=15V \)), the values of the ionization current of the chamber, \( I \), (Table 1) show a typical dependence on the distance between the electrodes \( x \). The graph of the curve \( I=I(x) \), as presented in Fig. 6, clearly shows a linear range, when \( x \to 0 \) this behaviour of the curve \( I=I(x) \) is very important, because it means that this ionization chamber, which we used for experiments, fulfills one of the most important requirements of the cavity-theory: the ionization current is proportional to the sensitive volume of the detector. In this case, \( (dI/dx)_{x \to 0} \) is a constant which leads to the corresponding value of \( \epsilon \), according Eq. (4).

The results of our experiments are a confirmation for the fact that the extrapolation chamber we built fulfill the requirements on the cavity- theory, and so, it is adequate for the absolute measurement of the absorbed dose (i.e. the energy absorbed per mass unit) in the solid material that surrounds the gas cavity. When this solid material is equivalent to the human tissue as is the case with this detector, the results of the measurements performed with this chamber lead to the value of the energy absorbed per mass unit of the human tissue.

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