TWENTY YEARS OF VISUAL MONTE CARLO

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ABSTRACT

The development of Visual Monte Carlo (VMC) started in 1993 at the Instituto de Radioproteção e Dosimetria (IRD). The twenty years of development has produced a robust, well documented and fully benchmarked Monte Carlo program. VMC has been applied to the calculation of gamma spectrometry systems and for dose calculations involving the transport of photons, alpha particles and protons. VMC is written in the Visual Basic language which provides a friendly graphics interface with the user. VMC developed into two main softwares: VMC in-vivo for simulation of whole body counter laboratories, and VMC dose calculation, for dose calculations due to exposure to radionuclides or X-rays. The two main VMC programs are freely available for download at the site http://www.vmcsoftware.com/Index.html. VMC can be considered a “specialized” Monte Carlo program as it is designed specifically to solve radiation protection problems, and the main geometry used is the voxel matrix. However, VMC can be programmed to perform calculations which would be difficult to execute using more “generic” Monte Carlo programs such as MCNP or GEANT. For example, matrices containing two or more anthropomorphic phantoms and special geometries for source tissues, such as the endosteum/cortical bone interface may be simulated. The development of VMC continues, and the next twenty years shows much promise.

1. INTRODUCTION

The development of Visual Monte Carlo (VMC) \cite{1} started in 1992 at the Instituto de Radioproteção e Dosimetria. VMC began as a solution to the problem of photon transport through voxel phantoms representing the human body, followed by the detection of the photons leaving the human body. Twenty years ago, the Monte Carlo programs available, MCNP \cite{2}, FLUKA \cite{3}, GEANT \cite{4} and EGS \cite{5} for example, did not accept large voxel matrix geometries, so the option was to write a new Monte Carlo program from the beginning. The idea seemed ambitious. However the problem to be solved represented a special case, with a limited number of materials and repetitive voxel geometry for the phantom and cylindrical geometries for the detectors.

The language chosen was Visual Basic 6, which allows the programmer to establish a user-friendly graphics interface. The main debugging method chosen was to represent on the video screen the phantom, the detector, and the complete history of each photon. If the photon was emitted in one direction, and the resulting interaction with the material happened in the exactly opposite direction, then there was clearly a serious problem with the program.
There are many parts to a Monte Carlo program for photon transport; the pseudorandom number generator, the algorithms to calculate the mass attenuation coefficients, the Compton scattering calculations with energy deposition and direction cosines. There are the detector routines, the line intersection algorithms with planes and cylinders, the calculations of the distance between interactions, and so on. Today, with the VB6 code resources that the internet affords, this work is considerably easier.

VMC evolved from its photon transport origins for calculating calibration factors for whole body counters to a program which now transports electrons, protons and alpha particles through many types of geometries. VMC developed into two main softwares: VMC in-vivo for simulation of Whole Body Counter laboratories, and VMC dose calculation, for dose calculations due to exposure to radionuclides or X-rays. The two main VMC programs are freely available for download at the site [http://www.vmcsoftware.com/Index.html](http://www.vmcsoftware.com/Index.html).

2. VMC APPLICATIONS

2.1. VMC applied to whole body counting laboratories

To evaluate the activity of a radionuclide deposited in a body organ, such as the lung, through direct bioanalysis methods, it is necessary to calibrate the counting geometry. In the laboratory routine this calibration is performed through the use of physical phantoms containing known activities of the radionuclide under investigation. Measuring the net cps in a given photopeak for the contaminated person and comparing it with the net cps for the phantom, it is possible to estimate the activity deposited in the contaminated person. However, physical phantoms are expensive and do not cover all the cases of radionuclides and contaminated organs that may arise. If a physical phantom is not available, it is possible to calculate the calibration factor using VMC in-vivo. The software VMC in-vivo has been extensively benchmarked in international intercomparisons against known activities in physical phantoms. The three main intercomparisons were the IAEA 2002 WBC intercomparison [6] and the EURADOS intercomparisons, one on the University of Cincinnati knee containing 241Am [7] and second with enriched uranium in the Lawrence Livermore National Laboratory (LLNL) lung phantom [8]. Figure 1 shows the simulated geometry of the second EURADOS intercomparison, with four germanium detectors placed over a voxel phantom of the lung.

![Figure 1. Counting geometry showing the position of the four germanium detectors and the voxel thorax with lungs containing enriched uranium.](image-url)
The agreement between the VMC in-vivo calculated values and the reference values in all cases has been very good. Figure 2 shows the comparison between the VMC in-vivo spectrum and the reference spectrum for the lung counting geometry shown in Figure 1.

![Figure 2. Intercomparison results, the red line represents the reference spectrum and the blue line the VMC in-vivo results. 185 keV is the main photopeak for $^{235}$U.](image)

The VMC in-vivo library contains a number of mathematical phantoms such as BOMAB, lung, knee, head, and 5, 10, 15 year old [9] and the ICRP adult male and female phantoms [10]. A multi-channel analyzer is simulated which reproduces the simulated energy spectrum as would be seen with the GENIE 2000 software from Canberra.

### 2.2. VMC dose calculation

VMC dose calculation allows Monte Carlo calculations to be performed for exposure to photon fields generated by radionuclides or X-ray equipment. The program is especially useful for calculating doses in the case of accidents where high activity sources are placed close to the body, for example in a pocket, for a certain time. The program calculates the Tissue equivalent dose to each radiosensitive organ as defined in the ICRP 103 [11] recommendation and also allows isodose curves to be established in the region close to the source. A typical calculation is shown in Figure 3.

![Figure 3. Axial slice of ICRP phantom showing position of 2.4 TBq source of Ir-192 which was kept in the back pocket for one hour.](image)
The Visual Monte Carlo code and the female voxel phantom FAX [12] were used to calculate organ and effective doses delivered by target–source irradiation geometries associated with radioiodine therapy treatments (Figure 4)[13]. Specific situations were considered: when a patient was accompanied during hospitalization, when a patient was accompanied on return to his or her residence, and when a patient received daily care at home. This simulation study showed that, in the 3 situations considered, the total effective dose to an individual in normal contact with the patient was less than 0.85 mSv for up to 11.1 GBq (300 mCi) of administered activity. The results of this study suggest that for these patients receiving radioiodine therapy, radiation protection procedures after hospital discharge are unnecessary.

![Figure 4. Simulation geometry which the patient homecoming in a car.](image)

Other VMC work compared the dose to an individual due to exposure from a radioactive patient using three models (point, line and volume), for three therapeutic regimens (hyperthyroidism, thyroid cancer and non-Hodgkin’s lymphoma) (Figure 5) [14]. For the volume source calculations, Monte Carlo simulations employing the VMC code and the voxel phantom FAX were used. For hyperthyroid patients, the point, line, and volume source models predicted doses to exposed individuals of 54, 24 and 14 mSv, respectively, at a distance of 0.3 m and 4.8, 4.0 and 3.3 mSv at a distance of 1 m. For thyroid cancer patients, the dose values were 85, 38, and 18 mSv at 0.3 m and 7.6, 6.4, and 4.4 mSv at 1 m, respectively. For non-Hodgkins lymphoma subjects, the doses were 230, 103, and 36 mSv at 0.3 m and 21, 17, and 10 mSv at 1 m. These results show that patient release based on point source calculations include unnecessary conservatism.
Recently, VMC dose calculation has been applied to the doses resulting from fluoroscopy procedures. In this case, the dose to the patient and the dose to the attending medical staff is calculated, see Figure 6.
VMC dose calculation has been extensively benchmarked against irradiations of physical phantoms containing TLD’s [6] and against the calculations of other Monte Carlo programs such as MCNP, GEANT and EGS NRC.

2.3. Alpha transport through highly detailed bone structures

VMC has been adapted to transport alpha particles through detailed micro voxel structures of the bone. The objective of the calculation is to evaluate the absorbed fraction of the energy deposited in each bone tissue due to alpha emitting bone seeking radionuclides such as Pu-239. The voxel bone phantoms are of 23 bone sites, and the cubic voxel side is of 50 μm. The small dimension of the bone voxels is due to the fact that alpha particles have a short range in tissues. A 6 MeV alpha particle will travel around 50 μm in tissue.

A slice through the trabecular bone structure of the femur is shown in Figure 7 below. The white voxels represent the cortical (hard) bone, the yellow voxels represent the inactive marrow (adipose marrow) and the blue voxels represent the active marrow. The endosteum, or bone surface, is represented by a 50 μm layer of active or inactive marrow cells which are immediately in contact with the cortical bone. The endosteum is the organ which may develop osteosarcomas.

![Image of femur trabecular bone](image)

**Figure 7. Slice through femur trabecular bone.** The white voxels represent the cortical (hard) bone, the yellow voxels represent the inactive marrow (adipose marrow) and the blue voxels represent the active marrow.

Recently, MCNP has also been used to transport alpha particles through micro voxel bone structures. The MCNP code is more limited than the VMC code, but it can be seen that MCNP agrees with the VMC results as to the absorbed fractions calculation, see Figure 8.
Figure 8. Calculation of absorbed fractions of energy (MeV/MeV) in the Os Coxae bone site as a function of alpha energy. The absorbed fraction is for alpha emitters in the active marrow (AM) irradiating the active marrow (AM) as target.

2.4. Proton transport through voxel structures

VMC was adapted to transport protons through voxel structures. Proton transport is complicated by the fact that protons straggle, they suffer nuclear interactions, and they scatter. Proton transport up to 188 MeV was implemented in VMC and the calculated results were benchmarked against results from the literature and through the QUADOS intercomparison of 2003 [15]. The intercomparison involved dose calculations for proton therapy to the eye: a 50 MeV modulated proton beam incident on an eye water phantom. The benchmarking results are shown in Figures 9 and 10 below.

Figure 9. The VMC proton dose as a function of distance and the reference values of the QUADOS intercomparison. The doses are normalized with respect to the maximum dose.
Figure 10. Slice through voxel structure of the skull showing proton beam isodoses for proton eye therapy.

3. CONCLUSIONS

Over the last twenty years, VMC has proved to be a useful tool for dose calculations and for the establishment of calibration factors in gamma spectrometry. The development work continues, and includes the calculation of dose rates as measured by portable dose rate meters near adults and children internally contaminated with gamma emitters, such as would possibly happen after a major release during a nuclear power plant accident. Electron transport will also be added to VMC which will allow for more accurate specific absorbed fraction calculations. An update of the programming language to Visual Basic 10 is also foreseen.

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