History of radiological protection and evolution of dosimetric quantities

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Abstract: The paper presents a brief history of radiation protection and the evolution of radiation quantities. Special attention is given to the history of tissue weight factors. The internationally adopted system of radiation quantities is presented.

Keywords: ionising radiation, radiation protection, radiation quantities, tissue weighting factors

1. Introduction

Ionizing radiation was discovered at the end of the 19th century. X-ray radiation, which is used extremely widely in medicine, but also in other fields, was discovered by Wilhelm Roentgen in 1895. Shortly after this invention, in 1896, radioactivity was discovered (Henri Becquerel), which represents the spontaneous transmutation of the atomic nucleus, with the emission of one or more particles or electromagnetic radiation. This was followed by discoveries of other types of ionizing radiation, such as, for example, neutron radiation.

The main characteristic of ionizing radiation is that it can ionize atoms and molecules of matter with which they interact when one or more electrons are ejected from the atom, leading to the creation of free electrons and positively charged atoms and molecules. For biology and medicine, the most important process is the ionization of water molecules, because there are many of these molecules in human cells. After ionization, the water molecule dissociates into H^+ and OH^-, which further interact with the present atoms and molecules. This process is called "radiolysis of water", and as a final result, it leads to the creation of free chemical radicals, which by diffusion can reach the DNA molecule and damage it with its chemical aggressiveness. Non-ionizing radiation cannot cause the ionization of water molecules, nor damage to DNA molecules, and that is the main difference between the two types of radiation. The text presented below is related only to ionizing radiation.

2. History of radiation protection

After the discovery of ionizing radiation, it was not known that it could cause damage to the tissue. Some great scientists sensed that radiation could be harmful or dangerous and issued some warnings. There is a record that Nikola Tesla, who was among the first to warn of the danger of X-ray radiation, expressed the thought "Experimenters should not get too close to the X-ray tube" in June 1896. On December 12, 1896, in the Western Electrician magazine, Wolfram Fush published a recommendation on how to reduce the effect of radiation in three points:

a) shorten the irradiation time as much as possible;
b) do not bring the x-ray tube closer than 12 inches to the body;
c) rub out the irradiated part of the skin gently with Vaseline.

It is not known whether he was aware of Nikola Tesla's opinion when making these recommendations, but the first two recommendations have become the basis of radiation protection. Despite these warnings, there was almost no radiation protection, and it was completely disorganized. Organized protection against ionizing radiation began only in 1925.

Until the twenties of the last century, it was not known that ionizing radiation could cause cancer and genetic effects. It was known that radiation could cause reddening of the skin. The connection between leukemia and radiation was discovered in a strange way, almost by accident. At that time, the watch industry was developed in the USA in New York. Clocks with hands and dials that glow in the dark were made by mixing some fluorescent substance with radium or thorium; such a mixture was applied in the form of paint with brushes on certain surfaces. Workers who worked in such factories were exposed to an increased dose of radiation due to significant internal contamination, and soon a higher incidence of leukemia was discovered among them than among the rest of the population. Leukemia is the first cancer that appears after radiation, a year and a half to two years. This fact contributed to the understanding of the connection between radiation and cancer. Other cancers appear much later after radiation, ten or more years, and it has been difficult to establish a connection between radiation and the effect.

2.1 Organized radiation protection

An organized approach to ionizing radiation protection dates back to 1925, when the first congress of radiologists was held in London. At this congress, a body was established which was called the "International Committee on the X Radiation Unit", which was later renamed the "International Commission on Radiological Units". Three years later, in 1928, another international body was formed, called the "International Commission on Radiological Protection". The Commission had seven members and the first president was Ralf Sievert, from its host country, Sweden.

The Commission soon began its work, and in 1934 they proposed a permissible, tolerable level of radiation exposure of 0.2 R/d; according to current measures, this corresponds to 500 mSv/year. This was three times less than the previously recommended value of 0.6 R/d which was independently proposed by Sievert and Arthur Marceller (1925). Sievert and Marceller's recommendation was based on the idea of preventing reddening of the skin, which is one of the first effects that appear after radiation. The ICRP Commission met once more before the Second World War, in 1937, and only after the war, in 1950, in London. At that meeting, a maximum permissible dose of 0.3 R per week, which corresponds to 150 mSv/year, was proposed for professionally employed persons.

At the beginning of the fifties of the last century, an intensive study of the effects of ionizing radiation on living tissue began. The survivors of the atomic bombings in Hiroshima and Nagasaki were studied and monitored in detail - it was a living laboratory. It has been discovered that in addition to leukemia, radiation can cause other types of cancer as well as genetic effects. It was considered that there is no dose threshold for genetic effects, and the Commission, at a meeting held in 1956, proposed reducing the maximum permissible dose for professionals from 0.3 R per week to 0.1 R per week, which in today's terminology amounts to 50 mSv/year. In addition, at the same meeting, a new concept was introduced, the protection of the population that does not work with radiation sources, and 1/10 of the dose for professionally employed persons was proposed for them.

Also, in the fifties of the last century, two more international institutions dealing with radiation protection and related problems were founded. The first of them was founded in 1956 by the United Nations, and was called the "United Nations Scientific Committee on the Effects of Atomic Radiation", abbreviated UNSCEAR. A year later, in 1957, the International Agency for Atomic Energy (IAEA) was founded, with headquarters in Vienna, Austria.

By the end of the fifties of the last century, numerous nuclear reactors were built - research, energy and other, and in addition to Hiroshima and Nagasaki, numerous test nuclear explosions took place, as well as two major nuclear accidents. The first of them occurred in England in Windscale, and the second in Kishtim near Chelyabinsk in the former USSR (current Russia). Both accidents led to significant environmental contamination in the wider area around the reactor. A significant accident occurred in Vinca Institute on October 15, 1958, which resulted in the irradiation of six people (one of whom died), but without contaminating the reactor environment. This accident led to the formation of an organized service for radiation protection at the Vinca Institute and soon to the adoption of the Law on Radiation Protection. Thus, the former Yugoslavia became one of the first countries in the world to have such a law. Atmospheric and other nuclear tests carried out in the fifties and sixties led to the global contamination of the world with radioactive fission products. In this situation, the influence of the ICRP and other agencies grew in this field . The main activity of the ICRP (and UNSCEAR) at that time was the collection, systematization and analysis of data on the sources and effects of radiation. On that basis, recommendations regarding radiation protection were issued in the form of publications - most countries in the world follow these recommendations, incorporate them into their legislation and represent the basis of radiation protection.

The recommendations issued in 1977 and 1991 [1,2] are particularly significant. The maximum permissible doses were reduced for the last time in the recommendations of 1991, and 20 mSv/year, averaged over 5 years, was recommended, with the condition that in one year the effective dose must not exceed 50 mSv. The annual maximum dose for the population is proposed to be 1 mSv.

2.2 Concepts adopted in ICRP publication no. 60, from 1991

After publication 26 [1], work continued on the adoption and further development of radiation protection. Special attention was paid to the ALARA principle because for its application it was necessary to adopt the monetary equivalent of a human life, which caused ethical discussions in which even the Vatican became involved. Also, for the first time, the radon problem is taken into consideration. As a consequence of the new development, the Commission adopted in 1990, and in 1991 published the new recommendations number 60 [2]. The most important is the reduction of the annual limit dose from 50 to 20 mSv averaged over 5 years. Also, the previous quantity, the *effective dose equivalent*, has been replaced by the *effective dose*. Instead of radiation quality factors, radiation weighting factors with the same numerical values for various types of radiation were introduced.

3. Evolution of radiation units

From the very beginning, the problem of determining how much an individual was irradiated appeared. This problem, in the opinion of the authors of this text, has not been fully resolved even today. It is necessary to define physical quantities (and units) that represent a person's exposure to radiation. At that time, it was well known that radiation, ionizing the air, creates a certain amount of charge in the air. It was logical to define a physical quantity that describes air ionization. This was the exposure dose (or just exposure), denoted by X, and was defined as the quotient of the charge, dQ created by the radiation (X and gamma) and the mass of air, dm, in which that charge was created:

$$X = \frac{dQ}{dm} \tag{1}$$

The exposure dose unit was defined as 1 R (one Rendgen, used above) and represents one electrostatic charge created in 1 gram of air. In parallel with this quantity, the rate of the exposure dose was defined, and the unit is 1 R/h. As a measure of irradiance, 1 R has been used for a long time. For example, if in some space the rate of the exposure dose is 0.1 R/h, and a person spends 10 hours in that place, then he "received a dose" of 1 R. This is a rough estimate of the actual exposure. For a better assessment of radiation, it is necessary to use more precise and better-defined sizes.

Ionization in the air, i.e., the amount of charge created, can be connected to the energy absorbed in the mass of air because an average of 34 eV is spent for one ionization event in the air. It was soon shown that the final biological effect is determined by the absorbed energy, and therefore a quantity called the absorbed dose, D, was introduced and defined as the quotient of the energy, dE, and the mass of matter, dm, in which the absorption occurred:

$$D = \frac{dE}{dm} \tag{2}$$

The unit for absorbed dose is 1 Gray, i.e., 1 Gy=J/kg.

Over time, it became clear that different types of radiation cause different damage and cause different effects. For example, comparing alpha radiation and gamma radiation reveals this difference. Gamma (as well as X) radiation creates spatially scattered, rare damage. On the other hand, alpha radiation creates very dense damage, and can, for example, at a distance of less than 100 μm create more than 100,000 ionizations. It is clear that the latter case is much more difficult to repair, which normally happens in the human body. In order to account for this difference, a physical quantity, the equivalent dose, was introduced, which was originally defined as

$$H = QND \tag{3}$$

where D is absorbed dose, *Q* quality factor of radiation, and *N* is the product of all other modifying factors. This definition was modified later, and it is as follows

$$H = \sum_R w_R D_R \tag{4}$$

where D_R is absorbed dose due to the radiation type R, w_R are radiation weighting factors and they are 1 for X and gamma radiation, 5 to 15 for neutrons and 20 for alpha radiation.

It was later shown that various organs and tissues in the human body are differently sensitive to radiation. To account for this difference, a new quantity was introduced called the effective dose, E, and is defined as

$$E = \sum_T w_T H_T \tag{5}$$

where H_T is the equivalent dose in the organ/tissue marked with T, and w_T is the so-called tissue weighting factor for the organ/tissue T: it represents the probability that cancer will appear in a given organ if the whole human body is uniformly irradiated. Tissue weighting factors were derived from studies of the surviving population irradiated in Hiroshima and Nagasaki at the end of World War II. Since this population has been followed since World War II, there has been some change and evolution of tissue weighting factors. Tissue weighting factors are shown in Table 1.

Table 1. Tissue weighting factors according ICRP 26 (1977), ICRP 60 (1991) and ICRP 103(2007) [1,2,3]

Main organs or tissue	Tissue weighting factors, w_T		
	ICRP26	*ICRP60*	*ICRP103*
Gonads	0.25	0.20	0.08
Red bone marrow	0.12	0.12	0.12
Colon	-	0.12	0.12
Lungs	0.12	0.12	0.12
Stomach	-	0.12	0.04
Bladder	-	0.05	0.12
Breast	0.15	0.05	0.12
Esophagus	-	0.05	0.04
Liver	-	0.05	0.04
Thyroid	0.03	0.05	0.04
Brain	-	-	0.01
Salivary glands	-	-	0.01
Skin	-	0.01	0.01
Endosteum	0.03	0.01	0.01
Remainder	0.30	0.05	0.12

In the last column of Table 1, the newly adopted numerical values for tissue factors for the specified tissue and organs are given, which range from 0.01 to 0.12 according to the recommendations in ICRP publication 103 from 2007 [3]. These recommendations have updated the tissue factors, based on the latest available scientific data on exposure to ionizing radiation.

The first group of organs/tissues with the highest individual weight factor of 0.12 consists of bone marrow (red), colon, lung, stomach, breast, blader and tissue of the "remainder". The remainder of the body consists of 13 organs: adrenal glands, extrathoracic region, gall bladder, heart, kidneys, lymph glands, oral mucosa, prostate (male), small intestine, spleen, pancreas, thymus, and uterus/cervix (female). All organs of the remainder are treated as one organ with a weighting factor of 0.12. The second group with a factor of 0.08 consists only of gonads. The new weighting factor for gonads is 2.5 times lower than the previous one, which was 0.20, which represents one of the biggest changes compared to the old recommendations. The third group with an individual factor of 0.04 consists of the esophagus, liver and thyroid. Finally, the tissue group with the smallest individual factor of 0.01 follows: skin, brain, salivary glands, and endosteum. Organs which have a probability smaller than 1 % are in the group remainder.

3.1 Current system of radiation units

According to current international standards, there are three groups of radiation quantities. The first group consists of physical quantities, Fluence, Kerma and Absorbed dose. The second group is the protective quantities, mean absorbed dose in an organ or tissue, equivalent dose and effective dose according to the definitions given in the previous text. The effective dose defined according to equation (5) requires knowledge of the equivalent (that is, the absorbed dose) by the organs of the human body, which means that it is not a measurable quantity. For this reason, a third set of quantities that are measurable and called operational quantities has been defined. Ambient dose equivalent, H*(d) and directional dose equivalent H'(d,Ω) are used for area monitoring. Personal dose equivalent, H_p(d), is used for monitoring the exposure of individuals. The relationship between these quantities is given in Figure 1.

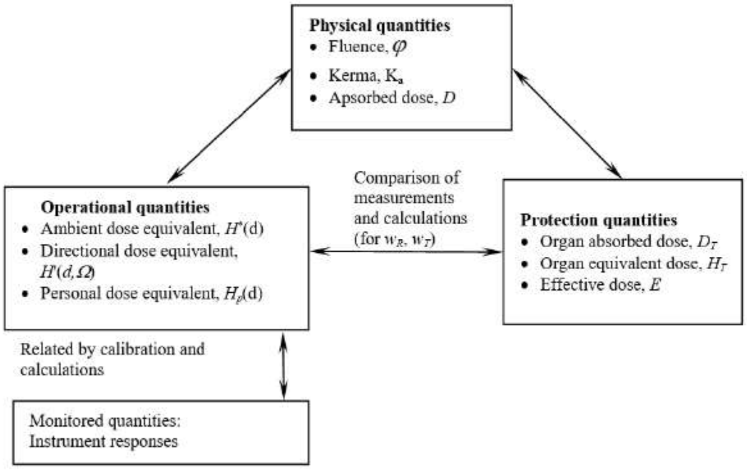

Fig. 1. The relationship between physical, protective and operational quantities

However, the current system has its drawbacks. Based on the joint ICRP/ICRU Report 95, it was proposed to significantly modify the more than 30-year-old approach to measuring quantities in radiation protection, based in part on the ICRU sphere concept.

Consequently, the ICRU, in collaboration with the ICRP, developed new operational quantities (ICRU, 2020) [4], which are shown in Figure 2. The main philosophical change is that the operational quantities are now defined as the product of fluence at a point in space with conversion coefficients which are defined in the same reference phantoms (ICRP110, 2009) [5] used to calculate protective sizes. In addition, the range of energies and types of radiation for which conversion coefficients are available has been expanded.

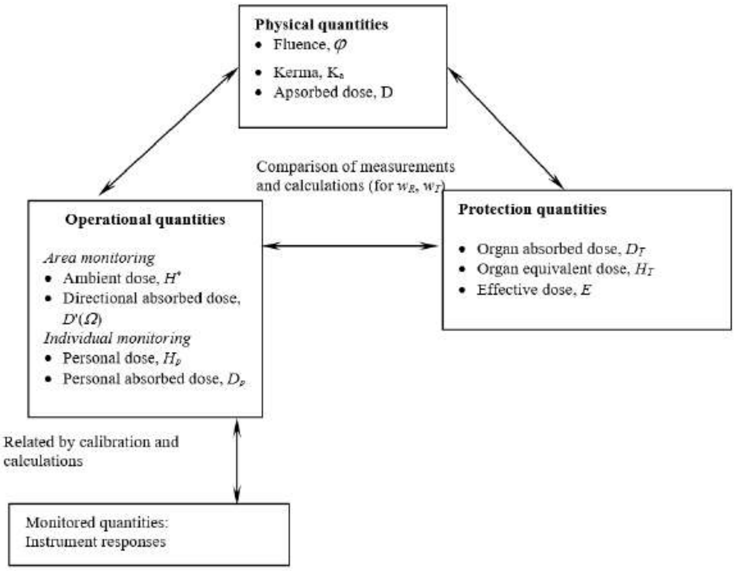

Figure 2. Relationship between radiation protection quantities and new operational quantities according to recommendations of ICRU Report 95 (ICRU, 2020)

4. Conclusions

Defining radiation quantities is a field that has been developing for almost 100 years. The target size is the Effective Dose, which best reflects how much a person is irradiated, but it is unmeasurable. That is why a set of measurable quantities is defined, which are translated into an equivalent and effective dose through the appropriate conversion coefficients.

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