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Using Monte Carlo methods to estimate efficiencies of gamma-ray emitters with complex geometries

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In the event of a radioactive disaster, one of the biggest tasks is to estimate the radiation dosage received by people to determine the actions of emergency response teams. The first and the most rapid screening method of internally contaminated people in case of an emergency response is to perform in-vivo measurements for gamma-emitters. Development of virtual gamma-ray calibration techniques will be critical for emergency in-vivo measurements because there are inadequate numbers of phantom types to approximate all body shapes and sizes. The purpose of this project was to find a reliable way to estimate the efficiency of gamma-systems using Monte Carlo computations, and to validate that efficiency by making measurements of a standard geometry. Two geometries, a 5-ml ampoule and a Bottle Manikin Absorption (BOMAB) phantom head, spiked with ^{67}Ga were used as standard geometries. The radioactive objects are measured at a number of distances from a high purity germanium (HPGe) detector, and the experimental efficiency for our gamma-spectrometry system is determined. The same set of experiments was then modeled using the Monte Carlo N-Particle Transport Code (MCNP). The conclusion of this project is that computationally derived detector efficiency calibrations can be comparable to those derived experimentally from physical standards.

Introduction

Radioactive materials are widely used in medicine, industry, agriculture and research and, despite efforts to ensure safety, accidents do happen. In the event of a radiation emergency, the issue of primary concern is the health of exposed individuals who may have been contaminated. Within the first hours and days after a radiological attack, people should be monitored with special equipment that is designed to detect radiation, either inside their bodies (internal) or outside their bodies (external) to estimate exposure dose.

Direct measurements use detectors placed external to the body to measure ionizing radiation emitted by the radioactive material contained in the body.

Indirect measurement, in contrast, refers to the analysis of excreta (urine, feces, sweat), or body fluids such as blood, breath or saliva to estimate the body content of radioactive material.

The direct measurement process includes ‘whole-body counting’, ‘organ counting’, or ‘in vivo measurement’. The main focus of population monitoring is on the detection, identification and quantification of internal contamination radionuclides in the whole body or regions of the body. The object of this project was to develop a computational subject-specific capability to calibrate whole-body gamma-ray detectors.

The technique for whole-body direct measurement is, in principle, the same as that for determining the content of gamma-ray emitting radionuclides in any other sample. In practice, however, radiation measurements of people is not straightforward because the human body comes in a great variety of complicated tissue shapes and sizes that require individual calibration and attenuation factors. Use of inappropriate calibration factors can seriously affect measurement accuracy. Furthermore, the distribution of radionuclides within the body is often unknown and cannot, in general, be considered uniform because the affinity for radionuclides varies with tissue type. In addition, the distribution of radionuclides within the body changes with time after the initial radionuclide intake. The duration of measurement is usually a limiting factor, and can lead to difficulties with achieving required detection limits. These factors all lead to difficulty calibrating radiation detectors.

As with any measurement, the accuracy of whole-body counting is greatly dependent on the use of standard reference materials for calibration purposes. Traditionally, in-vivo measurement systems are efficiency calibrated using human body phantoms. For screening purposes, sophisticated phantoms are not necessary because larger than usual measurement uncertainties are acceptable. However, for accurate and precise measurements, the radiation detectors should be efficiency calibrated based on the unique geometry of every measured person. This means that a calibration phantom should resemble the measured body as closely as possible in terms of shape, size, and composition. At the current time, however, personalized detector calibration using the traditional phantom method is not feasible because there are an inadequate number of phantoms available to approximate all body shapes and sizes. A practical alternative to building a population of

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physical whole-body phantoms would be to develop computational standards for calibrating radiation detector systems. This project explores the use of Monte Carlo computation to estimate the efficiency of gamma-ray systems, and to validate that efficiency against real measurements of standard geometries.

Experimental approach

Two standard geometries, a 5-ml ampoule and a BOttle Manikin ABsorption (BOMAB) phantom, were chosen as standard source geometries for efficiency determinations of our HPGe Virtual Gamma-ray Range system. The objects are spiked with a known amount of radioactive material and the efficiency of our gamma-ray spectrometry system is experimentally determined. The BOMAB phantom is a whole-body counter calibration device that consists of ten seamless bottles made of polyethylene plastic (Fig. 1). Each bottle has a recessed screw-type fill port which is leak proof when securely tightened. As the initial stage of the project, we chose to use only the bottle representing the BOMAB's head as our source geometry. The BOMAB head is shaped like a right elliptical cylinder.

Gallium-67 (Theragenics Corporation) was used to spike each of the two source geometries. This radionuclide, which is commonly used in medicine for diagnostic imaging, was chosen for this project because it met two of our requirements: (a) to use a short-lived radionuclide to avoid any long term contamination problems, and (b) to have multiple emission energies to get more than one efficiency value from a single measurement. Gallium-67 has a half-life of approximately 3.2 days and emits gamma-rays with ten different energies. Our focus was on only four of the emission energies: 184 keV (21% decay probability branch), 209 keV (2.4%), 300 keV (16%), and 393 keV (4.7%). The activity of the ^{67}Ga was provided by the Theragenics Corporation and verified by NIST scientists by ionization chamber analysis. Both the 5-ml ampoule and the BOMAB phantom head were filled with 0.75M HCl spiked with a known amount of ^{67}Ga.

Each geometry was measured at a number of distances from a HPGe detector with a germanium crystal of 69.9 mm diameter and 72.5 mm length and 1.5 mm thick beryllium window, operated at the bias of negative 3.5 kV. A positioning system was used to allow for reproducible placing of the objects against the detector. The system is a four axes Linear Positioning System (LPS), and consists of several modular sub-systems: – Framework that ensures the precision of alignment of the platform to the detector centerline; – Linear Rails that keep the platform exactly aligned to the detector centerline; – Four Axes Traverse System that maintains the X-axis horizontal and parallel to the detector centerline, the Y-axis horizontal and perpendicular to the centerline, the Z-axis vertical and perpendicular to the centerline, and the R-axis that rotates in the horizontal plane: – Platform that is designed for mounting the instruments and objects of study in a stable, reproducible fashion on the four-axis traverse system; – Drive System that is designed to provide ±0.5 mm positioning without sacrificing speed or ease of use; – Laser Alignment System that is a low intensity class II laser bolted to the rear wall to define the centerline of the detector. The laser is aligned with the detector centerline and points toward the detector from the opposite end of the LPS. Figure 2 shows the measuring system.

Theoretical approach

The experimental measurements are modeled using the Monte Carlo N-Particle Transport Code (MCNP) developed by Los Alamos National Laboratory. MCNP is a general-purpose Monte Carlo radiation transport code for modeling the interaction of radiation with matter, simulating photons, neutrons, electrons, and protons on a random move interacting with matter. The main task for the MCNP calculations is to create an accurate and realistic description of the measuring system (detector, source, and the environment). The computational environment creates mathematical or voxelized models.

In this project, two different methods were used to define the source geometry for MCNP. Computational objects of both the 5-ml ampoule and the BOMAB head can be described as either mathematical or voxel phantoms. In a mathematical phantom, the source geometry is described by mathematical expressions representing combinations and intersections of basic geometrical shapes such as planes, cylinders, spheres, cones, and tori. A voxel phantom, on the other hand, is more precise in its description of the source geometry because it is created by adding depth to a set of detailed cross-sectional images of the source object which are obtained through computer tomography (CT) or magnetic resonance imaging (MRI).

Mathematical models of the 5-ml ampoule and the BOMAB head were created by the Moritz/White Rocks Science Co. software[1] using the software's basic geometrical shapes and by providing the measured dimensions of each of our geometries. The voxel model of the BOMAB head was developed using data from CT scans performed at the National Naval Medical Center. The procedure to create a detailed computational geometry is shown in Fig. 3. Two hundred four cross-sectional CT scans 1 mm in width were made along a single axis down the middle of the head and a computer was used to convert the tomograms into digital pictures coded in the standard Digital Imaging and Communications in Medicine (DICOM) format. A program called Scan2MCNP/White Rock Science Co.[1] was then used to convert the DICOM files into a three-dimensional voxel phantom description of the BOMAB head for use in MCNP. The Scan2MCNP program writes the phantom as a lattice of rectangular voxels based on the user's assignment of materials to meaningful ranges of pixel values in the scan images. Approximately a quarter-million rectangular voxels of size 1 mm×5 mm×5 mm were used to describe the BOMAB head geometry. Then the voxelized BOMAB is imported into a computer model of the actual laboratory environment using Moritz program. This simulated laboratory environment is drawn to scale and the major surface boundaries are defined with planes and cylinders. Other than the source geometry, the most important object in the simulated environment is the detector. The material content and geometry of the detector were defined carefully according to scaled diagrams provided by the manufacturer. The mathematical or voxel phantom source geometry is placed within the simulated environment on a computer model of the source platform. This platform mimics the LPS in that it can be moved closer or further from detector depending on the desired location of the source for the MCNP computation. The framework of the LPS was not included in the environment because it was determined that its effect on the efficiency value was negligible.

After defining the whole environment and measuring system geometry, the user includes in the input file lines of code that tell MCNP to randomly choose starting photon positions within the HCl solution located inside the two source geometries. The initial photon energy is chosen randomly from a distribution corresponding to the gamma-ray emission energy spectrum of ^{67}Ga. As the program runs, MCNP keeps track of the particles as they travel through the simulated laboratory environment interacting with matter. Particles which enter the sensitive region of the detector are tallied into energy bins which are defined analogously to the channels of the actual detector. The MCNP output file includes an efficiency versus energy distribution. MCNPX v2.4.0 was used to run the input files on a desktop computer with a 2.8 GHz processor and 512 MB of RAM. Typically, 80 to 100 million particle histories were run to yield an efficiency value with an uncertainty of about 2% ($k = 1$). Computer time for the MCNP simulations is defined by the complexity of the source geometry and the number of particle histories run. MCNP simulations of the 5-ml ampoule source using the mathematical approach ran in a matter of minutes, while simulations of the mathematically modelled BOMAB head took about 1 hour to complete. Input files for the voxelized BOMAB head took, in general, six hours to run.

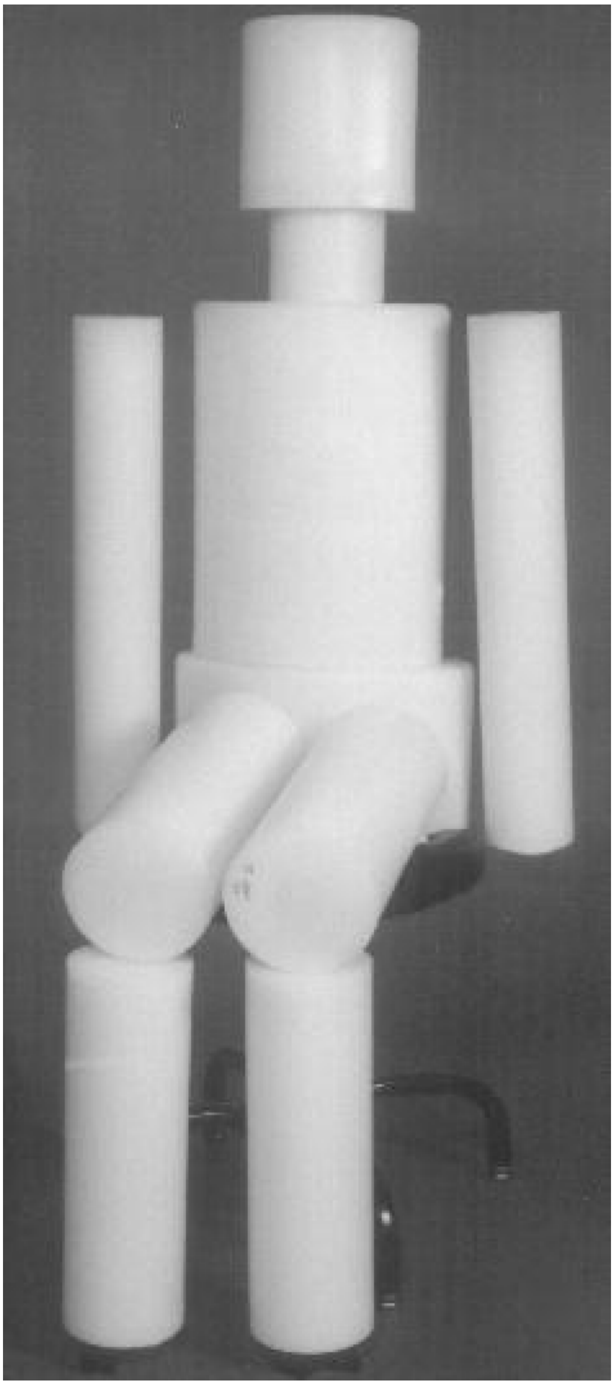

Fig. 1. The BOttle Manikin ABsorption (BOMAB) Phantom (http://www.llnl.gov/wbc/bomab.html)

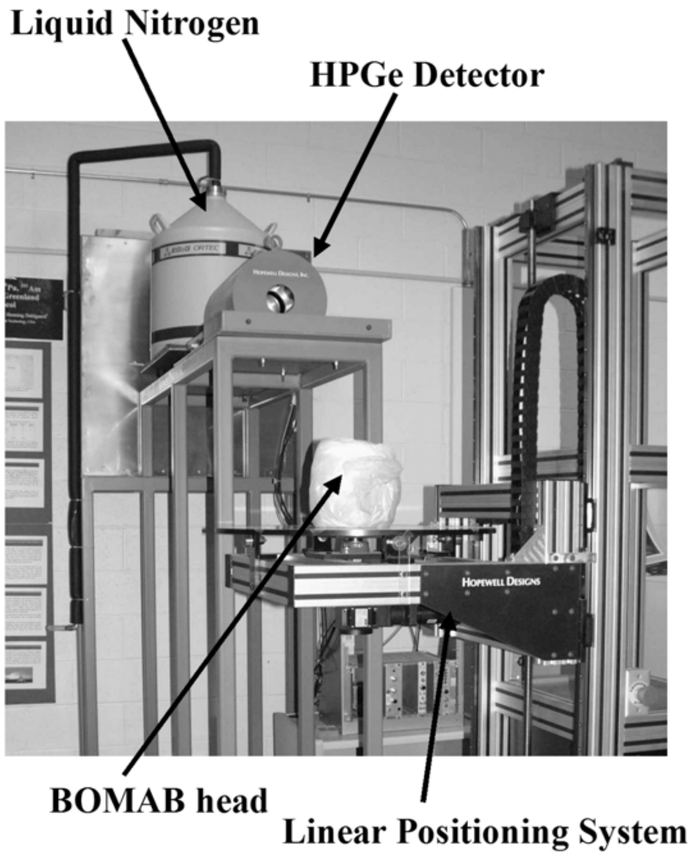

Fig. 2. Photograph of the measurement system

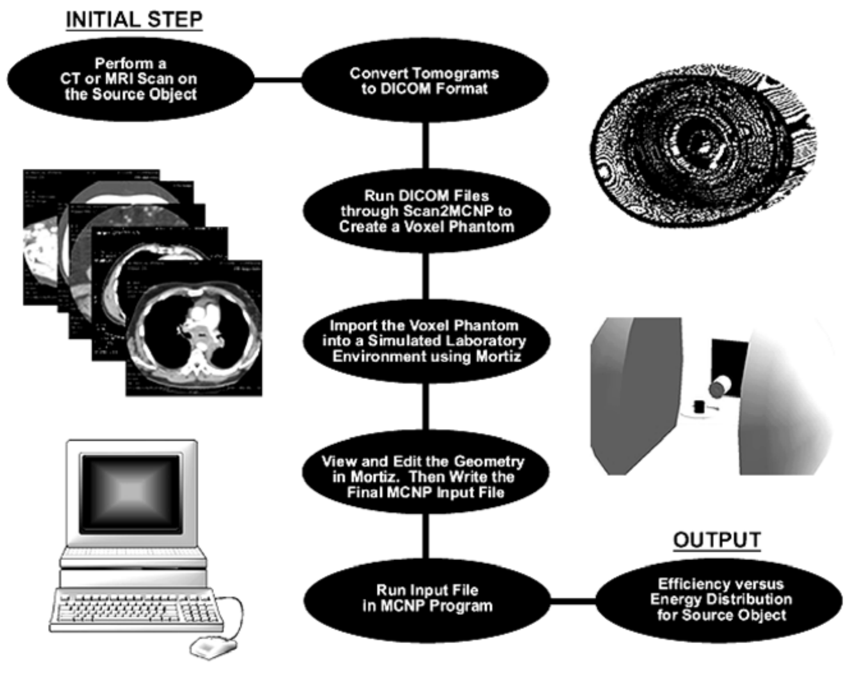

Fig. 3. Outline of the process of creating a voxel phantom to estimate the efficiency of a source object by means of Monte Carlo computation

Results and conclusions

Performing real measurements of both our geometries, BOMAB head and 5-ml ampoule, and running the MCNP simulation for different sets of measurements, allowed us to estimate the efficiencies for our HPGe detector. We found that the MCNP computed efficiencies using the mathematical phantom approach are in a good agreement with the experimentally derived efficiency values. The differences in the experimental and theoretical efficiency values (W. J. DIXON and F. J. MASSEY)[1] are within the uncertainty of each measurement (Table 1 and Fig. 4). MCNP efficiency data using the voxel phantom approach are still being recorded, but they are also expected to be in good agreement with the experimental results. MCNP was used to construct a theoretical efficiency curve for the 5-ml ampoule geometry corresponding to a wider range of energies than for the experimental measurements of ^{67}Ga. The curve was compared to the experimental results of NIST standards in 5-ml ampoules and again we found a good agreement (Fig. 5).

The dominating source of error in the experimental results is the emission probability of the gamma-rays. The uncertainty in the MCNP computed efficiencies is quoted in the output files as a relative error that describes the precision of the calculation that depends on the number of running particles and the quality of the description of the measuring system. In general, the relative error is inverse proportional to $\sqrt{N}$, where N is the number of counts (for experiment) or particle histories (for MCNP). The agreement between our experimental and theoretical data suggests that in addition to being precise, our MCNP calculations are at least as accurate as the values determined through the experimental approach.

The data (Table 1) appear to support the claim that efficiency estimates based on Monte Carlo computation can be just as reliable as high quality experimental measurements. Efficiency calibration using MCNP has the advantage of being cheaper, faster and more flexible than alternative experimental approaches.

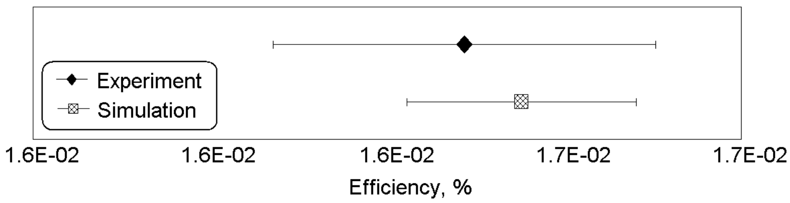

Fig. 4. Comparison of efficiency data for the 5-ml ampoule. The standard uncertainties are reported for $k = 1$

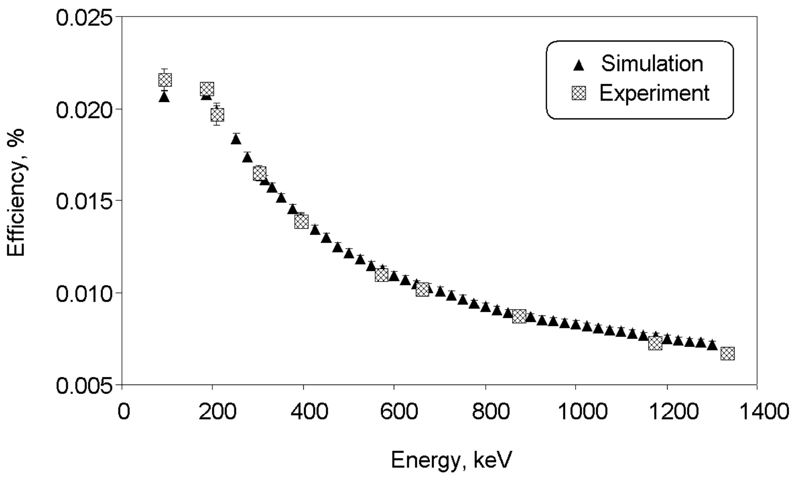

Fig. 5. Efficiency calibration curve for the 5-ml ampoule based on experimental and computational calculations (source–detector = 90 cm). The standard uncertainties are reported for $k = 2$

Table 1. Experimental and MCNP computed efficiency data for the BOMAB head. The MCNP efficiency was obtained using the mathematical phantom approach

Source–detector distance, cm	Experimental efficiency, %	Experimental efficiency uncertainty ($k = 2$)	MCNP computed efficiency, %	MCNP efficiency uncertainty ($k = 2$)	Difference between experimental and MCNP efficiency, %
184.6 keV					
88	1.322E-2	3.7E-4	1.314E-2	2.6E-4	0.59
90	1.263E-2	3.6E-4	1.260E-2	2.5E-4	0.26
100	1.036E-2	2.9E-4	1.019E-2	2.3E-4	1.66
110	8.59E-3	2.4E-4	8.47E-3	2.0E-4	1.47
130	6.18E-3	1.7E-4	6.11E-3	1.7E-4	1.13
140	5.31E-3	1.5E-4	5.32E-3	1.6E-4	0.03
150	4.66E-3	1.3E-4	4.62E-3	1.5E-4	0.95
160	4.11E-3	1.2E-4	4.05E-3	1.4E-4	1.45
208.9 keV					
88	1.275E-2	7.4E-4	1.280E-2	2.5E-4	0.38
90	1.214E-2	7.1E-4	1.223E-2	2.5E-4	0.76
100	1.007E-2	5.9E-4	9.96E-3	2.2E-4	1.10
110	8.26E-3	4.8E-4	8.23E-3	2.0E-4	0.40
130	5.93E-3	3.5E-4	5.95E-3	1.7E-4	0.48
140	5.15E-3	3.0E-4	5.16E-3	1.6E-4	0.28
150	4.46E-3	2.6E-4	4.51E-3	1.5E-4	1.14
160	3.90E-3	2.3E-4	3.96E-3	1.4E-4	1.64
300.2 keV					
88	1.110E-2	2.9E-4	1.124E-2	2.4E-4	0.28
90	1.045E-2	2.7E-4	1.073E-2	2.3E-4	0.06
100	8.65E-3	2.3E-4	8.75E-3	2.1E-4	0.62
110	7.22E-3	1.9E-4	7.26E-3	1.9E-4	1.32
130	5.17E-3	1.4E-4	5.23E-3	1.6E-4	0.44
140	4.51E-3	1.2E-4	4.54E-3	1.5E-4	1.21
150	3.94E-3	1.0E-4	3.94E-3	1.4E-4	2.69
160	3.46E-3	9.1E-5	3.47E-3	1.3E-4	1.30

A long term goal of this project is to create a NIST standard human body phantom. The theoretical efficiency of this phantom will be validated by comparing MCNP computations with experimental results. Existing phantoms can then be related to the NIST standard by using MCNP to estimate the efficiency of the phantoms based on their CT or MRI images.

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The materials identified in this document, and this identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the identified product is necessarily the best available for the purpose.

References

1. W. J. DIXON, F. J. MASSEY, Introduction to Statistical Analysis, McGraw-Hill, New York, 1969.