A New HPGe Detector Based Body Counter Capable of Detecting Also Low Energy Photon Emitters

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EDITOR'S NOTICE
This contribution is a shortened version of the thesis of the winner of the Rupprecht-Maushart-Prize for Young Scientists 2011, Olaf Marzocchi.

SUMMARY
In this work, a new system with both whole-body and partial-body counting capabilities is developed, installed and tested with both sample and real contamination cases. The new system amends the old scintillators with new HPGe detectors, improving the attainable resolution and also allowing a broader range of measurements. The HPGe detectors are modeled with the aid of Monte Carlo software and the resulting models are used for computational calibrations and for the optimization of the counting setups. Software is also developed to handle the different steps of measurements.

ZUSAMMENFASSUNG
Ein neuer HPGe-basierter Body Counter, der auch niederenergetische Fotonenemitter erfasst
Ein neues Body Counter-System mit Ganz- und Teilkörper-Messfähigkeiten wurde entwickelt, installiert und mit Versuchs- und realen Kontaminationsfällen getestet. Das System ergänzt die alten Szintillations- mit neuen HPGe-Detektoren, welche die erreichbare Auflösung verbessern und einen erweiterten Messbereich erlauben. Die HPGe-Detektoren wurden mithilfe einer Monte-Carlo-Software modelliert und die resultierenden Modelle für Computerkalibrierung und Optimierung der Messungen benutzt. Ebenso wurde eine Software für den Umgang mit den verschiedenen Schritten der Messungen entwickelt.

The Need to Assess Risks from Incorporated Low-Energy Sources

Radiological risks come from different sources, both from work and natural environments. Some examples are industries using radioactive sources to study defects in the metals, medical applications of radioisotopes, and the process of decommissioning of nuclear reactors, during which radioactive powders may be generated. These particles are at risk of incorporation through inhalation, but in other cases the incorporation path could be ingestion or via wounds. Radiological risks are also originated in the natural environment: the radon gas is often the most significant source of radiological exposure to the population, due to inhalation and incorporation of itself or of some of its decay products. In some cases measuring the amount of one of them, namely ^{210}Pb, can help assess previous radon exposure. The new counter was designed to be able to measure the ^{210}Pb-content of the body via the 46.5 keV gamma emission.

The KIT in-vivo monitoring laboratory (IVM)

The in-vivo monitoring laboratory (IVM) at Karlsruhe Institute of Technology (KIT), department KSM, is equipped with a whole body counter based on four NaI(Tl) detectors and a partial body counter with up to three phoswich detectors. The two systems are used for monitoring of workers at the KIT campus as well as for external customers. IVM is an approved lab for individual monitoring according to German regulation. IVM maintains a quality management system and is accredited to ISO/IEC 17025:2005. The laboratory is also involved in scientific studies and the education and training

of students and radiation protection workers.

Though the scintillators installed can achieve very good detection efficiency as result of their size (20 cm diameter), they all suffer from the intrinsic poor resolution of the crystals used: for example, the peaks of ^{40}K (1,460 keV) and the ^{60}Co (1,332 keV) partly overlap, resulting in difficult determination of peak area when both nuclides are present in the spectrum. The same problem applies to the identification of nuclides emitting multiple peaks in the lower-energy part of the spectrum, i. e. below 500 keV.

Significantly improved specifications

The four new coaxial HPGe detectors, bought specifically for the upgrade of the existing partial body counter, are manufactured by Canberra and use an electrical cooling system instead of liquid nitrogen. This new system excludes the risks of nitrogen leakage in the counting chamber and simplifies the handling of the system: a power outlet and a UPS (uninterruptible power supply) ensure continuity of operation. The new detectors offer significantly improved specifications compared to the old system: the resolution is increased by a factor of at least 10, going from 10–30 keV (phoswich detectors) to 0.9–2.5 keV, and the low-energy range is extended down to 10 keV due to a carbon epoxy window and to a significantly thinner crystal dead layer. The new detectors have mainly one disadvantage: the lower efficiency due to the smaller crystal size. This can be however compensated by an accurate optimization of the counting configurations.

Characterization of the detectors

An optimal counting configuration can be achieved with a time consuming iterative process of series of measurements in the laboratory or it can be achieved with a mathematical study using computer simulations. The latter option was chosen for this project and the Monte Carlo software MCNPX was used for the purpose.

Performing simulations with MCNPX is possible only with proper virtual models, but the manufacturer of the detectors initially provided overly simplified drawings, whose accuracy was questionable (as the literature also proved in other cases). As a result, it was decided to characterize the detectors using measurements of point sources. The data sheets were used as reference for the MC initial model.

Checking the alignment of the crystal

Two different sets of measurements were performed: one with point sources (^{241}Am, ^{137}Cs and ^{60}Co) placed on an array of nodes in front of the crystal to estimate the counting efficiency, and one set of measurements with a collimated ^{241}Am source scanning along the lateral and front side of the detector. These were used to check the alignment of the crystal within the housing. The position of the crystal was found to agree with the specification within the uncertainties, but the measured detection efficiencies differed in certain points of the array measurements significantly. The source of the deviations was found to be the incorrect model of the corners of the aluminum case: the reference drawings represented it as curved surface, but a more realistic model with a double inner

structure, able to hold the carbon epoxy window firmly, was expected. By contacting the manufacturer again it was possible to get improved drawings, then used to improve the MCNPX model and the results of the simulations.

Development of the PBC configuration

The development of the partial body counting ("PBC") configurations was initially performed in parallel for a stretched setup (the one previously used at IVM of KIT) and with a sitting setup, taken into consideration due to space constraints in the existing chamber.

As first step the MeetMan phantom, based on the Visible Human project and available only in stretched configuration, was adapted to a sitting setup by virtual cutting in blocks that were turned to get the sitting layout. Different simulations have been performed with both the original and the adapted phantom, each simulation with a different organ (muscle, liver, lungs, gastro-intestinal tract, bones) loaded with a uniform radioactive source (either ^{241}Am, ^{137}Cs or ^{60}Co) and no detectors in the virtual world. The resulting photon fluxes around the phantoms were plotted and the highest-flux regions identified. New simulations were performed including the detectors placed in these regions and the results used to estimate the detection efficiencies. Additional simulations with all the organs loaded uniformly with ^{40}K were performed to estimate the Compton scattering of ^{40}K affecting the low-energy region of the spectrum. This value, together with the detection efficiencies, was used to calculate the minimum detectable activity (MDA) according to the ISO 11929 standard. The MDA for the two setups were compared and the sitting setup was found to offer comparable or better performances in a smaller space with the help of a simpler supporting mechanics. Therefore, it was chosen as configuration for the new system. For more information on the topic, see [1]. Different measuring configurations were defined: skull (as representative configuration for bone-seeking nuclides), liver, lungs and gastro-intestinal tract (GIT).

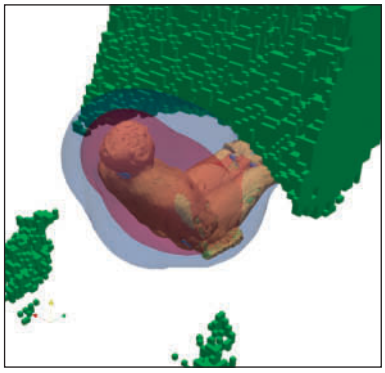

Fig. 1: Plot of the three phantoms used (overlapping each other) and of the iso-flux surfaces resulting from ^{40}K sources distributed in several organs of the phantoms. The green region represents the volume of space where the standard deviation among the detection efficiencies for ^{40}K in the different organs is lower than 20 %.

Using the constraints imposed by these setups, the supporting mechanics for the detectors were designed, a test portal was built and the results produced with simulations in the previous part of the work were compared with real measurements.

Concerning the stretcher or chair to be used for the new system, a compromise had to be chosen, because the old scintillator detectors, which shall also be used in future, require a flat stretcher and no suitable chairs were found in the catalogues. The final choice was therefore a wellness stretcher, configurable in flat or in reclined (arc-like) configuration. It was considered a better solution than a completely custom system. All the subsequent simulations were performed using the reclined setup.

Development of a WBC configuration

While the mechanics was being designed and built for the first tests, the whole body counting (WBC) configuration was developed.

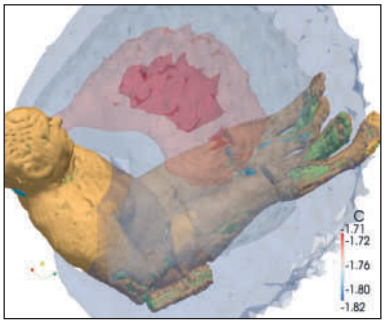

Fig. 2: Plot of the composite value C, resulting from the merge of standard deviation and average efficiencies

A WBC is significantly different than a PBC: in the latter the main goal is to enhance the detection sensitivity for a specific organ/source combination, while reducing as much as possible every other source of impulses; in a WBC the goal is to achieve good detection efficiency, but independently from the source organ, to be able to estimate the total body activity without knowledge about the location of the source.

Better performances in a smaller space

The method chosen was a modification of the one used for the optimization of the PBC configurations. As first step, simulations without detectors but only with sources in different organs (one source per simulation) were performed and the full energy (uncollided) photon flux around the phantom tracked. Different phantoms representing different body sizes and

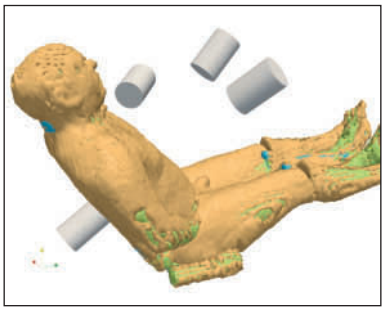

Fig. 3: Position of the detectors in the final WBC configuration

shapes were used for the task, not only MeetMan: The Godwin and Klara phantoms from HMGU had been recently acquired and they were put to use. Several photon energies were taken into account for each organ/phantom combination and the result was a series of over 70 data sets.

As opposed to the optimization of the PBC setup, iso-flux surfaces were not useful: they do not offer any information about the uniformity of the detection efficiency. The results of different simulations were therefore aggregated and new values calculated: average flux and standard deviation within the selected group of simulations. While the former is related to the expected counting efficiency, its standard deviation is related to the change in efficiency as function of the source organ. For example, all the simulations with a ^{40}K source in the different organs of the different phantoms were merged and the iso-average flux surfaces plotted in Figure 1. In the same figure the region of space where the standard deviation is lower than a specified threshold is also marked. The iso-efficiency surfaces generated by the single organs are smoothed out and the resulting averages appear as uniform shells around the phantom, but the region of space with low standard deviation has a cone-like shape, starting near the "focus point" of the arc-like reclined stretcher and expanding as the distance from the phantom increases. This behavior is expected, because the regions of space close to the phantom are characterized by detection efficiencies strongly dependent on the position and shape of the source, no more critical for higher detector-source distances.

Wellness stretcher in flat or reclined configuration

To ease the definition of the placement of the detectors, standard deviation and average flux were merged using the formula:

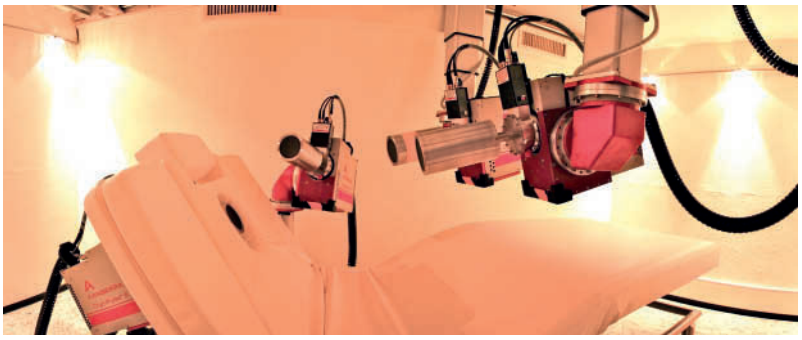

Fig. 4: Panoramic view of the new system in WBC configuration

$$C = \text{stddev} + k \cdot \log \text{eff}$$

with $k > 0$.

The resulting weight value is plotted and used to graphically show the compromises between high detection efficiency and low standard deviation: the lower the value, the better the compromise, see Figure 2. The final detector configuration is plotted in Figure 3 and a photo representing the same setup is shown in Figure 4.

Further information are given in [2].

Test measurements

Different tests were performed with the new system to calibrate it and to test its capabilities. Three of them are described here.

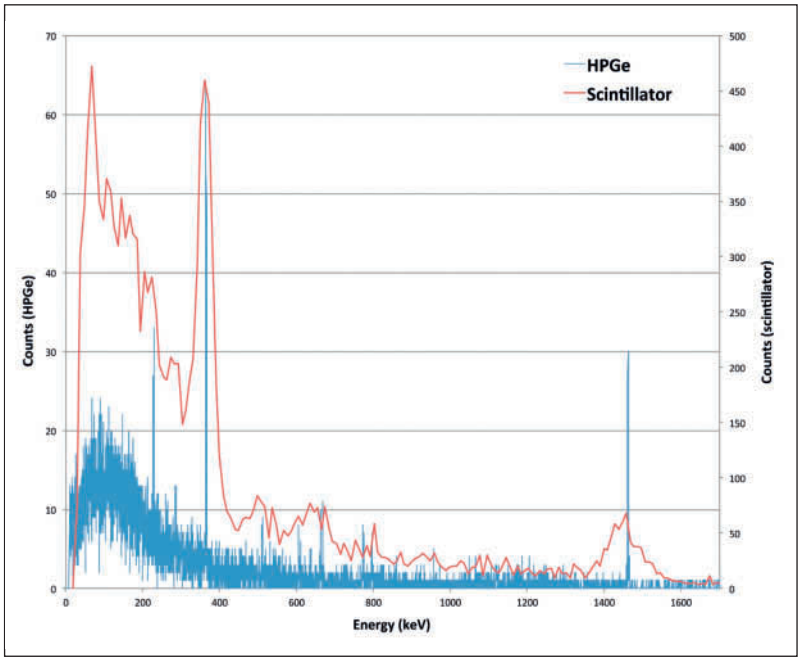

Fig. 5: Comparison of scintillator and HPGe detector spectra (not to scale). The most important peaks are marked.

The first one aimed to estimate the MDA for lung measurements, to compare it with the value of the previous PBC system. The efficiency calibration was performed with a LLNL torso phantom loaded with ^{241}Am in the lungs. The estimation of the local Compton and natural background around the ^{241}Am peak performed by measuring two uncontaminated subjects. It was found that two detectors alone, placed in front of the chest, are able to attain a MDA value comparable to the previous system (5.8 Bq ^{241}Am with the HPGe, 5 to 7 Bq with the scintillators for a 2,000 s measurement). Therefore, the remaining two detectors can be devoted to the measurement of other organs, namely GIT and liver. This approach is especially useful with complex contamination cases, where the radionuclide is distributed in multiple organs and multiple detectors can help to estimate the cross counts originated outside the main organ. The second test involved the measurement of two subjects potentially contaminated with ^{210}Pb due to past high levels radon exposure. It was performed with three detectors placed around the skull. Again the calibration data were obtained from MC simulations. The resulting MDA (referred to the whole-skeleton content) was 290 Bq or 374 Bq, depending on the subject, values acceptable considered the very low emission probability of the 46.5 keV gamma line (4.25 %). This MDA was however too high to detect ^{210}Pb in the two subjects, only one spectrum crossed the detection threshold but the result was considered as statistical noise.

Measurement of persons after a stay in Japan

The third important test involved the WBC measurement of different subjects returning to Germany after a period in Japan, during which the Fukushima accident happened. Only one of them showed a small contamination: Different nuclides were identified (^{131}I, ^{132}I, ^{132}Te, ^{134}Cs, ^{137}Cs) and the committed dose was found to be lower than 10 µSv. In this case the new system proved the usefulness of high resolution detectors, since a measurement with the old scintillators was unable to separate the different peaks found in the spectrum: For example, the ^{137}Cs and ^{132}I peaks (662 keV resp. 667 keV) overlap in a NaI(Tl) spectrum. Figure 5 compares the spectra of one scintillator and one HPGe detector.

Traceable calibration for nuclides, organs and phantoms

Conclusions and future work

The system described has been installed, tested and the improved capabilities put to use in different cases. The system has not yet been introduced in the routine operation of the laboratory due to the need of official documentation and complete calibration data, all of them required for the ISO/IEC 17025:2005 accreditation. This step is planned for 2012, when also the software for the handling of the routine operations will be ready for operation. In the meanwhile, the system is being used for additional measurements in cases where contaminations are found with the old system. The results of these measurements with the two systems can then be used to validate the new counter.

The system described here can be improved in different ways. First of all, the MCNPX models can be made more accurate until they are able to replace all the physical calibrations: This would make possible a traceable calibration for nuclides, organs and phantoms not available at IVM. Another possible improvement is the connection of the mechanics to a computer to read the position of the detectors in the room and automatically produce input files for the simulations: This would greatly reduce one of the biggest sources of uncertainties, namely the position of the detectors in relation to the subject. All these topics will be taken into account

after the validation and implementation of the new system into the quality management documentation at IVM for the start of routine measurements, the most important future step. ■

KEYWORDS
Monte Carlo modeling, numerical phantoms, partial-/whole-body counter development

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