Conceptual basis of dose monitoring in radiological imaging using personalized computational models

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***Abstract*— Using too much radiation in radiological imaging procedures may lead to unnecessary radiation dose to the patient, while using too little may not provide sufficient information and produce diagnostic quality images. Each radiological imaging procedure requires optimization for the medical task at hand, the equipment being used and patient characteristics. The assessment of absorbed dose and associated risks play a key role in managing quality and monitoring safety when using medical radiological equipment. In this work, we aim at developing a methodology for personalized organ-level dose assessment for both internal and external radiation exposures. The proposed methodology consists of a number of utilities including patient representation, radiation dose calculation and radiation risk assessment and can be used for both monitoring of cumulative radiation exposure of patients and for epidemiological studies.**

Index Terms*— Computational models; radiation dose; radiological imaging, Monte Carlo simulations

I. INTRODUCTION

The use of ionizing radiation in connection with radiological imaging and nuclear medicine examinations has significantly increased in the last decade and has led to major improvements in the diagnosis and treatment of a number of human diseases. Annually, more than 3.6 billion x-ray examinations and 37 million nuclear medicine procedures are performed worldwide. While patients gain substantial benefits from radiation producing healthcare technologies, they may also be exposed to unnecessary irradiations and suffer from potential health hazards in case of inappropriate usage. It was reported that about 1%–2% of all cancers are caused by CT examinations and that more than 14’500 cancer deaths and 29’000 additional cancers in the United States are caused by CT studies each year.[1] Radiological medical procedures need to be optimized for the medical task at hand, the equipment being used, and patient characteristics. It is the role of medical physicists providing physics support to imaging centers and involved in daily activities of busy radiology departments to develop appropriate methodologies enabling to estimate radiation absorbed dose and associated risks as part of safety management.

In this work, we propose a personalized dose assessment approach consisting of a number of components, including patient representation, radiation dose calculation and radiation risk assessment. The proposed methodology consists of three main parts: (1) construction of a library of computational anthropomorphic models based on statistical anthropometric parameters of body morphometry to represent various patient population; (2) mapping patient-specific anatomical images to a computational model belonging to the constructed phantom library to build a patient-specific computational model and (3) perform Monte Carlo calculations using as input the patient-specific computational model to estimate the radiation dose and detrimental radiation risks to an individual patient from the considered radiological imaging procedure.

II. METHODS

A. Construction of a library of computational anthropomorphic models

The construction of the computational phantom library is performed using the Visualization ToolKit (VTK),[2] standardized anchor phantoms and reference datasets of anthropometric data. The remodeling procedure includes two basic components: firstly, a set of desired physical characteristics (the 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} structure percentile data of height, weight, BMI, sitting height/stature ratio (SSR), waist circumference) for human bodies of various groups (including the newborn, 1-, 5-, 10-, 15-, 25-, 40-, 60-year old male and female and pregnant female at different gestations) is obtained from published statistical data of Caucasian populations. Secondly, the initial deformable phantoms are modified using an automatic deformation algorithm. Figure 1 illustrates both female and male models with 10^{th} and 90^{th} mass, 10^{th} and 90^{th} standing height, 10^{th} and 90^{th} SSR, as well as models with 50^{th} mass, 50^{th} standing height, and 50^{th} SSR for the 15 year-old pediatric models.

B. Construction of patient-specific computational models

According to the BMI, weight and height of the patient, the best model fit in the phantom library is selected as an anchor phantom. The selected anchor model of the closest anthropometric parameter is then registered to patient’s CT image to produce new personalized pregnant phantoms with well-defined anatomical structures. Image registration is performed using the Insight Toolkit (ITK).[3] Figure 2 shows two representative examples of patient-specific computational phantoms together with clinical CT images of corresponding patients.

C. *Monte Carlo simulations*

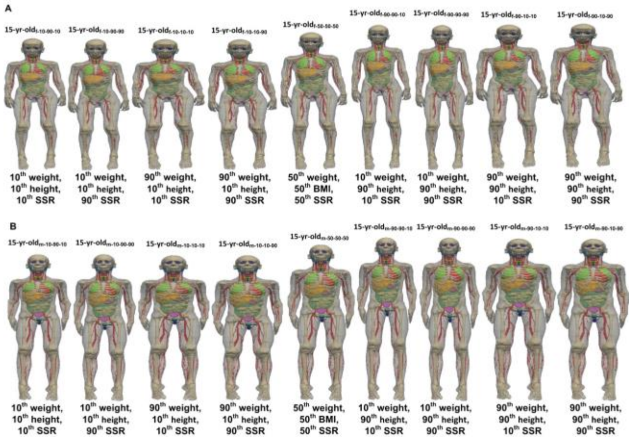

Figure 1. 3D visualization of computational phantoms at 10th, 50th and 90th mass, height and SSR for (A) 15 year-old female and (B) 15 year-old male.

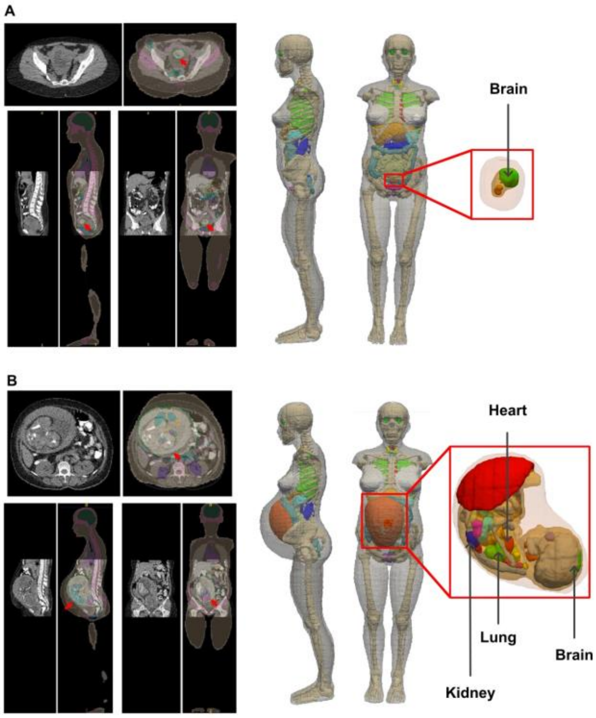

Figure 2. Representative slices showing transverse (top), sagittal (bottom/left) and coronal (bottom/right) views of two examples of the developed patient-specific computational phantoms for pregnant patient at (A) 8 weeks and (B) 35 weeks age illustrating image registration between abdominal CT images of the patient and the computational phantom.

The developed patient-specific computational phantoms are imported to the Monte Carlo code for radiation transport simulations.[4] S-values, absorbed doses and the effective dose of uniformly distributed radiation sources in identified tissues are calculated according to MIRD dosimetry schema.[5] We designed a CT source model corresponding to the GE 750HD x-ray CT scanner installed in our facility equipped with Performix Pro VCT 100 x-ray tube with 56 degree fan-beam angle, 7 degree target angle, allowing the selection of a beam collimation thickness of 1.25 - 40 mm. The scanner's x-ray energy spectrum was generated and described as a function of the number of photons per keV energy intervals in the Monte Carlo code. The Teflon bowtie filter and beam collimation were also included in the CT model. Simulations of x-ray photon transport were performed in the CT model using the generated patient-specific computational phantoms as input (Figure 3).

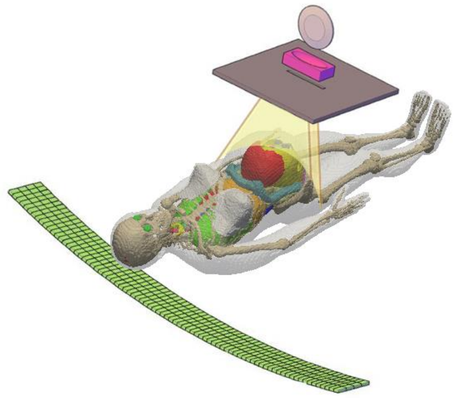

Figure 3. CT model for radiation dosimetry calculations.

III. RESULTS

The developed library contains 1100 pediatric computational phantoms [6] and 8 pregnant phantoms and was used for construction of patient-specific models towards personalized radiation dosimetry in radiological imaging procedures.

IV. CONCLUSION

The constructed library of computational anthropomorphic models and developed patient-model mapping methodology can be used to estimate patient-specific radiation dose and cancer risks in radiological medical imaging and other nuclear medicine procedure (such as targeted radionuclide therapy) and provide an individual monitoring of cumulative radiation exposure of patients and patient-specific dosimetric data for epidemiological studies.

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