Abstract
In the event of a radiological accident caused by an external source, estimating the dose distribution in the victim's body is a relevant indicator in assessing biological damage from this exposure. This dose distribution can be assessed by physical dosimetric reconstruction methods. Physical dosimetric reconstruction can be achieved using experimental or numerical techniques. This article presents the laboratory-developed SESAME tool specific to dosimetric reconstruction of a radiological accident through numerical simulations, which combines voxel geometry and the radiation-material interaction MCNP(X) Monte Carlo computer code. The experimental validation of the tool in photonic field and its application to a radiological accident in Chile in December 2005 are also described.
Introduction

In the event of a radiological accident caused by an external source, estimating the dose distribution in the victim's body is a relevant indicator in assessing biological damage from this exposure. This dose distribution can be assessed by physical dosimetric reconstruction methods, which are made possible using experimental techniques; this involves irradiating a tissue-equivalent anthropomorphic model equipped with dosimeters under similar conditions as the accident. These techniques are however cumbersome to apply and it can prove impossible to reproduce the circumstances of the accident exactly. Thus methods using numerical phantoms combined with a particle transport code have been developed. These methods consist of modelling the victim, the source and victim's environment and calculating the doses absorbed by the organs and the dose distribution in the organism using a radiation-material interaction code. The victim can be modelled by a standard mathematical anthropomorphic phantom made up of simple geometric elements or by a so-called voxel phantom. This type of phantom is generated from scanner or MRI images of the victim. These phantoms are made up of a huge number of small volumes called voxels and provide a more realistic description of the human anatomy than mathematical phantoms, as they are based on real anatomical data. These phantoms are therefore particularly interesting when localised irradiation is involved or when anatomical precision proves to be essential.

The Institute for Radiological protection and Nuclear Safety (IRSN) has been using mathematical anthropomorphic phantoms based on models developed in the External Dosimetry Department and models commonly used in radiological protection (MIRD phantom (Cristy and Eckerman 1987)) for dosimetric reconstruction of a radiological accident for over ten years (Bottollier-Depois et al. 2000; Roux et al. 2000; IAEA Report 2000a; IAEA Report 2000b; Clairand et al. 2006). Voxel phantoms are commonly used in dosimetry and more particularly radiological protection combined with various transport computer codes.
(Lemosquet et al. 2003). Thus IRSN has developed a specific tool called SESAME - Simulation of External Source Accident with MEdical images - for the dosimetric reconstruction of a radiological accident by numeric simulations, which combines voxel geometry and the radiation-material interaction MCNP(X) Monte Carlo computer code (Breismeister 1997; Waters 2002). The advantage of this tool is that it can simply and automatically generate voxel phantoms and the input file in the MCNP(X) code format with a user-friendly GUI.

This article describes the SESAME graphic interface and the experimental validation of the tool in photonic field. Finally, the application of this tool to an accident which occurred in Chile in December 2005 is presented.

**Description of the SESAME tool**

**General principle**

SESAME is a user-friendly graphic interface developed under the PV-Wave environment. SESAME deals with the entire dose reconstruction procedure for a radiological accident by numeric simulations. The tool's block diagram is illustrated in Figure 1. This tool is used to:

- generate voxel phantoms from scanner or MRI images,
- reconstruct the accident (description and position of the source, walls and screens),
- generate the input file automatically in MCNP(X) format for the calculation,
- display the calculation results.

**Construction of voxel phantoms**

The images acquired by scanner or MRI must pass through a certain number of operations to be used to construct a voxel phantom. The tissues and organs have to be identified and segmented before they are allocated physical properties. The first stage in constructing the voxel phantom is to import the scanner or MRI images of the victim in DICOM format into the radiotherapy treatment planning software program Dosigray® and to create the external
contours and the organ contours in each slice. These images are then imported into SESAME to generate a voxel phantom with the developed segmentation module. Based on the raw image, the segmentation creates an image grouping zones with identical properties. Voxels with a same colour (even density) are matched automatically to a same composition under the segmentation procedure. The result is a segmented voxel phantom.

Position and definition of the source and of the victim's environment

A user-friendly module positions and defines the source. The source can be a point or a volume (sphere, cylinder, parallelepiped) and emit neutrons, photons or electrons. The phantom is displayed according to the three space planes (sum of all the slices according to the transverse, sagittal and frontal planes) and a cursor system is used to move the source in relation to the phantom. The nature of the source must be defined once it has been positioned. The user firstly selects the constituent radionuclides and then the type of source particles to be generated, the particles to be tracked, the density of the material, the source activity and the exposure time. Figure 2 illustrates the source positioning and definition module developed in SESAME.

A module can also define the victim's environment. It is therefore possible to position and define screens and walls in similar fashion to the source positioning and definition module.

Dose calculation module

This module is used to select the dose calculation sought. It is possible to calculate a dose absorbed at various points, an averaged dose in organs or a dose distribution. For the dose in organs calculation, the organs present in the voxel phantom, for which the average dose is sought, are selected in a window. The absorbed dose (MCNP(X) tally f6 or *f8) is calculated in each cell. When the results file is used subsequently, the average dose in the organ is obtained by totalling the results from each cell. When calculating dose distribution, the user selects the slices for which he wishes to obtain the dose distribution and also defines the
calculation zone. In this configuration, the absorbed dose (MCNP(X) tally f6 or *f8) is calculated in each voxel.

Constructing an input file in MCNP(X) format

A module automatically generates the input file for calculation with the MCNP(X) code. The segmented voxel phantom geometry can be generated in two different ways: by using the voxel coupling or by using the repeated structures.

In voxel coupling, the phantom is described as a sum of parallelepiped rectangles. This involves coupling the neighbouring voxels made up of the same material and with the same density in a single MCNP(X) cell. The algorithm is based on the extension of a three-dimensional parallelepiped until another material is found. It then checks whether it is possible to extend the box simultaneously under two dimensions. If the two-dimensional extension is impossible, it tests if an extension under a single dimension is still possible. The extension stops when all single-dimensional movements become impossible. The six planes defining each cell are thus defined. Figure 3 represents a voxel phantom with and without voxel coupling for an anthroporadiometric application (Borissov et al. 2002). From left to right are seen in succession no coupling, single-dimensional coupling and three-dimensional coupling. This method of describing the geometry is sufficient when calculating a dose in organs. However, given that MCNP(X) is limited to 100,000 cells, a distribution dose cannot be calculated for the whole phantom at once. Thus repeated structures were implemented.

A repeated-structures phantom is written as a lattice network. Here, each voxel constitutes an element in the lattice network to which is associated the corresponding universe (i.e. the material making up the voxel). The advantage of this method is that the phantom is described using only a few cells: one cell for the lattice network and as many cells as there are materials making up the phantom. With this writing, the dose distribution in the whole phantom, i.e. for each voxel, can therefore be performed in a single calculation.
Calculation and results display

The calculation is launched outside the application in UNIX stations or clusters specific to scientific calculations and the output file is recovered so that the results may be put to good use. The results for the average doses in the organs, the average dose for the entire body and the dose absorbed at certain points are presented in tabular form. For the dose distributions, SESAME offers a very interesting function, that of superimposing the 2D isodose curves on the anatomic slices of the victim.

Experimental tool validation (photonic exposure)

The tool has been validated experimentally in neutron and photonic fields. The neutron validation was carried out in the SILENE reactor and the results of this validation have already been presented (Lemosquet et al. 2004).

Materials and methods

The experimental validation in photonic field was performed in an IRSN facility using a $^{60}\text{Co}$ source. For this experimental validation, the RANDO tissue-equivalent physical model, fitted with 132 thermoluminescent alumina oxide dosimeters, was placed at a distance of 1 m in front of an isotropic source of 376 GBq of $^{60}\text{Co}$ for twenty hours. Eighteen dosimeters were placed on the abdomen to simulate a fictitious parallelepiped organ, 43 were distributed randomly inside the model, eighteen were spread over the outside of the model and 53 were arranged in one and the same slice to assess the dose distribution in this surface area. The source was located in a circular room 7 m in diameter and 4 m high with 30 cm-thick concrete walls.

The entire irradiation reconstruction procedure was then carried out using the SESAME interface. Firstly, the tomodensitometry of the RANDO physical model was acquired and a voxel phantom made up of 0.23 cm$^3$0.23 cm$^3$1 cm voxels was generated from 175 scanner
sections. Five internal structures were defined: bones, lungs, teeth, soft tissue and the fictitious organ at the abdomen. The dosimeters were also modelled to get as close as possible to the experimental conditions. The source and walls were defined and positioned via SESAME and the input file in MCNP(X) format was generated. The three possibilities offered by the SESAME tool were each investigated using the radiation-material interaction MCNP4c2 Monte Carlo code (Breismeister 2000): the absorbed dose at various points, an average dose in an organ and dose distribution. Figure 4 shows a picture of the model during irradiation, a 3D representation of the segmented voxel phantom without its envelope and a 3D representation of the modelling of the phantom and of its environment.

Results and discussion

The results obtained for the absorbed dose at various points distributed randomly through the entire phantom are presented in Figure 5. The most significant discrepancy between the measurement and the calculation is 22% whereas the average discrepancy is in the order of 5%. Larger discrepancies are noted generally in the external points at the rear of the phantom, due to the lack of statistics at these points.

For the dose in the fictitious organ, the measured dose was assessed by taking the average of doses read in the eighteen dosimeters spread uniformly in the organ. The dose thus obtained was 2.04 Gy +/- 0.15 Gy. The calculation produced 1.85 Gy +/- 0.17 Gy, i.e. a discrepancy in the order of 10% between the measured dose and the calculated dose. This is a satisfactory discrepancy given the difficulty in modelling the experimental conditions accurately (possible difference in the fictitious organ location between the experiment and the simulation, possible error of a few centimetres in measuring the distance between the source and the model's thorax).

Finally, Figure 6 presents the calculated dose distribution. The smoothed isodoses determined from the experimental results have been superimposed for easier comparison. The calculated
and measured curves are similar. Note however discrepancies in the isodoses at the rear of the phantom. This is explained in particular by the limited number of experimental points, with the resulting poor performance of the smoothing algorithm under PV-Wave, and by the lack of statistics at these points.

**Application to the radiological accident in Chile in December 2005**

This tool was used in real time in an accident which occurred in Chile in December 2005.

**Accident context**

On 15 December 2005, in Chile, a worker in a cellulose plant picked up a $^{192}$Ir source which had fallen inadvertently from a gammagraphy device. He handled it with his bare hands and also put it in the back left-hand pocket of his trousers before it was detected by someone with an electronic dosimeter, about forty minutes after the worker had found the source. An erythema very quickly developed on the victim’s left buttock. Chile called on the IAEA for assistance which appointed a number of people on site to investigate. The victim was transferred to France on 29 December 2005 for treatment at the Percy Military Training Hospital in Clamart near Paris.

IRSN was requested to perform the dosimetric reconstruction by numeric simulations on 19 December.

**Materials and methods**

Data used to perform the dosimetric reconstruction were taken from the enquiry carried out by the authorities in Chile and also from the report drawn up by the people appointed to assess the site by the IAEA.

The source was a cylindrical $^{192}$Ir source measuring 1 mm in radius and 2 mm in height enclosed in a steel cylinder measuring 2 mm in thickness and 6 mm in height. A picture of the source is shown in Figure 7. Source activity at the time of the accident was 3.3 TBq (90 Ci).
\(^{192}\text{Ir}\) is a very dense metal and its radioactive half-life is 74 days. As it disintegrates, it emits beta minus particles with a maximal energy of 256, 590 and 670 keV and, in particular, complex radiations made up of several gamma lines with an average energy of 350 keV.

According to the scenario, which is based mainly on the victim’s own account, he handled the source for several minutes with his bare hands, passing it from one hand to the other. The source was also placed for about ten minutes in the back left-hand pocket of his trousers. Given the uncertainties over the position of the source and the exposure time when the victim held it in his hands, it was impossible to reconstruct this sequence. Thus only the reconstruction of the localised irradiation to the buttock is presented here.

Once the victim had been hospitalised in France, the scanner and MRI images taken at the Percy hospital became available. 163 scanner sections from mid-abdomen to mid-thigh were selected. Then, using the SESAME software, a voxel phantom (voxel size 0.22 cm*0.22 cm*0.18 cm) with external contours and bone structure was generated and the source was defined and positioned. Given the source geometry, only the photonic component of the \(^{192}\text{Ir}\) source was taken into account. Finally, the area for which we wanted to calculate the isodoses, i.e. at the centre of the lesion, was selected. A 3D representation of the voxel phantom and of the source is shown in Figure 8. The input file in MCNP(X) format was generated and the dose distributions were calculated with the radiation-material interaction MCNPX Monte Carlo code version 2.5f (Waters 2002).

Results

The distributed dose obtained in the lesion section is presented in Figure 9. The absorbed dose at the skin surface is very high (1900 Gy) but drops rapidly at depth due to the combined effect of distance and tissue attenuation. It is 20 Gy at a depth of 5 cm. Up to the isodose 5 Gy, the deep dose and the surface dose are perfectly symmetrical.
Based on this mapping, an excision measuring 5 cm in depth by 10 cm in diameter was performed on the buttock on 5 January 2006 by the plastic surgery team at the Percy Military Training Hospital in Clamart.

**Conclusion**

A tool called SESAME, which combines voxel geometry and the radiation-material interaction MCNP(X) Monte Carlo computer code, has been developed to create the numerical reconstruction of radiological accidents caused by an external source. This tool has a user-friendly GUI used to manage all the stages in the physical reconstruction of a dose by numeric simulations. The tool has been validated experimentally in photonic and neutron fields.

This tool was applied under the radiological accident which occurred in Chile in December 2005. Surface and deep dosimetric mapping of the left buttock was established using a voxel phantom generated from scanner images of the victim. Based on this mapping, and for the first time in a case of radiological burns, anticipatory surgery was performed (Figure 10).

The recent developments (repeated structures) have reduced the calculation time. However, other, so-called "variance reduction" techniques aimed at further reducing calculation times without loss of the required accuracy should be introduced. In addition, the inclusion of the morphology and posture of the victim modelled from voxel geometry will also be investigated.

**Bibliography**


List of figures

Figure 1 SESAME tool block diagram
Figure 2 Source positioning and definition module
Figure 3 Representation of a voxel phantom with and without voxel coupling
Figure 4 Photograph of the model during irradiation, a 3D representation of the segmented voxel phantom without its envelope and a 3D representation of the modelling of the phantom and its environment
Figure 5 Comparison of experimental and calculated results for dosimeters distributed in and on the phantom
Figure 6 Comparison of isodoses obtained experimentally and by calculation
Figure 7 Photo of the $^{192}$Ir source fallen from the gammagraph
Figure 8 3D representation of the voxel phantom and the source
Figure 9 Dose distribution calculated in the lesion section
Figure 10 Dosimetric reconstruction using numerical simulations: dosimetry guided surgery
**INPUT DATA**

- MRI or CT images
- Geometries of the source and of the environment
- Source particle type
- Choice of output data

**RESULTS TREATMENT AND DISPLAY**

- Dose to points
- Mean dose to organs
- Mean dose to whole body
- Dose distribution

**MONTE CARLO CALCULATIONS**

1. MRI or CT images
2. Geometries of the source and of the environment
3. Source particle type
4. Choice of output data
5. Dose to points, Mean dose to organs, Mean dose to whole body, Dose distribution

**MCNP(X) input file**

**MCNP(X) output file**
(a) CT images of the victim
(b) Voxelised phantom
(c) Dose distribution
(d) Dosimetry-guided surgery