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A novel database of ^{90}Y voxel S-Values including Internal Bremsstrahlung and an analytical model extending the calculation to any voxel size

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Summary. — In this paper we summarize our work aimed at producing via Monte Carlo (MC) simulations an updated database of Voxel S-Values (VSVs) for the radioisotope ^{90}Y, widely used in nuclear medicine therapies. The usually neglected contribution due to Internal Bremsstrahlung accompanying β-decay was included in the computation of the VSVs, increasing their accuracy with respect to pre-existing databases. An analytical model enabling to extend the VSVs calculation to any voxel size of interest was additionally developed, to overcome the limitation due to the finite number of sizes directly evaluable via MC.

1. – Introduction

Internal dosimetry is fundamental in nuclear medicine, playing a critical role in evaluating treatment efficacy for radionuclide therapies and healthy organs safety. Three-dimensional (3D) dosimetry at voxel level enables the assesment not only of average absorbed doses (ADs) in volumes of interest (VOIs), but also of metrics like Dose Volume Histograms (DVHs) and isodose contours. Among the 3D dosimetry calculation

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(*) Corresponding author. E-mail: `daniele.pistone@unicampania.it` approaches, the VSVs convolution with activity maps is the most widely used in clinics, thanks to its balance between calculation speed and dosimetric accuracy [1]. VSVs are defined as a 3D matrix made by the average AD per decay event in each voxel of a regular voxelized geometry of homogeneous material, surrounded indefinitely by the same material, due to a radiation source homogeneously emitting from the central voxel. VSVs are calculated with Monte Carlo (MC) simulations, and public databases are available, though containing VSVs for a limited number of voxel sides [2].

^{90}Y, an almost pure β^- emitter, is one of the most employed isotopes in radionuclide therapies, with main applications in selective internal radiation therapy for hepatic carcinomas and peptide radio-receptorial therapy for neuroendocrine tumours [3]. Recent studies highlighted the significant impact on the absorbed dose distribution for ^{90}Y, in some irradiation scenarios, of the process of Internal Bremsstrahlung (IB), usually neglected in β emitters dosimetry. This phenomenon consists in the emission of a continuous spectrum of photons due to the interaction of the β particle with its own parent nucleus [4, 5].

This work presents the develpment of an updated database of VSVs for ^{90}Y, incorporating the IB contribution, and of an analytical model for extending the ^{90}Y-VSVs evaluation to cubic voxels of any practical dimension.

2. – Methodology

MC simulations were implemented using the toolkit GATE v9.1, based on GEANT4 v10.07 [6]. Cubic geometries of soft tissue (elemental composition from NIST database, density 1.03 g·cm^{-3}), with scoring grids of $15 \times 15 \times 15$ voxels within the $World$ volume, were set. The voxel sides l of the grids were set between 2 mm and 6 mm, in steps of 0.5 mm. For each geometry, the central voxel was set as a homogeneous isotropic source for two types of simulations: a) standard ^{90}Y decay through the *G4RadioactiveDecay* module of GATE/GEANT4; b) IB photons, set using the energy spectrum developed by Italiano *et al.* [4]. For each simulation, AD matrices were scored, and then, via dedicated Phyton scripts, the VSVs were calculated for ^{90}Y, both neglecting and including IB contribution (in this latter case by appropriately weighting its ADs for the IB integrated probability per decay event), as detailed in [7]. For each l, the ^{90}Y VSVs including and neglecting IB were compared each other and with the dataset by Lanconelli *et al.* [8], in terms of relative percent difference (RPD) in each voxel.

Starting from the obtained ^{90}Y VSVs database including IB contribution, an analytical model was developed to extend the calculation of VSVs for any voxel size between 2 and 6 mm. The adopted approach consisted in representing the VSVs as a function of the normalized radius $R_n = R/l = \sqrt{i^2 + j^2 + k^2}$, where R is the absolute distance between the center of the (i, j, k)-th voxel and the center of the central voxel (0, 0, 0). Then, VSVs(R_n) were fitted for each l with the eight-parameters function described in eq. (5) of [7]. The optimized parameters were then fitted as a funciton of l with different functions, depending on the parameters [7]. Exploiting the optimized parameters of these last mentioned fits, a spreadsheet calculating the VSVs for any voxel size and only requiring as input from the user the desired value of voxel size, was implemented. The VSVs obtained with the analytical method were compared with direct-MC ones for all the l values used to build the model and for additional ones randomly selected and for which dedicated MC simulations were run. The comparison was made in terms of RPDs for any considered R_n value.

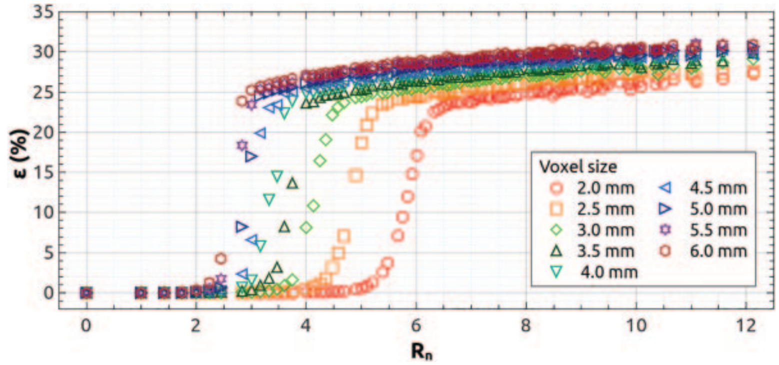

Fig. 1. – RPDs (ϵ) between GATE MC VSVs including IB and not including IB.

3. – Results and discussion

The ^{90}Y VSVs obtained with the GATE MC simulations performed in this work, when neglecting IB, are in close agreement with Lanconelli's ones for all the l sizes, with RPDs within ±5% for almost all the R_n values. Instead, when including IB in GATE MC, RPDs with respect to Lanconelli arise to about +30% for R_n values corresponding to $R > 11\,\mathrm{mm}$, a distance equal to the maximum range of ^{90}Y's β particles in water-like materials. Similar RPDs are found comparing GATE including IB with GATE neglecting IB, as reported in fig. 1.

These results indicate that including IB does not alter the fact that, within the range of β particles, the energy deposition is governed by the β themselves. However, IB becomes significant for radial distances larger than the β range, for which it complements the external Bremsstrahlung contribution already accounted for in previous VSVs calculations, such as Lanconelli's one. Consequently, the updated ^{90}Y VSVs, by including IB, enhance the accuracy of dosimetric estimations at distances where photon contribution is dominant. These findings are in agreement with the ones by Auditore *et al.* [9] on the impact of IB on ^{90}Y Dose-Point Kernels (DPKs) in water.

Regarding the analytical method, all the values of optimized parameters can be found in [7], together with the spreadsheet implementing the method. By comparing the VSVs(R_n) obtained with GATE MC with the ones of the analytical method, for all the l values of the described MC database (from 2 to 6 mm in steps of 0.5 mm), RPDs are within ±5% in the central voxel and for the Bremmstrahlung tails (R_ns corresponding to $R > 11\,\mathrm{mm}$), within ±10% for the first neighboring voxels, within about ±30% for the other voxels at distances $R \leq 11\,\mathrm{mm}$. Similar results were found comparing VSVs from GATE MC and analytical method for additional l values randomly selected (namely: 2.39, 2.84, 4.41, 5.19 mm), as reported in fig. 2. These results show a general improvement with respect to the the pre-existing analytical model by Amato *et al.* [10], whose VSVs, compared with the GATE MC ones (including IB) of this work, show higher RPDs for almost all the R_n values, also given the neglection of IB in Amato *et al.*

The proposed analytical model can be a useful, fast and user-friendly tool for calculating ^{90}Y VSVs for non-standard voxel dimensions, offering an alternative to resampling activity maps or implementing *ad hoc* direct MC simulations for specific voxel dimensions. Even if by including IB the presented database and analytical model can be considered as state-of-the-art for ^{90}Y VSVs calculation, further effort is needed in the

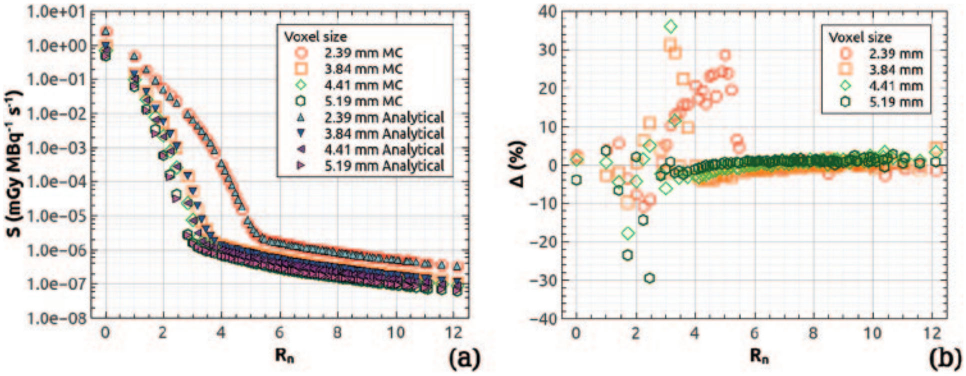

Fig. 2. – (a) ^{90}Y VSVs including IB evaluated for four randomly selected l sizes with GATE MC and with analytical method; (b) theor respective RPDs Δ.

nuclear medicine and insternal dosimetry community, in view of a recent work by Danieli *et al.* [11]. This paper points out how VSVs for ^{90}Y and ^{177}Lu computed with different codes and approaches exhibit non-negligible discrepancies, that reflect on non-negligible discrepancies in the estimated ADs on patient cases, due exclusively to the use of different VSVs. The need of finding the causes of discrepancies and decreasing them clearly emerges, in order to strengthen the consistency of AD calculations among centers.

4. – Conclusions

In this study, we computed updated ^{90}Y VSVs using GATE MC simulation, accounting for the Internal Bremsstrahlung (IB) contribution. Including IB in MC simulations resulted in VSVs showing a significant increase, of about +30%, beyond 11 mm from the source, *i.e.*, for distances larger than the maximum range of ^{90}Y's β particles, where the photon component dominates. Additionally, we developed a user-friendly analytical model for ^{90}Y VSV calculations for any voxel dimensions between 2 and 6 mm, accounting for IB for the first time and improving accuracy compared to previous analyical models.

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