Assessment of Expected Individual Effective Dose of Internal Exposure

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Abstract. When referring to ionizing radiation effect on a human body, we should acknowledge first the physical process of interaction of radiation with tissues and organs. In this interaction, the energy of the particles goes for ionizing and exciting of atoms and molecules. Passing through the fabric, different radiations deposit their energy in a different way on one hand, while the same type of radiation (gamma rays, neutrons, alpha- or beta particles) having the same magnitude has a different influence on the different tissues in the body. The process of work planning in an environment with ionizing radiation is of significant importance for the safety and health of workers, with a number of rules and conditions aiming at the minimum impact on the organism. The present work provides an overview of the method and stages in assessment of the individual effective dose of internal exposure in an environment with ionizing radiation.

Keywords: ionizing radiation, absorbed dose, equivalent dose, effective dose, internal exposure, dose assessment

1. INTRODUCTION

The effects of particles travelling through matter depend on the type of material they encounter, as well as their nature. A charged particle passing through a medium would start an ionization process by continuously taking out electrons from the atoms and molecules, while a neutral particle, gamma or neutron do not interact directly, but rather achieve an indirect ionization through interactions with charged particles - a gamma would knock on an atomic electron, a neutron - a proton or a light nucleus (Public domain, Radioactivity).

The mass of the incoming particle also plays an important role - alpha particles (He^{2+} nucleus), which are nearly 7,300 times heavier than beta particles (either an electron or a positron), are capable of stronger ionization of the medium, but slower down much more quickly. Beta particles, on the other hand, are able to penetrate even more, but without achieving the same ionizing effect. The alpha, beta and gamma radiations have not enough energy to make matter radioactive, while neutrons intrude easily inside the nucleus, provoking nuclear reactions and inducing radioactivity. Radiation can lead not only to ionization, but also to disturbing the atomic structure and causing the molecules to break apart.

Understanding the way radiation interacts with matter allows us to protect ourselves from the harmful effects. Still, calculating the effect of radioactivity dose on any given individual is incredibly complex, given the high number of considerations involved. Only certain thing is that high doses lead to death.

2. INDIVIDUAL EFFECTIVE DOSE ASSESSMENT

2. 1. Radiation exposure

The two principal types of human exposure to radiation are internal and external.

External exposure takes place when the radioactive source is located outside the specimen, and it is mostly due to gamma rays coming from natural radioactivity of cosmic radiation, rays emitted by rocks, as well as exposer of all medical examinations. This type of exposure lasts only for as long as the specimen is in proximity to the source and that makes it less dangerous considered long term.

Internal exposure, on the other hand, occurs when the source of ionizing radiation is located inside the specimen, which makes it much more dangerous, as radioactive rays have direct impact on specific organs and tissues for a long period. Usually internal exposure is a consequence of ingestion (contaminated food or water) or inhalation of radioactive substances (mostly radon gas). This exposure is mainly used in medicine when placing radioactive tracers inside the body for either diagnostic or therapeutic purpose.

2. 2. Dose definition

Evaluating impact of radiation by measuring physical quantities and monitoring the biological effect is one of the main objectives of dosimetry. The International Commission on Quantities and Units (ICRU) and International Commission on Radiological Protection (ICRP) are the two international scientific bodies, which provide all terms and conditions used in dosimetry.

There are three main quantities describing the biological effects of ionizing radiation – absorbed dose, equivalent dose and effective dose (Fisher et al., 2017).

Absorbed dose (D_T) gives the ionizing radiation local energy deposition in an absorbing medium. It is related to the number of ionization events in the target region, and ionization events are related to the caused physical damage. The unit of absorbed dose is called gray (Gy), where 1 Gy is equivalent to 1.0 $J.kg^{-1}$.

Equivalent dose (H_T) describes local biological dose – it is calculated for individual organs as the sum of absorbed doses in an organ or tissue times the weighting factor specific for this organ or body part, reflecting the effectiveness of radiations (alpha, beta, gamma particles, neutrons etc.), as shown in Eq. 1.

$$H_T = \sum_R D_{T,R} W_R \quad (1)$$

$D_{T,R}$ is the absorbed dose for all different types of radiation, averaged over the tissues or organs (T), and W_R is the radiation-weighting factor, which describes the toxicity of the radiations involved for an equal amount of deposited energy. The unit for Equivalent dose is Sievert (Si), but rem is also used (1Sv = 100 rem).

Effective dose (E) is a mathematical construct, shown in Eq. 2, used in radioprotection, which determines how dangerous an individual's exposure to radiation can be. It gives the dose for the entire body as the sum of all equivalent doses for all organs times the specific weighting factors for each tissue.

$$E = \sum_T H_T W_T \quad (2)$$

H_T is equivalent dose, while W_T stays for weighting factors for different tissues, shown in Fig. 1.

Tissue	Tissue weighting factor, wT	ΣwT
Bone-marrow (red), colon, lung, stomach, breast, remaining tissues(*)	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
	Total	1.00

(*) Remaining tissues: Adrenals, extrathoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (♂), small intestine, spleen, thymus, uterus/cervix (♀)

Fig. 1 The ICRP tissue weighting factor values recommendation (ICRP, 2007).

The main uses of effective dose should be:

- Prospective dose assessment for planning and optimization in radiological protection;
- Demonstrating compliance with dose limits for regulatory purposes;
- Establishing a radiation worker's dose record;
- Comparing typical doses from different diagnostic procedures in medical examinations.

2. 3. Methodology

Determination of doses after internal and external radiation exposure of workers and members of the public is a complex procedure. There are no operational dose quantities defined, that provide a direct assessment of the expected effective dose. This implies application of different methods to assess the equivalent or effective dose due to radionuclides in the human body. These methods combine various activity measurements and application of biokinetic and dosimetric models (Paquet et al, 2016).

The total number of radioactive decays, occurring within specific tissues, organs or body regions over a given time period, are calculated using biokinetic models for individual elements and their isotopes. For professional workers in environment with possible radioactive contamination, usually this time period is 50 years, while for normal population (non-professionals) it goes up to 70 years. Dosimetric models are then used to calculate the deposition of energy in all important organs and tissues for transformations occurring in each body region, taking account of the energies and yields of all emission (ICRP, 2008).

Methods for calculating the expected effective dose after intake of radionuclides are shown in Fig. 2.

The dose coefficients and bioassay functions from these methods could be used for both prospective and retrospective assessments of exposure. Prospective assessments use information on projected exposures to radionuclides and are designed to estimate intakes and resulting doses for workers engaged in specific activities, or for members of the public, exposed in specific circumstances. These assessments generally make use of default assumptions on exposure conditions and default values for parameters describing material-specific properties (particle size distribution of an inhaled aerosol, absorption characteristics of a material after inhalation or ingestion, etc.). Retrospective assessments, on the other hand, use the results of individual and workplace monitoring in order to maintain individual dose records and demonstrate compliance with regulatory requirements.

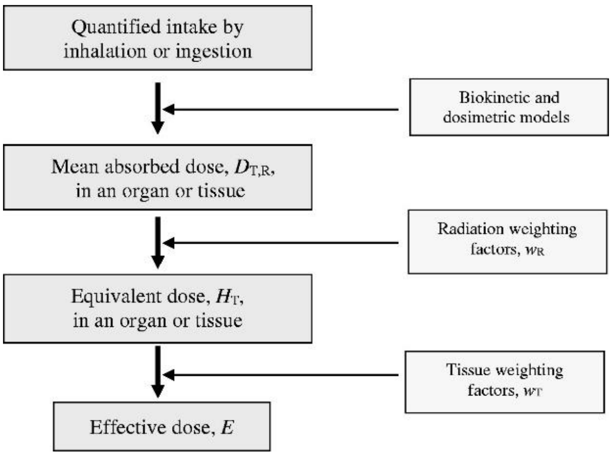

Fig. 2 Calculation of absorbed dose and ICRP's protection quantities, equivalent and effective dose, for intake of radionuclides (ICRP, 2015).

Doses from intakes of radionuclides can also be assessed retrospectively from bioassay measurements (e.g. daily urinary and fecal excretion) or from direct measurements of the radionuclides in the body.

2. 4. Uncertainties

When referring to internal effective dose assessment, the uncertainties depend on (Paquet et al, 2016):

- Uncertainties in measurements for activity determination of radionuclides either in vivo, or in a biological sample;
- Uncertainties in the exposure scenario, which interprets the bioassay results, including factors such as the route of intake, the time pattern of intake, the specific radionuclides taken in the body, as well as the chemical and physical form of the deposited radionuclides;
- Uncertainties in the biokinetic and dosimetric models, which are used to interpret the bioassay results.

Direct information and observation on humans is the preferred type of information on which to base a biokinetic model and thus to eliminate or reduce the uncertainties.

3. EXPERIMENTAL SETUP AND QUALITY CONTROL

Assessment of expected individual effective dose of internal exposure is based on direct measurements of the radionuclides in the human body. Best and most detailed high quality results on radionuclides are obtained using gamma-ray spectrometry.

Gamma-ray spectroscopy is a non-destructive technique used to estimate electromagnetic radiation in the gamma-ray spectrum of radioactive sources (Guembou et al, 2017). It is performed through the procedure of counting and measuring the energies of all individual photons emitted from the different elements present in the body. High-resolution gamma-ray spectroscopy usually uses germanium detectors, since they allow the estimation of gamma rays for determination of the elemental composition of a wide assortment of sources. The measured energy of a gamma ray then corresponds to the type of element and its isotopes, while the number of counts resembles the abundance of the radionuclides present in the measured body.

3. 1. HPGe Detector – Principle of Operation

High purity germanium detectors are semiconductor detectors, which principle of operation can be summarized as follows:

- Ionizing radiation enters the sensitive volume of the detector (germanium crystal) and interacts with the semiconductor material.
- High-energy photon passing through the detector ionizes the atom of the semiconductor and produce electron-hole pairs. The number of electron-hole pairs is proportional to the energy of the radiation interacting with the semiconductor. As a result, a number of electrons are transferred from the valence band to the conduction band, and an equal number of holes are created in the valence band.
- Germanium can have a depleted sensitive thickness of centimeters, which allows it to absorb high-energy photons totally (up to few MeV).

- Electrons and holes then travel to the electrodes, under the influence of an electric field, resulting in a pulse, which can be processed using the electronics.
- This pulse carries all the information about the energy of the incident radiation. While the number of such pulses per unit time gives information on the intensity of the radiation.

3. 2. Experimental set up

Each HPGe gamma spectrometry apparatus used for effective dose assessment has a similar experimental set up, shown in Fig. 3.

- High purity broad energy germanium detector (HPGe) – including germanium crystal and all protection material;
- High voltage supply;
- Analog-to-digital converter (ADC);
- Pre-amplifiers;
- Amplifier;
- Multi-channel analyzer (MCA);
- Nitrogen cooling system;
- Specialized computer software for analyzing the data and calibration of the detector.

An example of HPGe detector gamma ray spectra for different radioactive nuclides can be seen in Fig. 4.

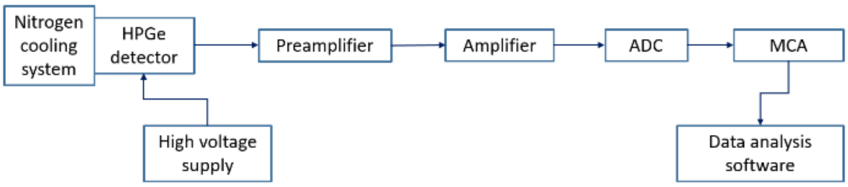

Fig. 3 A schematic view of an HPGe gamma spec-trometry apparatus.

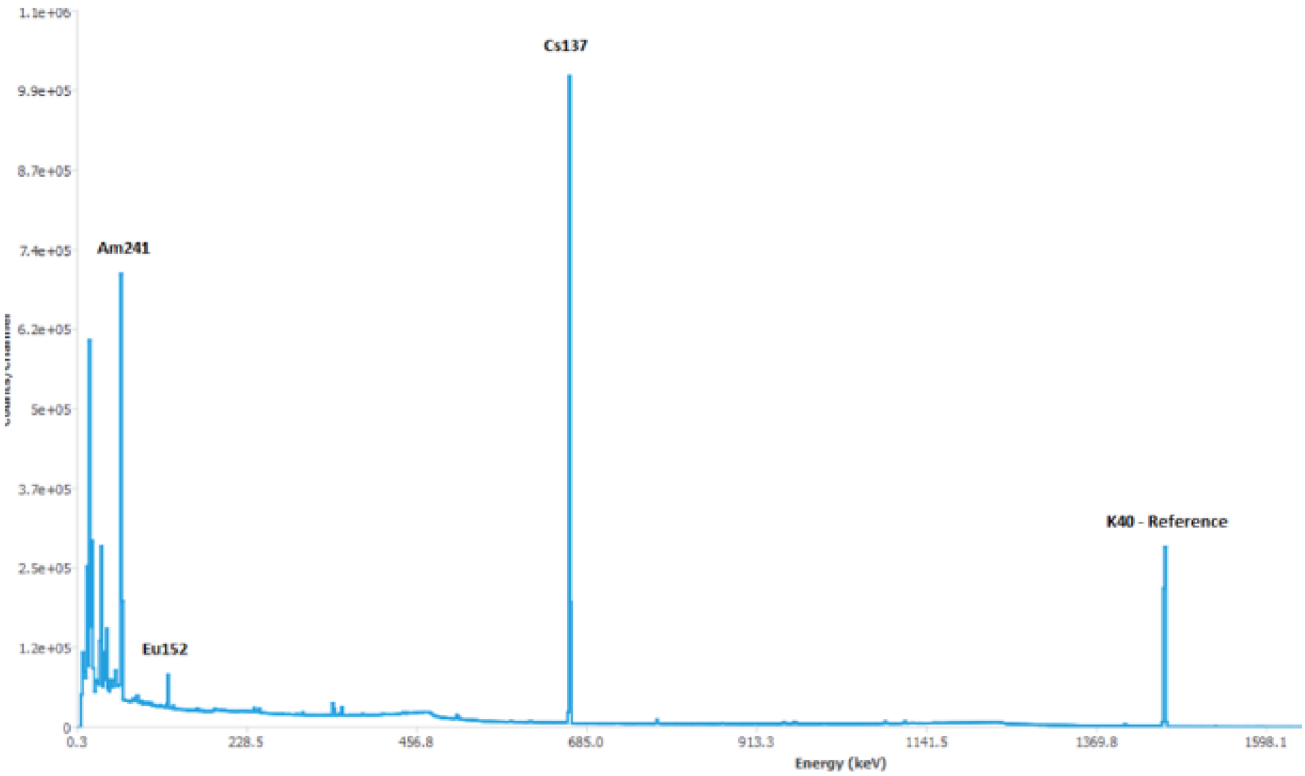

Fig. 4 HPGe gamma spectra showing the presence of the isotopes of Cesium 137 (Cs-137), Americuim 241 (Am-241) and Europium 152 (Eu-152) (Public domain, PhysicsOpenLab).

3. 3. Quality control

Quality control in assessment of expected individual effective dose of internal exposure is achieved by calibration of the experimental gamma ray set up.

Gamma ray spectrometer calibration includes energy calibration and detection efficiency calibration (Yavar et al, 2014). The energy calibration object is to derive a relationship between the corresponding gamma ray energy and peak position in the spectrum. It is usually accomplished by measuring the spectrum of a source emitting gamma rays with precisely known energy (reference source) and comparing the measured peak position with energy. The detection efficiency calibration, on the other hand, is to calculate the relationship between number of counts and disintegration rate.

Calibration of gamma ray spectrometers for effective dose assessments should be performed regularly on a weekly/monthly basis, thus ensuring the precision of obtained results.

4. CONCLUSIONS

This work presented an overview of the method and stages in assessment of the individual effective dose of internal exposure in an environment with ionizing radiation. A brief overview of the different types of ionizing particles, as well as the different types of human radiation exposure were given. The main quantities to measure the biological effects of ionizing radiation were presented, as well as the different models used for accurate dose assessment.

In addition, gamma-ray spectroscopy and HPGe detectors were described, revealing the best way to obtain direct information and observation on radionuclides in human bodies.

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