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Numerical model of detector for in vivo internal dosimetry in radiological incidents

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The aim of this work was to create a numerical model of scintillation detector and to check whether such detector can be used for the measurements of internal contamination in emergency conditions. The purpose of the measurements would be only detection of possible contamination, without identification of radioactive isotopes, and hence without estimation of effective dose. However, in emergency conditions, it is sufficient for the rapid selection of a group of contaminated persons, who should be subjected to careful inspection in the laboratory conditions. The calculations were performed for three detector positions relatively to the phantom. The distribution of dose rate was also calculated, in order to find the best geometry for dose rate measurements around human body. Another problem under consideration was the possible influence of radioactive contamination in the environment on the registration of the gamma spectrum emitted from the whole body phantom. Performed calculations showed that there is a possibility to measure internal contamination outside laboratory, even in contaminated area.
Key words: radiation protection, numerical modeling, MCNPx, FLUKA

Introduction

During routine measurements of internal contamination the spectrometric systems with scintillation or germanium detectors are used. They register the energy spectrum of gamma rays emitted from the inside of the human body and allow for easy identification of accumulated radionuclides.

In this work, it is assumed that in emergency conditions, a dose rate counter may also be used for the measurement of internal contamination if it used in such a way that it measures radiation emitted from the inside of the human body. This solution will only indicate possible contamination, without identification of radioactive isotopes, and hence without possibility of estimation of effective dose due to the internal contamination. However, in emergency conditions, this is sufficient for the rapid selection of a group of contaminated persons, who should be subjected to careful inspection in laboratory conditions.

A part of this project was the development of numerical model of the detector and whole body phantom, which will be used for calibration of the dose rate counters. The model will be useful for determination of the best measurement geometry that can be used when measuring in emergency conditions. The selected geometries will be later verified during experimental measurements, however, numerical models will allow carrying out various tests, and then to confirm the choice of the best geometry in experimental research.

Detector

The detector simulated in numerical modeling was a scintillator detector NaI(Tl) 2x2 inches manufactured by Polon (Poland) and mounted in the measurement system of the thyroid radiation counter, used in the National Centre for Nuclear Research in Świerk (NCBJ). When connected to multichannel analyzer, the detector, can be used for routine monitoring of radioiodine activity in thyroid gland in the laboratory conditions. Its design allows for using it also as a mobile system. In some calculations the detector was considered as shielded by a 1 cm thick lead overlay.

In order to determine the response of the dose rate counters located near the contaminated person or phantom, calculations of the distribution of the dose equivalent rate around the phantom, without setting specific measurement systems were also performed.

The calculated dose equivalent (H) is absorbed dose at a point in tissue weighted by a distribution of quality factors (Q) related to the LET distribution of radiation at that point. This method is used within MCNPx code, using ICRP 21 coefficients [1].

Phantom

In order to calculate the response of the detectors to the radiation emitted by radionuclides in the human body, two numerical whole body phantoms were defined. The first one is a bottle phantom based on the standard human silhouette, the second - a simplified whole body phantom.

The bottle phantom model, shown in Fig. 1, simulates the phantom used for calibration of whole-body counter at Radiation Protection Measurements Laboratory (LPD) of NCBJ. It consists of 17 containers of the volumes given in the Table 1, and represents the human body of a standard weight 70 kg and height 170 cm [2, 3]. The phantom was modeled as filled with aqueous solutions of cesium (Cs-137). The containers shapes were simplified to cuboids with polyethylene walls of 0.5 mm.

Figure 1. The bottle phantom reproducing the standard human silhouette (70 kg, 170 cm) serving as a calibration phantom at Radiation Protection Measurements Laboratory

For the calibration of the whole body radiation counter, the LPD uses also phantoms of four other types of human silhouette: short and slim man (55 kg, 152 cm), tall and slim (64 kg, 186 cm), short and thick (76 kg, 153 cm) tall and thick (92 kg, 185 cm). The model can be easily modified, in order to reproduce any of these silhouettes. Figure 2 shows the model of the phantom as well as the detector defined within the MCNPx code.

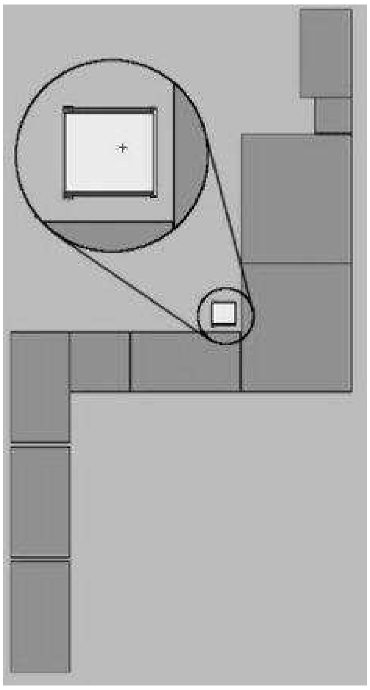

Figure 2. The bottle phantom and the detector modeled using MCNPx code

The second of the developed models is a simplified phantom of the human body which consists of only two (or three) containers with a capacity of 10 and 20 (and 1) liters. The smallest of the containers, simulating the human neck, was filled with an aqueous solution of iodine I-131, the other two with solution of cesium Cs-137. The simplified whole-body phantom was designed for calibration of measuring devices proposed for the use during emergency measurements of internal contamination. This calibration has to be simpler than the calibration of whole-body radiation counter, mainly in terms of size of the phantom elements and the difficulty of positioning. Figure 3 presents the simplified numerical model of the phantom developed using Fluka code.

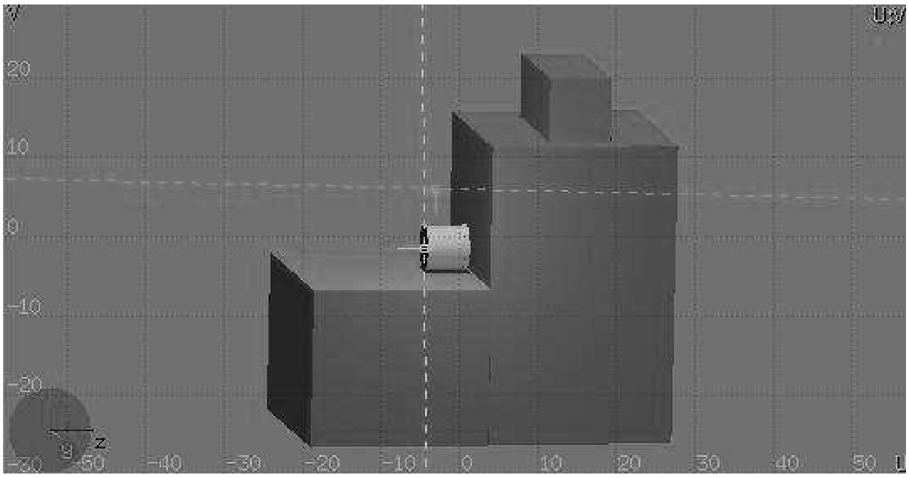

Figure 3. The simplified phantom and detector modeled within the FLUKA code

Results and discussion

The calculations were performed for three positions of the detector relatively to the phantom.

The first calculations were made for the detector placed in 1 cm distance from the phantom torso and 1 cm distance from the legs (14 cm from the chair plane) - see Fig. 2. In the basic geometry, for further calculations the detector was placed the same way as in LPD's whole body counter (in this system the measurement is performed using germanium detector, while in the calculations a scintillation detector was modeled). The distance between detector and chair was 24 cm and 17 cm between the detector and phantom torso.

In the last geometry consisted, the detector was still 17 cm away from the torso, but it was lying directly on the containers representing phantom's thighs (13 cm from the chair plane).

The response of the detector to the source of radiation located in the phantom containers was calculated. The calculations were performed using Monte Carlo method for both phantoms described above – for the bottle phantom with the MCNPx code and for the simplified phantom with both MCNPx and FLUKA codes. The results of the calculations were the energy spectra of gamma rays emitted from the phantom volume, deposited in the scintillation crystal being a part of the modeled detector.

The source of radiation in the MCNPx modeling was monoenergetic 662 keV gamma line like the Cs-137 source and the following lines of the I-131 source: 80 keV, 177 keV, 284 keV, keV, 364 keV, 503 keV, 636 keV, 624 keV and 722 keV with rates, respectively, 0.27 % 2.62 % 6.14 % 0.274 % 0.36 % 81.7 % 7.17 % 0.217 % 1.773 % [4]. In the FLUKA model the source of radiation were isotopes of Cs-137 and I-131 with gamma radiation lines defined within the code.

In the preliminary calculations, the photon emission probability of each phantom container was proportional to its volume, hence the iodine source emitted only about 1.4 % of all photons emitted from the source in the bottle phantom and about 3.3 % in the simplified phantom for the calculations performed with the MCNPx code. In the case of FLUKA code, the number of photons emitted from the iodine source was 3.2 %. As a result, the contribution from the iodine lines in the spectra is small. In the future calculations the iodine activity will be modified to give the actual contribution from iodine in the obtained spectrum.

Figure 4 presents the spectrum calculated for the bottle phantom and Figure 5 for the simplified phantom. All values are normalized to a single particle emitted from the source.

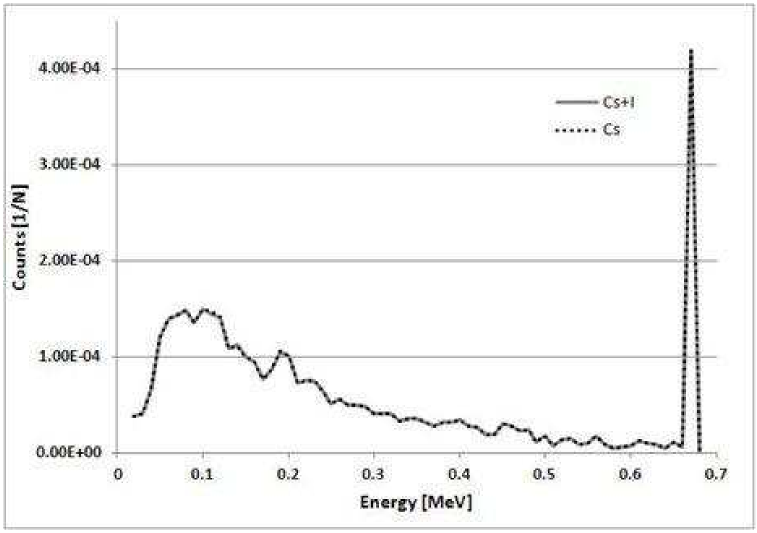

Figure 4. Calculated energy spectrum of gamma radiation deposited in the scintillation detector placed near the bottle phantom

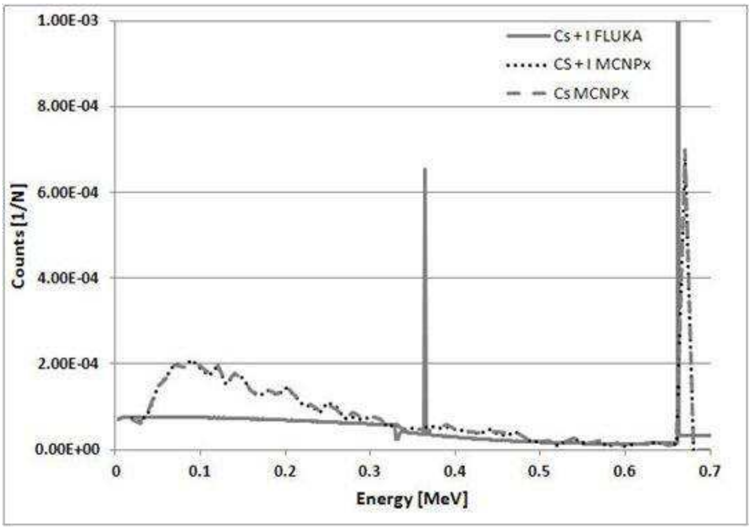

Figure 5. Calculated energy spectrum of gamma radiation deposited in the scintillation detector placed near the simplified phantom

Figures 6 and 7 show the distribution of the dose equivalent rate around bottle phantom and simplified phantom, respectively, both filled with I-131 and Cs-137.

In case of phantoms filled with Cs-137 only, the distribution of dose rate did not differ significantly.

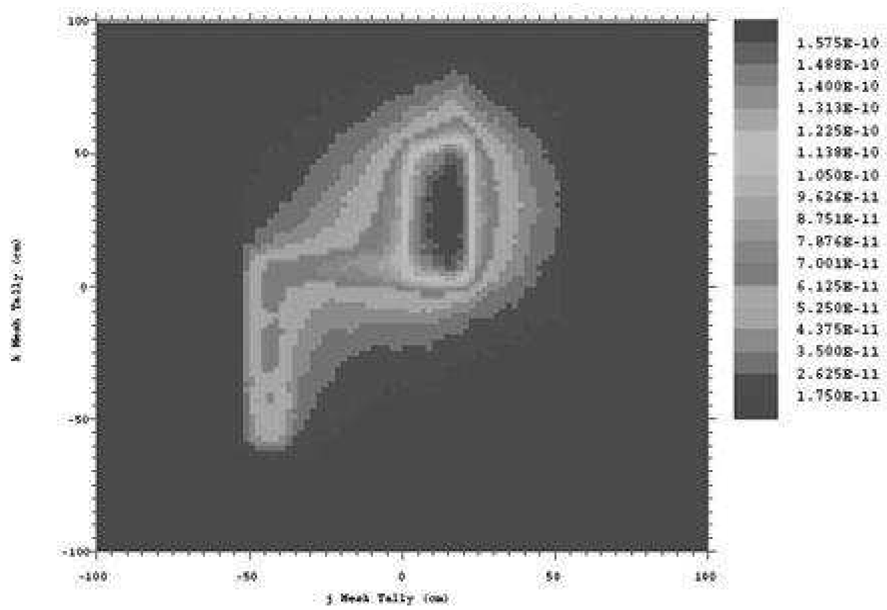

Figure 6. The dose rate distribution (Sv/h)/(particles/cm^2 ·sec) near the bottle phantom filled with solution of Cs-137 and I-131.

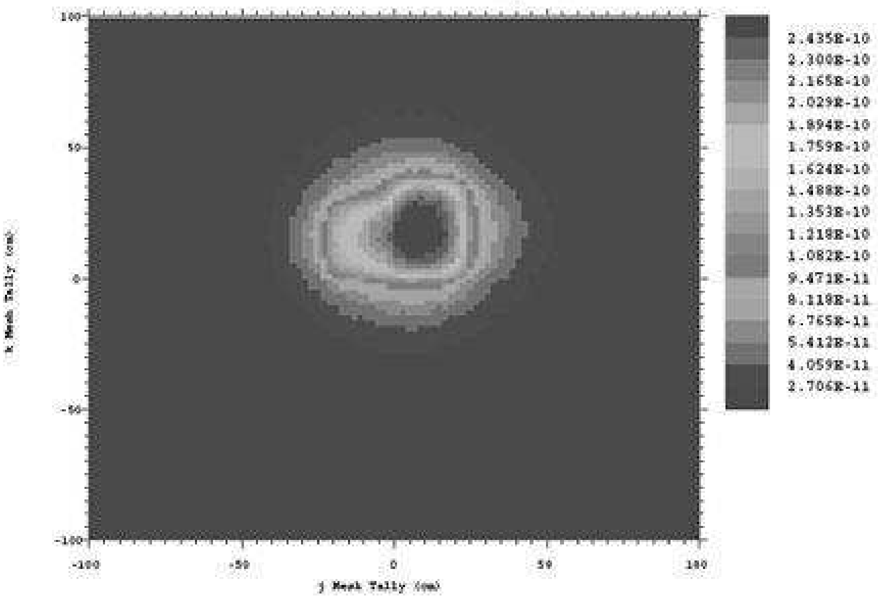

Figure 7. The dose rate distribution (Sv/h)/(particles/cm^2 ·sec) near the simplified phantom filled with solution of Cs-137 and I-131

The next step consisted of studying the effect of changes in the measuring geometry and contamination occurring at the place where the measurement is made on the recorded gamma spectrum, emitted by radionuclides contained in the human body.

The calculations of the energy emitted by Cs-137 deposited in the detector were performed for two different measurement geometries: the detector with and without lead collimator. The resulting spectrum is shown in Fig 8.

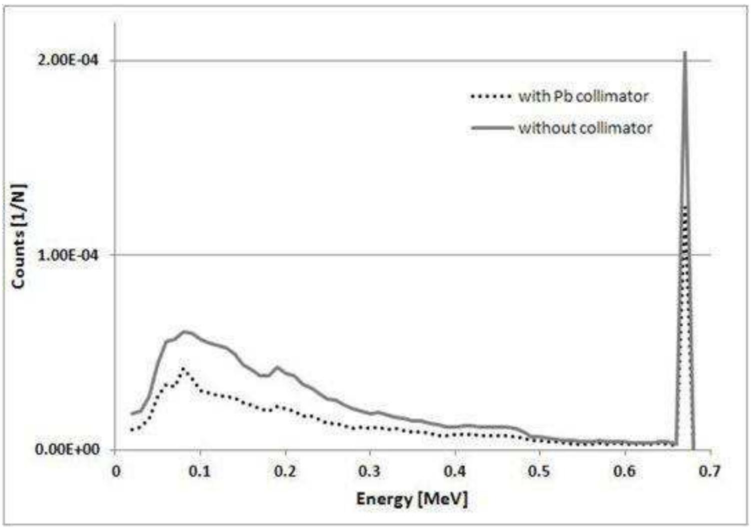

Figure 8. Calculated energy spectrum of gamma radiation deposited in the scintillation detector with and without lead collimator

Comparison of the two spectra obtained showed that only 61 % of counts for the maximum were recorded in the 662 keV peak for the measurement with the collimator in comparison to the system without collimator.

Another problem studied was the registration in the detector the gamma spectrum emitted from the whole body phantom in conditions of environment radioactive contamination. This model was designed in order to answer the question whether it would be possible to perform internal contamination measurements when there are objects contaminated with radioactive substances in the vicinity of the detector and the controlled person. For this purpose, an additional volume source was implemented in the air surrounding the phantom and the detector. In the air, like in the phantom, the gamma radiation of the isotope Cs-137 (662 keV) was emitted. Several models for various air pollution activity, relatively to the activity of the radionuclide in the phantom were developed. In subsequent simulations the energy spectra registered in the detector were calculated for various levels of contamination, described as activity of 1 m^3 of air in relation to the activity in phantom: 5.83, 10.68, 16.50, 21.36, 41.75, 83.50 and 145.63 %.

Table 2 shows the difference in the heights of the 662 keV peaks for various levels of air contamination. Figure 9 shows the comparison of spectra of energy deposited at the detector during the measurement performed in clean air and contaminated (with the 83.5 % of activity in the phantom).

Table 2. Calculated 662 keV peak height for various air contamination levels.

Activity of 1 m^3 of air relatively to the activity in the phantom [%]	Maximum height of the peak [1/N]	Ratio of the peak height in the polluted air to the height in the clean air
0	$2.05\cdot10^{-4}$	1
5.83	$2.11\cdot10^{-4}$	1.03
10.68	$2.16\cdot10^{-4}$	1.05
16.50	$2.49\cdot10^{-4}$	1.21
21.36	$2.54\cdot10^{-4}$	1.24
41.75	$3.13\cdot10^{-4}$	1.53
83.50	$4.43\cdot10^{-4}$	2.16
145.63	$5.83\cdot10^{-4}$	2.84

The same calculations, with and without lead collimator, were performed for the other detector position, on “phantom’s thighs” (Fig. 10).

Comparison of both measurement geometries showed that the height of the 662 keV peak registered in clean air in detector lying on phantom’s thighs is 40 % greater than the one recorded with the detector raised, and the in the contaminated air at the 83.5 % level by 10 %. For the detector located directly on the phantom’s thighs the air pollution at the level of 83.5 % increases the peak height by 70 %.

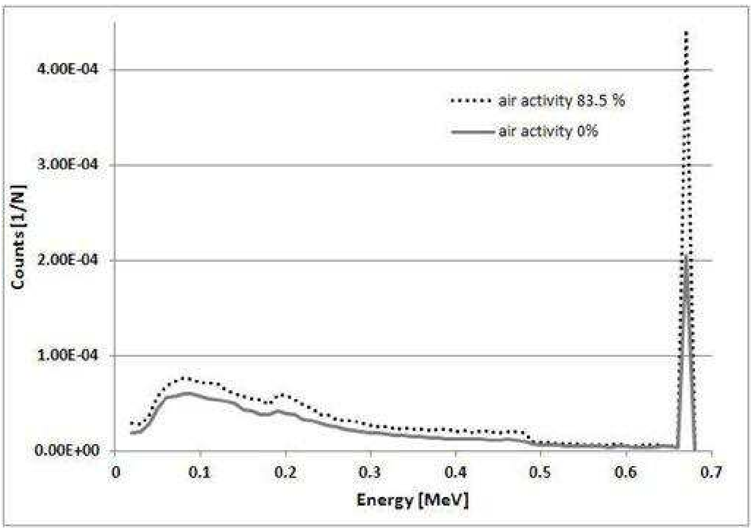

Figure 9. Calculated energy spectrum of gamma radiation deposited in the scintillation detector in clean and contaminated air.

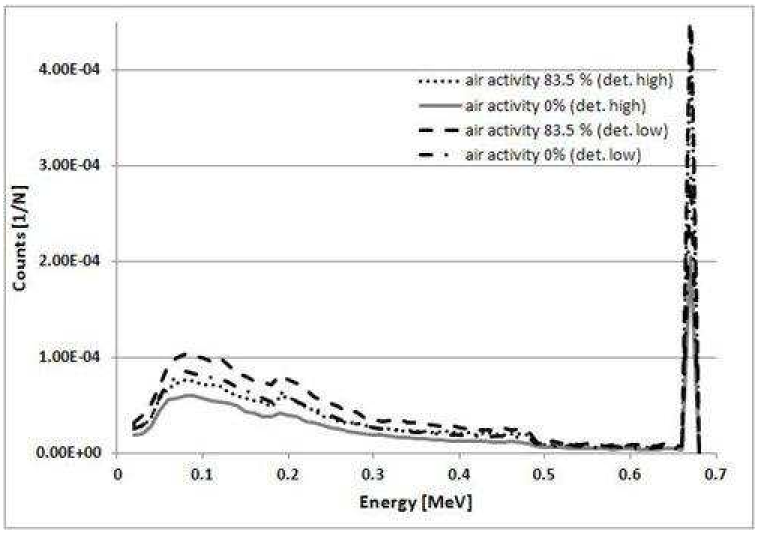

Figure 10. Calculated energy spectrum of gamma radiation deposited in the scintillation detector in clean and contaminated air at two detector positions: 24 cm above the chair plane and directly on the phantom (13 cm above the chair plane).

Conclusions

The calculations performed have shown that the simplified whole body phantom is a sufficient approximation of the more complex bottle phantom and can be used for efficiency calibration of the measuring system for the internal contamination of the whole body.

The obtained energy spectra of Cs-137 and I-131 isotopes contained in the two phantoms do not differ significantly, within both Monte Carlo codes.

Comparison of spectra obtained using the MCNPx and FLUKA code showed some differences. In the FLUKA calculated spectrum the 364 keV peak originating from the I-131 is much larger than in the spectrum calculated with MCNPx. At the present stage of development it is difficult to explain the cause of this situation. This issue will be considered in the further studies.

The largest values of gamma dose rate around the whole body phantom are observed in the biggest containers representing the torso. This is due to the fact that the probability of photons escaping from an object of small volume is greater. In larger volumes multiple scattering is more likely, resulting in a substantial part of the energy of the photon being absorbed in the phantom.

The developed models of detectors can be used to select an appropriate measurement geometry for certain conditions, such as silhouette of the person being measured, size and type of contamination, the possible distribution of the radionuclide in the human body.

The calculations have shown that there is no need for additional collimators, shielding part of the detector during the internal contamination measurements. The shielding prevents part of the radiation emitted from the body from reaching the detector. On the other hand, the effect of background radiation on the measurement of high activity is not significant enough to increase the uncertainty of the measurement. The necessity for shielding in routine measurements is due to the low level of the measured activity, often below the level of the background.

If the measurement of internal contamination would have to be made in environmental pollution conditions, the impact of higher background level on the result would be noticeable, but only for high contamination level. Activity of radionuclides in 1 m^3 of air at about 80 % of the activity of the radionuclide in the whole body would result in doubling of the energy peak area recorded by scintillation detector placed at a height of 24 cm from the chair plane and 70 % for the detector on the phantom’s thighs (13 cm from the chair plane).

The influence of environmental pollution on the measurement result is greater in the case of the detector moved away from the human body. The body provides a shielding for the detector from the high background radiation. This means that, if there would be a need for rapid evaluation of internal contamination, such a measurement can be performed even at a short distance from the location where the emergency event occurred. In the case of a high level of internal contamination, slight contamination of the environment is not expected to significantly affect the result, especially when the detector is shielded by the person's body.

The models and calculations performed are compared with experimental measurements carried out in parallel.

Acknowledgements

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