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Original Paper

A Monte Carlo simulation for the estimation of patient dose in rest and stress cardiac computed tomography with a 320-detector row CT scanner

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ABSTRACT

Purpose: To estimate organ dose and effective dose for patients for cardiac CT as applied in an international multicenter study (CORE320) with a 320-Detector row CT scanner using Monte Carlo (MC) simulations and voxelized phantoms. The effect of positioning of the arms, off-centering the patient and heart rate on patient dose was analyzed.

Methods: A MC code was tailored to simulate the geometry and characteristics of the CT scanner. The phantoms representing the adult reference male and female were implemented according to ICRP 110. Effective dose and organ doses were obtained for CT acquisition protocols for calcium scoring, coronary angiography and myocardial perfusion.

Results: For low heart rate, the normalized effective dose (E) for cardiac CT was higher for female (5.6 mSv/100 mAs) compared to male (2.2 mSv/100 mAs) due to the contribution of female breast tissue. Averaged E for female and male was 11.3 mSv for the comprehensive cardiac protocol consisting of calcium scoring (1.9 mSv); coronary angiography including rest cardiac perfusion (5.1 mSv) and stress cardiac perfusion (4.3 mSv). These values almost doubled at higher heart rates (20.1 mSv). Excluding the arms increased effective dose by 6–8%, centering the patient showed no significant effect. The k-factor (0.028 mSv/mGy.cm) derived from this study leads to effective doses up to 2–3 times higher than the values obtained using now outdated methodologies.

Conclusion: MC modeling of cardiac CT examinations on realistic voxelized phantoms allowed us to assess patient doses accurately and we derived k-factors that are well above those published previously.

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Introduction

The application of cardiovascular imaging with computed tomography (CT) is well integrated in routine clinical practice. CT scanners allowing axial single heart beat imaging with 320 detector rows have advanced the field of cardiac CT [1,2]. With single-beat cardiac CT, image quality improves whereas acquisition time, patient dose, and image artifacts are reduced [3]. Such new technologies for cardiovascular CT imaging demand an accurate assessment of radiation exposure to patients. Reliable patient dose assessment is also required for the calculation of radiation risks that are associated to cardiac CT.

Proper estimation of organ doses and effective dose in cardiac CT is a challenging task. The development of methodologies for accurate and practical assessment of patient dose in cardiac CT is lagging behind the developments in CT technology and applications. The latest generic recommendations were introduced in 2007 by the ICRP (International Commission on Radiological Protection) to estimate the effective dose for radiation protection purposes [4]. Besides, the ICRP standardized voxel phantoms were introduced in 2009 [5]. It is generally acknowledged that the latest recommendation for the calculation of effective dose is associated with an increase of the effective dose for cardiac CT, but little in depth information is available. According to the ICRP, the standard adult voxel phantoms are now state of the art in dose assessment and thus, organ dose values for both internal and external radiation sources should be derived for such phantoms. The ICRP published a detailed description of the two voxel phantoms, representing the reference adult male (AM) and female (AF) [5]. These phantoms are

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the international standard for the calculation of radiation exposure of adults. These two concepts, the latest recommendation for effective dose and the ICRP voxel phantoms, have not yet been implemented for patient dosimetry in radiology in general and for cardiac CT with modern CT scanners and the latest acquisition protocols in particular.

The primary goal of this study was to calculate organ doses and effective dose for the cardiac CT acquisition protocol applied in an international multicenter study (CORE320), with a 320 detector row volumetric CT scanner, according to the internationally recognized standards in dosimetry [6]. The cardiac CT protocol included CT calcium scoring, CT coronary angiography and CT myocardial perfusion. For this task, Monte Carlo simulation software was used to calculate the dose distribution in two ICRP anthropomorphic voxel phantoms for this specific scanner and these acquisition protocols [7].

In clinical cardiac CT it is common practice to use an offset in the positioning of the patient so that the heart is centered relative to the axis of rotation of the scanner, and the arms of the patient are generally removed from the scanned range by positioning them along the head. However, most generic models for patient dosimetry assume that the CT scan is performed with the patient's body, not the heart, centered along the axis of rotation. The arms of the ICRP voxel phantoms are positioned along the body, which is also not according to clinical practice in cardiac CT. Therefore, a secondary goal of this study was to investigate the effect of the positioning of the patient and the arms on the assessment of effective dose. Dose calculations were thus performed for acquisition geometries in which the patient's body or heart is placed in the center of rotation of the scanner and for phantom configurations with the arms along the body and with the arms removed from the scanned range. These different configurations for the simulations were investigated to enable the comparison of the results of this study with those based in other existing generic models for patient dosimetry in the literature. Finally, the third goal was a comparison between the dose values obtained in this study based on dedicated MC simulations and those existing in the literature based on k-factors [8–14] and also with results obtained with the ImPACT CT Patient Dosimetry Calculator [15].

Materials and methods

Voxel phantoms of an average female and male adult

Two voxel phantoms representing the female (AF) and male (AM) standard adults were prepared for use in combination with the Monte Carlo (MC) dose simulation algorithm [16]. The voxel phantoms are a more realistic representation of a human compared to the MIRD type mathematical reference phantoms (based on the ICRP publication from 1975), which were used until recently [17]. Two complementary representations of each of the ICRP voxel phantoms had to be created to implement them in the simulations. One representation defines the spatial distribution and identification number for 141 organs and tissues; the other provides the 53 different atomic compositions of the different materials in the phantoms plus the atomic composition of the air outside body and CT table. The voxel phantoms represent an average female (height 163 cm, weight 60 kg, body mass index (BMI) 22.6 kg/m^2) and an average male (height 176 cm, weight 73 kg, BMI 23.6 kg/m^2). The voxel size is respectively $1.78 \times 1.78 \times 4.8$ mm^3 (AF) and $2.14 \times 2.14 \times 8$ mm^3 (AM). In addition, the phantoms were customized without the upper extremities (arms) to reproduce the clinical setting in cardiac CT. When removing upper extremities, the mass of the tissues in these volumes was taken into account for the calculation of absorbed dose. Figure 1 shows the two AF and AM voxel phantoms in two depictions, one showing sagittal and lateral views with the different materials and tissue weighting factors in different colors, and one surface rendering.

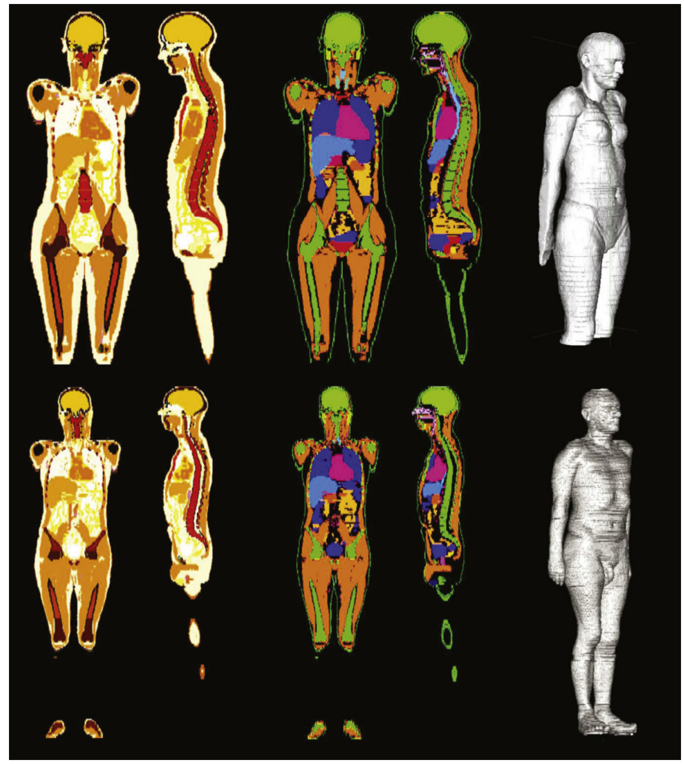

Figure 1. From left to right: coronal and sagittal images showing in different colors the different organs and materials (left) and the tissue weighting factors assigned to these organs (middle); and a 3D surface rendering (right). Above the female phantoms, below the male phantom. Note, in this configuration of the phantom, the arms are present, and aligned along the body.

Monte Carlo dose simulations of the Aquilion ONE CT scanner

The MC code used to estimate the radiation exposure resulting from a CT scan simulates the radiation transport in a voxelized space. For this study, the simulation takes into account specific characteristics of the technical design of the Aquilion ONE CT scanner. The MC algorithm is a modified version of a previously validated one that was used for dose calculations in CT examinations with other Aquilion CT scanners [8,18] and in another cone beam CT for oral and maxillofacial radiology [16,19]. For the Aquilion ONE CT scanner special attention was paid to accurately modeling of the beam geometry (including the penumbra), the X-ray spectrum, the bow tie filter, and the heel effect. A benchmarked Electron Gamma Shower V4 (EGS4) application [20] in combination with a Low Energy Photon Scattering Expansion [21] was used for the calculation of radiation transport. The program was developed and validated for the Aquilion ONE CT scanner in a previous study, comparing results from MC simulations with the actual measurements acquired under the same conditions in standard CT dose phantoms [7]. The measurements agreed with the MC results across all conditions with relative differences up to 6%. MC simulations were performed in a cluster computer (CSUC), composed by 14 Bull Nova Scale R422E1 servers with 28 nodes and 56 Xeon 4 core processors running at 3.0 GHz with 896 GB as total memory. For the simulations 2•10^7 photon histories were used. Thus absorbed doses by all tissues included in ICRP publication 103 were calculated and subsequently used to assess effective dose [4]. Special attention was paid to estimate the absorbed dose in the skeleton. To calculate the absorbed dose in bone

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