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Detailed Heart Models for Adult and Pediatric ICRP Mesh-type Reference Computational Phantoms (MRCPs)

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1. Introduction

The International Commission on Radiological Protection (ICRP) indicated in Publication 118 [1] that radiation-induced damage to the vascular endothelium can accelerate atherosclerosis, leading to cardiovascular diseases (CVDs), particularly pronounced in major arteries such as the coronary arteries. Furthermore, epidemiological studies have reported that the risk of CVDs may increase even at moderate to low radiation doses, highlighting the need for dose assessments for major arteries. In a proactive response to the need for coronary artery dose assessment, the ICRP Committee 2 decided to develop detailed heart models for adult and pediatric ICRP Mesh-type Reference Computational Phantoms (MRCPs) at its annual meeting in November 2024, enabling dose assessment for major internal cardiac structures including the coronary arteries. Accordingly, in the present study, the detailed heart models were developed for both adult and pediatric MRCPs, and the coronary artery doses were calculated using the developed heart models under external and internal exposure conditions. The calculated coronary artery doses were then compared with the heart doses of the original MRCPs.

2. Methods and Results

The detailed heart models were developed by separately constructing the chamber and coronary artery models, which were not defined as independent structures and were included within the heart tissue of the original MRCPs. Since the anatomical locations of the coronary arteries are defined in relation to the atrial and ventricular chambers, chamber models were first constructed, upon which the coronary artery models were subsequently constructed.

2.1 Chamber Model

The chamber models consisted of the right ventricle, left ventricle, right atrium, and left atrium. These models were derived from age-specific models developed by the US National Cancer Institute (NCI) based on CT images, and were morphed to the original MRCPs heart structure employing a vector-field-based morphing approach. The total mass of the morphed chamber model was adjusted to match the mass of blood contained in the heart as defined in the MRCPs, while the relative masses of each chamber were adjusted according to the mass ratios presented in ICRP Publication 23 and scientific literature. In addition, anatomical parameters such as heart wall thickness and inter-chamber distances were also considered, based on the ICRP Publication 89 and scientific literature.

2.2 Coronary Artery Model

The coronary artery models consisted of the right and left coronary arteries. These models were derived from those developed by the University of Florida (UF), which accounts for the blood distribution within the heart. Since the UF models were developed for the UF detailed heart models, anatomical misalignment and structure overlap were observed when implemented in the MRCPs. Therefore, the coronary artery models were manually refined using a 3D modeling software to ensure anatomically accurate positioning relative to the hearts and their atrial and ventricular structures of the MRCPs. During this refinement, the position-specific coronary artery diameters, reported by Dodge et al. (1992) [2] for adult and Cantinotti et al. (2024) for pediatrics [3], were also considered.

2.3 Results of Detailed Heart Model for MRCPs

The detailed heart models for adult and pediatric MRCPs were developed based on the chamber and coronary artery models from the NCI and the UF. The total mass was matched to the heart mass defined in the MRCPs, and the anatomical parameters such as coronary artery diameters were adjusted to within 0.1% of the target values. An automatic installation program was also developed for quick installation of the detailed heart models in the MRCPs distributed through ICRP Publications. Some representative examples are shown in Fig. 1 for the adult and pediatric male MRCPs.

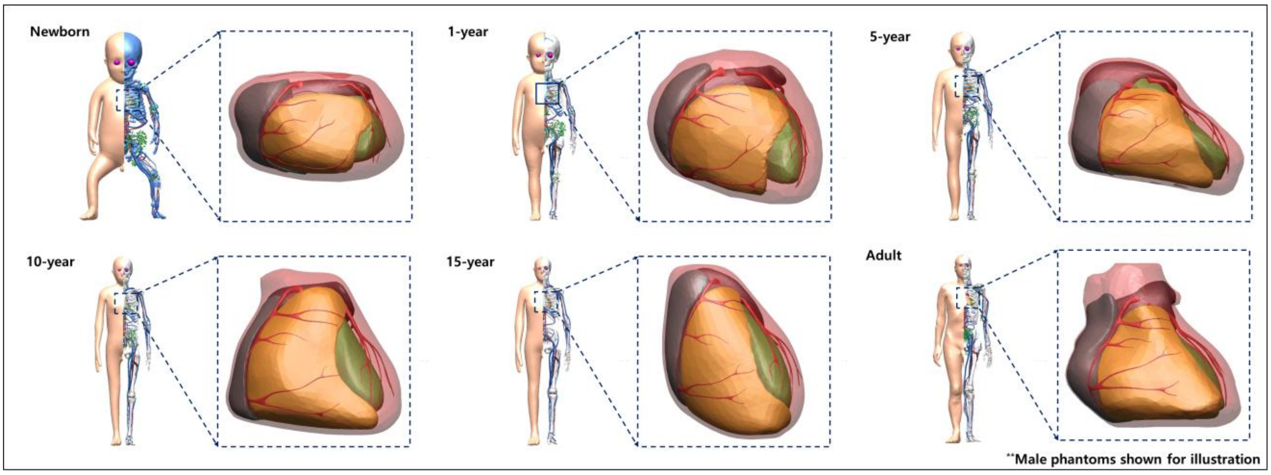

Fig. 1. Detailed heart model implemented in the adult and pediatric ICRP mesh-type reference computational phantoms (MRCPs). The male phantoms are shown as examples.

2.4 Results of Dose Assessment

To evaluate the dosimetric impact of the developed detailed heart models, Monte Carlo dose calculations were performed using the Geant4 toolkit for the adult female and 1-year-old female phantoms under two exposure conditions: (1) external exposure in the anterior-posterior (AP) irradiation geometry with photon energies ranging from 0.015 to 10,000 MeV, and (2) internal exposure from the liver uniformly contaminated and emitting photons of 0.015 to 10 MeV (Fig. 2).

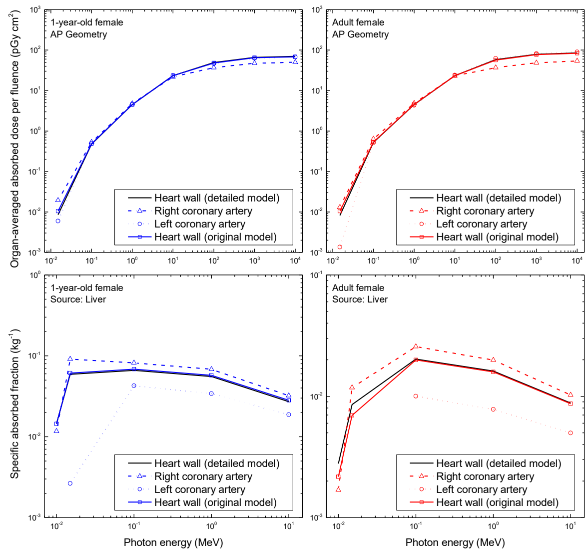

Fig. 2. Organ-averaged absorbed dose per fluence (pGy cm^2, AP geometry) and specific absorbed fraction (kg^{-1}, liver as source) for the adult female and 1-year-old female MRCPs.

For both phantoms, the heart wall doses evaluated in the heart tissue showed no significant differences between the original and detailed heart models across photon energies and exposure conditions. In contrast, the coronary artery doses showed significant differences. For external exposure, at lower photon energies, the left coronary artery showed up to 87% lower doses (adult female phantoms, 0.015 MeV), whereas the right coronary artery up to 86% higher doses (1-year-old female phantoms, 0.015 MeV). For internal exposure, the left coronary artery consistently received lower doses across all energy range due to its greater distance from the source organ (i.e., liver), with values up to 100% lower than the heart wall dose (adult female phantom, 0.015 MeV). In contrast, the right coronary artery showed up to 69% higher than the heart wall dose (adult female phantom, 0.1 MeV). These findings indicate that the original MRCPs heart models, which define the coronary arteries as single structures embedded within the heart tissue, does not adequately reflect the variation in dose distribution according to their anatomical positions. As a result, the actual doses to the coronary arteries may be significantly higher or lower than those estimated by the original model, suggesting that the original models may underestimate the coronary artery dose.

3. Conclusions

In the present study, detailed heart models including the coronary arteries as independent structures were developed and incorporated into adult and pediatric MRCPs. To assess their dosimetric impact, coronary artery doses were calculated, and the results indicated that the original heart models provides limited representation of dose variations by anatomical position, potentially leading to underestimation of coronary artery doses. The developed models are expected to be useful for assessing radiation-induced cardiovascular effects and for the derivation of heart-related dose coefficients.

REFERENCES

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