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Feasibility of reducing differences in estimated doses in nuclear medicine between a patient-specific and a reference phantom

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ABSTRACT

The feasibility of reducing the differences between patient-specific internal doses and doses estimated using reference phantoms was evaluated. Relatively simple adjustments to a polygon-surface ICRP adult male reference phantom were applied to fit selected individual dimensions using the software Rhinoceros®4.0. We tested this approach on two patient-specific phantoms: the biggest and the smallest phantoms from the Helmholtz Zentrum München library. These phantoms have unrelated anatomy and large differences in body-mass-index. Three models approximating each patient's anatomy were considered: the voxel and the polygon-surface ICRP adult male reference phantoms and the adjusted polygon-surface reference phantom. The Specific Absorbed Fractions (SAFs) for internal photon and electron sources were calculated with the Monte Carlo code EGSnrc. Employing the time-integrated activity coefficients of a radiopharmaceutical (S)-4-(3-^{18}F-fluoropropyl)-L-glutamic acid and the calculated SAFs, organ absorbed-dose coefficients were computed following the formalism promulgated by the Committee on Medical Internal Radiation Dose. We compared the absorbed-dose coefficients between each patient-specific phantom and other models considered with emphasis on the cross-fire component. The corresponding differences for most organs were notably lower for the adjusted reference models compared to the case when reference models were employed. Overall, the proposed approach provided reliable dose estimates for both tested patient-specific models despite the pronounced differences in their anatomy. To capture the full range of inter-individual anatomic variability more patient-specific phantoms are required. The results of this test study suggest a feasibility of estimating patient-specific doses within a relative uncertainty of 25% or less using adjusted reference models, when only simple phantom scaling is applied.

1. Introduction

Radiation-based modalities are used extensively in diagnostic and therapeutic medical applications. Their usage requires the estimation of radiation doses to the patient. International Commission on Radiological Protection (ICRP) Publication 110 [1] describes the reference voxel computational phantoms that are widely used in dosimetric calculations. Xu [2] stated that for medical dose tracking individualised dosimetry is needed. This is in contrast to the "Reference Man" methodology promulgated by ICRP and used in prospective radiation protection. Bolch et al. [3] mentioned the limited use of reference phantoms in medical imaging and therapy applications, because anatomical variations among individuals can notably contribute to the uncertainty of the estimated organ doses. These variations are disregarded if reference phantoms are employed. Thus, the application of individualised phantoms has the potential to improve the accuracy of medical dosimetric calculations. This is especially important for medical dose estimation in therapeutic applications. The accuracy level of dosimetry depends on the application and on the available resources. The accurate segmentation of a complete patient-specific phantom in nuclear medicine is often difficult, due to the very time-consuming manual work necessary. Another shortcoming of the segmentation of

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individual phantoms is the need of individual tomographic images of sufficient resolution and body coverage, which are usually not available in routine nuclear medicine procedures.

Up to now, many groups created families of human computational phantoms via segmentation from available individual tomographic data or via scaling BREP (Boundary REPresentation) phantoms in terms of body height and weight [4–19]. Total body height, weight or body mass index (BMI) are often used as parameters for matching a specific individual with a library of available phantoms for the purpose of dosimetric calculations. Nonetheless, this usually does not reflect the organ topology of the investigated individual and could cause large differences between the real patient-specific doses and those obtained for the available computational phantom. Zhang et al. [20] investigated the differences in organ doses, effective doses, and risk indices in computed tomography (CT) examinations for adults, caused by the employment of four types of computational phantoms in the dosimetry. This included the extended cardiac-torso (XCAT) family [21], the reference voxel phantoms described in ICRP Publication 110 [1] and two stylized mathematical phantoms. The study of Zhang et al. [20] revealed considerable differences in organ doses from CT even in case of closely matched weight, height and organ masses of the investigated phantoms. Other authors also quantified and showed cases with notable differences in individual organ dose conversion coefficients for external irradiation [4,6] and Specific Absorbed Fractions (SAFs) or organ absorbed-dose coefficients for internal irradiation [22–24], caused by the variations in organ masses and locations in different computational phantoms.

This work focuses on nuclear medicine diagnostic investigations. In this case, organs and tissues of a patient receive low to moderate doses due to the accumulation of an administered radiopharmaceutical in various body organs and tissues, so-called source regions. There are two components of an organ absorbed-dose: (1) the dose from the self-absorption (for source regions only), (2) the dose from the cross-fire from other source regions [25,26]. The self-absorption dose is the dose deposited in a tissue from radiation contained in the tissue itself. The dose from the cross-fire denotes a dose deposited in a tissue from radiation coming from the radionuclides contained in another tissue. The relative values of the two dose components depend upon the organ, the emitted radiation type and its energy. The positron radiation emitted in positron emission tomography (PET) is absorbed in short distances from the emission point. Thus, the self-absorption component is the dominant dose component for source regions. A numerical example of this is given in the Results. Organ self-absorption is dominated by organ mass, as demonstrated in Pamphlet 11 of the Committee on Medical Internal Radiation Dose (MIRD) [27], which provides a guidance on how patient-specific scaling of reference radionuclide SAF values is to be done. This scaling requires only the mass of the target (=source) region and is, hence, otherwise independent of the organ topology of an individual. The cross-fire (except the cross-fire from blood and total body), on the contrary, is influenced by the organ topology. Thus, this study focuses on the anatomy-dependent cross-fire components of organ absorbed doses. We evaluate whether the accuracy of internal dose estimations can be efficiently improved with less effort than would be required were we to segment a patient-specific model.

Whalen et al. [28] demonstrated the feasibility of reducing the uncertainties in organ volumes to 21–29% for all organs, except spleen, by using the trunk height as a parameter to match a patient with a library of computational phantoms. Whalen et al. [28] also showed that the uncertainties in organ volumes can be further reduced, if ventral cavity volumes are matched. Little work has been done to investigate the possible reduction in the uncertainty of estimated dose that is achievable by adjusting reference phantoms to match the individual patient.

The objective of this work is to check the feasibility of reducing the uncertainties in the cross-fire component of organ internal doses by adjusting a reference phantom to selected external dimensions of individuals. Since it is beyond the scope of this study to evaluate the differences of the cross-fire SAFs for all potential source/target region combinations, as an example, we focused on the biokinetic behaviour of a novel radiopharmaceutical (S)-4-(3-^{18}F-fluoropropyl)-L-glutamic acid (^{18}F-FSPG), for which comprehensive datasets were available.

2. Methods and materials

2.1. Voxel and polygon-surface based ICRP adult male reference computational phantoms

ICRP Publication 110 [1] gives the detailed description of the voxel ICRP adult reference computational phantoms, their applications and possible limitations. These models are the official computational models of reference adults, adopted by ICRP [1]. Voxel-based computational phantoms are limited in their flexibility though [2,3]. Such phantoms can be modified only by increasing or decreasing the dimensions of each voxel [29] or adding or removing of voxel layers in an organ. Selective adjustment or scaling of various body parts of a voxel phantom by different factors cannot be easily done. Thus, as a base model in the current work we used the polygon-surface ICRP male reference phantom [30]. It was developed by converting the voxel ICRP male reference phantom to a polygon-surface format. As a BREP model, the polygon-surface phantom can be relatively easily modified and deformed [2,3]. Note that the polygon-surface ICRP male reference phantom used here and described by Yeom et al. [30] is not the final version, since it is currently under development [31,32]. Analogous to the abbreviation for the voxel ICRP adult male reference computational phantom used by e.g. Schlattl et al. [33] and utilised in this work (RCP-AM), we denote the polygon-surface ICRP adult male reference computational phantom as P-RCP-AM in the following.

2.2. Target patient-specific voxel models and adjusted characteristics

Two voxel models from the Helmholtz Zentrum München (HMGU) model library were considered to be fictitious individual target patients in this work. We refer to these models as to patient-specific phantoms. The proposed approach was to apply relatively simple adjustments to P-RCP-AM and, thus, to make P-RCP-AM more specific to the two selected individual target patients. The goodness of this approach was subsequently evaluated depending on how close the organ doses for the adjusted reference phantoms are to the real patient-specific doses. To test the approach on phantoms segmented from individuals with potentially high differences in anatomy, the biggest available model Visible Human [6] and the smallest available model Irene [5,6] (see Fig. 1) were selected as fictitious patients. The BMI of Visible Human and Irene is equal to 31.9 kg/m^2 and 19.2 kg/m^2, respectively. Despite P-RCP-AM being male, the female model Irene was chosen since no male model with similarly small BMI is available in the HMGU model library. Thus the doses for gender-specific organs could not be compared between Irene and P-RCP-AM adjusted to Irene. The comparison of the doses for other target regions appears to be appropriate though.

The Visible Human model used here was segmented from the CT images obtained from the National Library of Medicine's Visible Human Project. This phantom is a partial-body phantom covering

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