

Development of voxelised numerical phantoms using MCNP Monte Carlo code: Application to *in vivo* measurement

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ABSTRACT Although great efforts had been made to improve the physical phantoms used for calibrating *in vivo* measurement systems, for technical reasons they can only provide a rough representation of human tissue. Substantial corrections must therefore be made to calibration factors obtained with such calibration phantoms for extrapolation to a given individual. These corrections are particularly crucial and delicate in low-energy *in vivo* measurement when absorption in tissue is significant. To improve calibration for such special conditions, the possibility has been raised of using voxelised numerical phantoms associated with Monte Carlo computing techniques. In the method described below, a mathematical phantom, consisting of a voxelised representation derived from scanner images is used, with a specially-designed interface making it possible to not only reconstruct widely-differing contamination configurations and specify associated tissue compositions, but also automatically create an MCNP4b input file. After validation of the different sources and geometries, the complete procedure of reconstruction of the phantom and simulation of ^{241}Am lung measurement was carried out using a tissue equivalent calibration phantom of the type commonly used for lung calibration for actinides. The purpose of this work was to extend the use of this principle to the reconstruction of numerical phantoms on the basis of physiological data of individuals obtained from magnetic resonance and scanner images. The results obtained and the current limitations of this approach in the context are discussed.

RÉSUMÉ Développement de fantômes numériques voxelisés associé au code Monte Carlo MCNP : application à la mesure anthroporadiométrique.

Bien que d'importants efforts aient été réalisés pour améliorer la fabrication des fantômes physiques servant à l'étalonnage des installations anthroporadiométriques, ils ne peuvent fournir, pour des raisons techniques, qu'une représentation plus ou moins grossière des tissus humains. Par conséquent, des corrections significatives doivent être faites sur les facteurs d'étalonnage obtenus par ces fantômes d'étalonnage en vue d'une extrapolation à un individu donné. Ces corrections sont particulièrement cruciales et très délicates pour la mesure *in vivo* basse énergie tant les absorptions dans les tissus sont significatives. Pour améliorer l'étalonnage dans ces conditions particulières, l'utilisation de fantômes numériques voxelisés associant les techniques de calcul Monte Carlo a déjà été évoquée. La méthode présentée ici utilise un fantôme mathématique, produit sous la forme de voxels reconstruit à partir

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d'images scanners, à l'aide d'une interface spécialement développée permettant d'une part, la reconstruction de configurations très variées de contaminations et de définir les compositions tissulaires associées et d'autre part, la création automatique du fichier d'entrée de MCNP4b. Après validation sur différentes sources et différentes géométries, la procédure complète, reconstruction du fantôme et simulation de la mesure pulmonaire de ^{241}Am , a été réalisée à partir d'un fantôme d'étalement équivalent tissus généralement utilisé pour l'étalement pulmonaire des actinides. Le but du travail présenté ici sera d'étendre l'utilisation de ce principe à la reconstruction de fantômes numériques basée sur les données physiologiques des personnes obtenues à partir d'images scanner ou IRM. Les résultats présentés et les limitations actuelles de cette approche sont discutés dans ce contexte.

1. Introduction

As a result of the rapidity with which it can be implemented, *in vivo* lung measurement constitutes the preferred method for estimating contamination after the inhalation of radiotoxic substances. Actinides (particularly ^{239}Pu) emit low energy x-rays and gamma-rays. Although detection has been improved by the introduction of the high-volume germanium detector, equipment performance results in measurement uncertainties that are still far too high (Franck *et al.*, 1997). Although great efforts have been made to improve the physical phantoms used for calibrating *in vivo* measurement systems, they actually represent only an approximate geometry and generally only provide for uniform distribution of radioelements in contaminated tissue. In addition, the high attenuation of photons of energies between 10 and 100 keV in human tissue constitutes a major obstacle to the detection of the radionuclides responsible for contamination. Therefore, knowledge of the thickness of the extrathoracic tissue and of its composition is crucial to correct estimation of the calibration factors for a given individual. In general, thickness is estimated by ultrasonic methods or by bioparametric measurements essentially consisting of weight and height (Kang *et al.*, 1993; Vickers, 1996). However, such procedures lack the necessary precision to properly cover biochemical differences such as the proportion of fat, and make no allowance for other differences, such as organ size. It is therefore important to develop new calibration techniques that are more adaptable to such variations, and earlier work has shown the possibility of using the Monte Carlo method (Mallett *et al.*, 1995; Hunt *et al.*, 1998).

The purpose of the work described here is to extend this principle to the reconstruction of numerical phantoms using anatomical and physiological data relating to individuals to be measured, with the longer-term goal of flexible use in a large number of different applications such as measurement of wounds, measurement of the thyroid and measurement of the lung. This would involve an original calibration method that has been developed, combining the creation of numerical phantoms in the form of voxels obtained from tomographic images (CT) or magnetic resonance images (MRI) with Monte Carlo calculations. It involves

the use of a graphical user interface (named Anthropro) specially developed with the PV-Waves© software suite. The Monte Carlo code used is MCNP4b (Briesmeister, 1997), which is specially adapted to simulating the transport through tissue of photons with energies corresponding to the range of interest, *i.e.* 10 to 1400 keV.

The procedure was first validated with different diffuse sources, then applied to the specific case of low-energy lung measurements on Livermore phantoms, the mannequins generally used in *in vivo* counting, in order to compare the results of simulation and measurement.

2. The equipment and methods

2.1. The “Anthropro” interface

The Anthropro interface between the physician in charge of measurement and the MCNP4b code based on magnetic resonance or scanner images and technical data relating to a particular *in vivo* measurement system, operates by automatically creating an input file corresponding to the geometry of the phantom (individual measured + detector). The interface was developed with the PV-Waves© software suite. This was chosen as it makes it possible to develop extremely user-friendly graphical man-machine interfaces, to process and carry out all kinds of operations on data arrays with up to 256 dimensions, and to display the data. Finally, PV-Waves© includes a number of preset applications for signal and image processing (mathematical deconvolution and FFT) which can be used to develop special image processing modules that are extremely useful for determining the boundaries of organs during the segmentation stage. All these modules are objects in the computer-science meaning of the term, enabling easy and efficient object-oriented programming. It is therefore highly suited to the task of reconstruction of three-dimensional images from radiological acquisition systems. All the source code of the applications, written in a specific PV-Waves© language, is available and can be modified according to the user’s requirements.

2.2. Anthropro interface functionality

The interface is specially designed for the data required for MCNP4b to enable correct simulation of the photon spectra in the detectors generally used in gamma spectrometry and *in vivo* measurement system laboratories. Its architecture is shown in Figure 1.

The Anthropro interface input data is of three orders: (i) magnetic resonance or scanned images of different sections of a phantom or a person, (ii) source description, *i.e.* the type of source (point or diffuse), the number of gamma-radiation lines

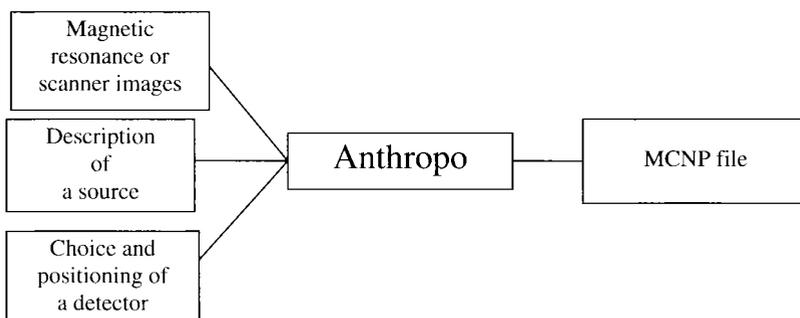


Figure 1 – Diagram of Anthropro interface operation.
Schéma de principe de l'interface Anthropro.

used, their energy, their probability and the activity of the sources, making it possible to directly calculate the number of histories used in the simulation with MCNP4b and finally, (iii) the geometry of the detector and its positioning relative to the numerical phantom.

In addition to the basic arrangement, there are modules for saving, and for image processing and display. The latter are first used for segmenting the images on the basis of the different shades of grey obtained when creating images by tomography or magnetic resonance (Fig. 2), and then for associating different organs with the tissue densities specified by the ICRU (ICRU44, 1989). The MCNP4b code input file is then automatically written by the Anthropro interface. It consists of the above data plus data relating to the geometry of the detector and the materials it is made of, the nature of the sources and finally the quantities required from the calculations (referred to as the “tally” in THE MCNP code), *i.e.* in our case, the spectrum of the energy deposited in the counter. This stage is completely automatic. To check that the MCNP4b input file is properly configured, the overall geometry (phantom + detector) is displayed using the Sabrina code (Kenneth, 1994).

The Anthropro interface has few limitations. These essentially result from the intrinsic limitations of both the MCNP4b code, for which the maximum number of cells is 100 000, and also the computer used to run the simulation in terms of the amount of available RAM, the size of the input files and, depending on its speed, the fact that calculation times may be very long with a phantom made up of a very large number of voxels.

Anthropro’s independence from the input data, particularly the type of phantom and the sources, should make it possible to use the interface both for diagnoses and

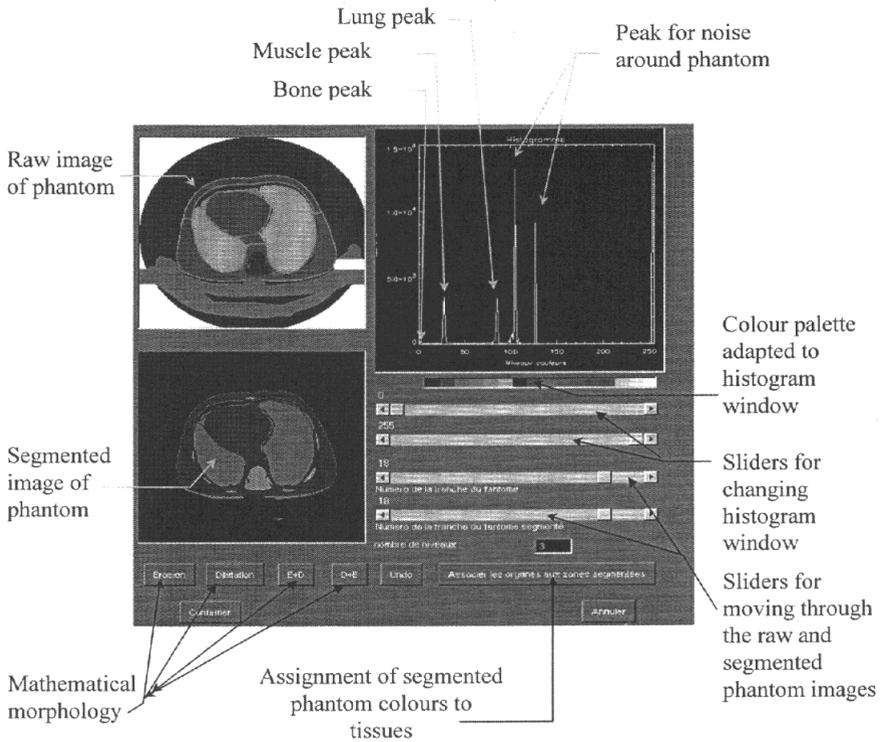


Figure 2 – Segmentation procedure window of the Anthropo interface.

Image de la fenêtre utilisée pour la procédure de segmentation du fantôme numérique dans l'interface Anthropo.

for *in vivo* counting in cases of actual contamination or studies of non-uniform contamination, as well as a means of optimising detector positioning.

3. Validation of the Anthropo interface

3.1. Comparison of experimental spectra with sources of different geometries

The MCNP4b code input parameters were validated by comparing the simulated and measured efficiencies with a series of sources of different geometries. Table 1 shows that the differences found between measurement and numerical simulation for areas of peaks are always less than 10% at energies greater than 26 keV

TABLE I

Standard deviation of peak area obtained between experimental and simulated measurements with 3 types of source geometries.

Écart relatifs sur les surfaces des pics entre la mesure expérimentale et la mesure simulée pour 3 différents types de géométries de sources.

	Energy (keV)	Emission (percentage)	Relative error at surface (/Surface exp.)
Point source - ^{241}Am Activity = 31 848 Bq	13.90	13%	-12.1%
	21.01	4.8%	10.7%
	26.34	2.4%	5.3%
	59.54	35.9%	-2.7%
4cc bottle of ^{57}Co Activity = 81.3 Bq	122.06	85.7%	-7.8%
	136.47	10.70%	-8.6%
500 cc bottle (SG500) ^{133}Ba Activity = 20 883 Bq	30.97	98.8%	-0.5%
	34.92	18.9%	-0.8%
	81.00	34.1%	-5.5%
	160.61	0.64%	4.0%

and less than 15% for the x-ray lines (13.9 and 21.0 keV), which is completely satisfactory in view of the difficulty normally encountered in measuring these low energy lines.

3.2. Comparison of the results of *in vivo* measurement of ^{241}Am in the lung with those of numerical simulation

Using these results, a realistic comparison with *in vivo* measurement was made. This involved the use of a tissue equivalent Livermore phantom for calibration of *in vivo* lung measurement containing a uniformly-distributed charge of 70 kBq of ^{241}Am for reference purposes. The procedure was carried out in three stages: creation of images, creation of simulation file and comparison with the results of experimental measurement.

3.2.1. Creation of images

The images used to validate the method were obtained by tomography. As the phantom used consisted exclusively of polyurethane and therefore contained no free hydrogen, MRI would not have given usable images. The Livermore phantom was scanned at the Gustave Roussy Institute. Forty 515×512 pixel images were obtained, corresponding to the entire phantom.

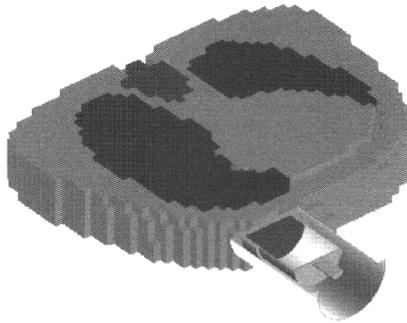


Figure 3 – Cross section of detector + Livermore phantom geometry visualised with Sabrina from MCNP4b file obtained with Anthropro interface.

Vue en coupe de la géométrie détecteur + fantôme de Livermore visualisée par Sabrina à partir du fichier MCNP4b réalisé par l'interface Anthropro.

3.2.2. Creation of MCNP4b file

The Anthropro interface was used to reconstruct the numerical phantom, to position the detector and carry out a simulation of diffuse contamination of the lungs. However, as a result of the limited number of voxels that MCNP4b can handle, the amount memory of the computer used and the long computation time necessary for the simulation, the number of pixels of the phantom was reduced. This was done by only using the images corresponding to the lung area and by reducing the definition of the phantom from $515 \times 512 \times 40$ voxels (*i.e.* 1.05×10^7) to $64 \times 64 \times 20$ voxels (*i.e.* 81 920). This resulted in loss of detail which, as explained later, can affect the results of simulation. A file with a format that the Monte Carlo MCNP4b code can use was then automatically written. An example of phantom image sections and detector positioning obtained and displayed with the Sabrina program is given in Figure 3. The various operations making up this stage can be carried out in 15 minutes.

3.2.3. Comparison of the results of simulation and experimental measurement

The energy deposit spectrum in the LEGe detector was then calculated by MCNP4b on a 280 MHz Pentium II computer with 64 Mb of RAM, and compared with the actual spectrum obtained with the same geometrical arrangement in our laboratory (Fig. 4). For an actual measurement time of 10 minutes, the Monte Carlo calculation lasted 12 hours, with an equivalent statistical error of 6% for the peak analysed. If the areas of the peaks obtained by simulation and measurement

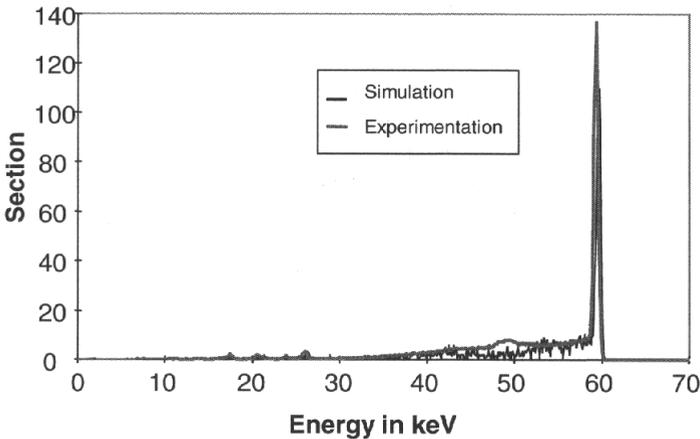


Figure 4 – Comparison of simulated (black line) and experimental (grey line) spectra for Livermore phantom loaded with lung contaminated with ^{241}Am .

Comparaison des spectres simulés (noir) et expérimentaux (gris) obtenus pour un fantôme de Livermore dont les poumons étaient contaminés en ^{241}Am .

are compared, experimentation gives results that are 17% better. This can be explained by a number of factors:

- measurement error including statistical error and calibration error, which can be estimated at around 10%;
- error due to degradation of image resolution as a result of reduction of the number of pixels, which was found to be necessary to conduct the simulation. The operation results in a slight increase in the extrathoracic thickness of the scanned images, as shown in Figure 3, which, in view of the low energy of the lines measured and the resulting self-absorption in the mannequin, can be estimated at around 10%.

4. Conclusion and outlook

Calibration associating voxelised numerical phantoms with Monte Carlo calculations has already been suggested as a means of solving *in vivo* measurement system x-ray and gamma-ray spectrometry calibration problems. It has accordingly been demonstrated that this approach has considerable potential for the calibration of *in vivo* counting systems for measuring low energy x-ray and gamma-ray emitters in the lung. The work described in this document was carried out with a view to extending use of this principle to the reconstruction of numerical phantoms based on physiological data relating to individuals to be measured, using magnetic

resonance and scanner images. The interface designed makes it possible to automatically create a MCNP4b computer code input file with complex three-dimensional phantom geometry reconstituted from images.

The results of the first simulations are extremely encouraging. With sources of different geometries, directly simulated spectra have been obtained that are comparable to those obtained by experimentation, with relative error between simulation and experimentation of less than 20%, and in most cases less than 10%. This result has been confirmed by a study of simulation of lung count measurements on a phantom contaminated with ^{241}Am . In this more complex case, a difference of 17% was observed between the results of experimental measurement and Monte Carlo calculation. In view of the approximations made in reconstruction of the numerical phantom and, particularly, the image resolution, the results are entirely satisfactory.

Consequently, as a result of its flexibility in accommodating complex geometry, the method developed not only represents a diagnostic tool for *in vivo* measurement, but also opens up new possibilities such as the optimisation of detection systems, the study of contamination with mixed actinides and any other simulation using MCNP4b where complex geometry is derived from a set of superimposed images.

However, improvements still need to be made. First of all, some uncertainties, such as those concerning efficiencies, can be further reduced. It has also become clearly apparent that although the total numerical phantom reconstruction time can be substantially reduced by means of development tools (two hours in our case), the calculation time remains prohibitive for problems requiring both exploration of a large volume and fine definition of its component parts. This remains the main limitation of this type of approach. Some authors (Xu *et al.*, 1999) have, however, demonstrated that considerably shorter calculation times could be achieved by modifying the MCNP4b source code and increasing the power of the host computer (approximately 1 hour of calculation for a phantom with 6×10^6 voxels with one million photons emitted, as compared to the current 12 hours of calculation for a phantom with 90 000 cells and one million photons emitted using our current computer equipment). However, this optimisation has only been applied to calculation of the dose to organs and requires calculation tools on the workstation which may be difficult to use in many laboratories. Adaptation to *in vivo* measurement is in progress.

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