ICRP Pregnant-female Mesh-type Reference Computational Phantoms – Development of Maternal Phantoms

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1. Introduction

The International Commission on Radiological Protection (ICRP) has released the adult and pediatric voxel-type reference computational phantoms (VRCPs) [1, 2] to produce reference dose coefficients. The VRCPs were constructed based on the anatomical images of a real person, realistically representing the human anatomy. Due to their limited voxel resolution, however, the VRCPs do not accurately represent small or thin organs, which leads to unreliable dose coefficients (e.g., weakly-penetrating radiations) [3]. In 2016, to address the limitations of the VRCPs, the ICRP established Task Group 103 (TG 103) to develop mesh-type reference computational phantoms (MRCPs) by converting the current VRCPs into a high-quality mesh format. In 2020, the adult male and female MRCPs were developed and released in ICRP *Publication 145* [4]. Recently, the pediatric MRCPS for newborn, 1-, 5-, 10-, and 15-year-old male and female were successfully developed and will be released in upcoming ICRP Publication.

In 2021, the ICRP Committee 2 decided to additionally develop reference pregnant-female phantoms for the fetal ages (=time since fertilization) at 8, 10, 15, 20, 25, 30, 35, and 38 weeks, each of which comprises maternal and fetus phantoms, directly in mesh format. Therefore, the TG 103 is currently developing the pregnant-female MRCPs (pfMRCPs). As part of this, in the present study, we developed the maternal phantoms of the pfMRCPs. Then, to see the dosimetric impact of the developed maternal phantoms, the phantoms representing each trimester of the pregnancy (i.e., fetal ages at 10, 25, and 38 weeks) were implemented into the Geant4 Monte Carlo toolkit [5] to calculate averaged absorbed doses for some selected organs for external exposures to photons and the results were compared with those of the adult female MRCP (afMRCP).

2. Materials and Methods

First, the reference organ masses inclusive of blood content were calculated. Table 2.8 of ICRP *Publication 89* [6] provides the reference organ masses for the adult female and Table 12.2 of ICRP *Publication 89* [6] provides the weight gain of some organs during pregnancy. Note that from the fact that Table 12.2 provides the weight gain of the organs for some selected fetal ages (i.e., 10, 20, 30, and 38 weeks), the data for the other fetal ages (i.e., 8, 15, 25, and 35 weeks) were calculated by linearly interpolating the provided data. The masses of organ parenchyma were calculated by adding these two data. Then, the blood-content masses in each organ were derived by using the regional blood volume fractions given in Table 2.14 of ICRP *Publication 89* [6], except for the uterus and placenta. Note that due to the fact that the blood-content masses for the uterus and placenta increases during pregnancy, the blood-content masses for these organs were derived by using the data given in various literature [7–9].

Then, considering the anatomical and morphological changes during pregnancy, we developed the fetal-age-specific models for the ribs, spine, pelvis, breasts, and outer skin, referring to scientific literatures [10-12]. Note that for the outer skin, nine anthropometric parameters, i.e., upper arm, forearm, chest (above, at, and below breasts), waist, hip, thigh, and calf circumferences, were considered.

Finally, the abdominal organs of UF pregnant-female phantom series [13] in NURBS format, which were constructed based on the actual anatomy of pregnant female, were converted into a high-quality mesh format and installed in the abdominal cavity of the afMRCP, while matching the reference organ masses. Note that the replaced organs were carefully positioned under the guidance of the anatomists.

The developed maternal MRCPs were implemented in Geant4 code (version 10.06.p02) [4] to calculate averaged absorbed doses for colon and breasts, as examples, for external exposures to photons in antero-posterior (AP) irradiation geometry for primary particle energies ranging from 10 keV to 10 GeV. The physics library of *G4EMLiverMorePhysics* was used and the statistical relative errors were less than 5%. The calculated values were then compared with those calculated by using the afMRCP.

3. Results and Discussion

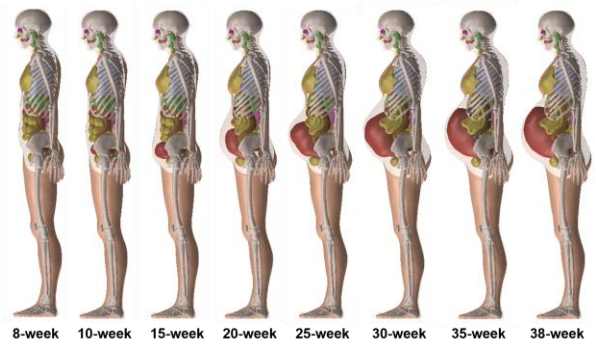

Figure 1. Developed maternal phantoms of pregnant-female MRCPs.

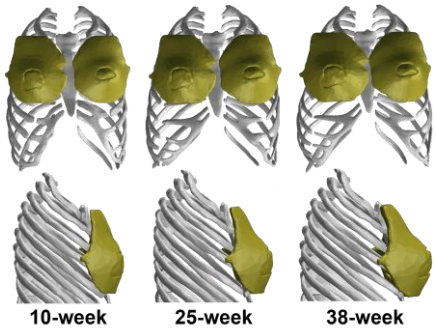

Figure 2. Developed fetal-age-specific ribs and breasts of pregnant-female MRCPs.

Figure 1 shows the maternal phantoms of the pfMRCPs developed in the present study. The pfMRCPs consist of eight phantoms (i.e., fetal ages at 8, 10, 15, 20, 25, 30, 35, and 38 weeks). The masses of organ are precisely matched to the reference organ masses inclusive of blood content calculated in the present study, within 0.1% of deviation. The abdominal organs of the UF pregnant-female phantom series are well installed in the developed phantoms. Figure 2 shows the ribs and breasts for fetal ages at 10, 25, and 38 weeks, as examples. Due to the expansion of the uterus, for the ribs, the antero-posterior diameter and medio-lateral diameter increased while height decreased during pregnancy. For the breasts, the breasts protrusion increased the most compared with the breast base width and height. Although it is not shown in the figures, like the ribs and breasts, the anatomy and morphology of the spine, pelvis, and outer skin are also precisely reflected in the developed phantoms.

Figure 3 shows the averaged absorbed doses of some selected maternal phantoms representing each trimester of pregnancy (i.e., fetal ages at 10, 25, and 38 weeks) for colon and breasts for photons in AP direction, as examples, along with those calculated by using the afMRCP. For colons, the doses of the present study were smaller than those of the afMRCP at low energy ranges (<0.1 MeV) while showed larger values at high energy ranges (>10 MeV). The differences are approximately 124 and 3 times at 0.01 keV and 10 GeV, respectively, for 38-week phantom. Due to the expansion of the uterus, the waist circumference increased the most during

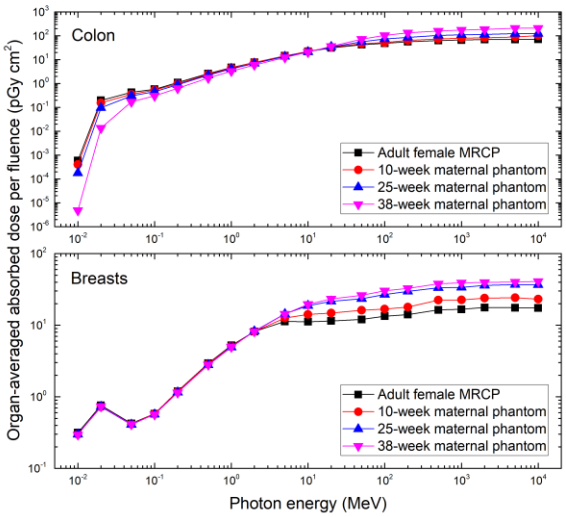

Figure 3. Organ-averaged absorbed dose per fluence (pGy cm^2) of 10-, 25-, and 38-week maternal phantoms for colon and breasts for photons in AP direction, along with adult female MRCP.

pregnancy. Therefore, the distance of the colon from the skin surface gets longer with fetal ages, showing smaller dose values for the present study at low energy ranges. At high energy ranges, on the other hand, the opposite results were observed due to the build-up region of high energy photons. For breasts, at energies less than 10 MeV, the organ doses of the present study were generally in a good agreement with those of the afMRCP. At higher energies (≥10 MeV), on the other hand, the breasts doses were larger than those of the afMRCP. The differences increase with fetal ages. The maximum difference is approximately two times at 10 GeV for 38-week phantom. These results are due to difference in the breasts protrusion during pregnancy. The minimum depth of the breasts are similar between the maternal phantoms and the afMRCP as there are no big differences in skin thickness, while the maximum depth of the maternal phantoms are larger than that of the afMRCP as the breasts protrusion increases with fetal ages, resulting in higher dose values.

4. Conclusion

In the present study, we developed the maternal phantoms of pfMRCPs for fetal ages at 8, 10, 15, 20, 25, 30, 35, and 38 weeks by calculating the reference organ masses, constructing the fetal-age-specific models, and installing the abdominal organs of the UF pregnant-female phantom series into the afMRCP. The developed phantoms were confirmed by the anatomist that the anatomy and morphology of the pregnant female are precisely reflect in the phantoms. Then, the averaged absorbed doses were calculated for the colon and breasts for external exposures to photons and compared with those calculated by using the afMRCP. The significant differences were observed (i.e., by up to a factor of 124 for the colon) due to the changed anatomy of the

pregnant female. Currently, the fetus phantoms are under development and the pfMRCPs will be completely developed by installing the fetus phantoms inside the uterus of the maternal phantoms.

REFERENCES

[1] ICRP, Adult reference computational phantoms, ICRP Publication 110, Ann. ICRP 39 (2), 2009.
[2] ICRP, Paediatric reference computational phantoms, ICRP Publication 143, Ann. ICRP 49 (1), 2020.
[3] ICRP, Conversion coefficients for radiological protection quantities for external radiation exposures, ICRP Publication 116, Ann. ICRP 40 (2–5), 2010.
[4] ICRP, Adult mesh-type reference computational phantoms, ICRP Publication 145, Ann. ICRP 49 (3), 2020.
[5] Allison J., Amako K., Apostolakis J., et al., Recent developments in Geant4, Nucl. Instrum. Methods Phys. Res. Sect. A., Vol. 835, pp. 186–225, 2016.
[6] ICRP, Basic anatomical and physiological data for use in radiological protection: reference values, ICRP Publication 89, Ann. ICRP 32 (3–4), 2002.
[7] Hytten F.E. and Cheyne G.A., 1969. The size and composition of the human pregnant uterus. J. Obstet. Gynaec. Brit. Cwlth. 76, 400–403.
[8] Osgood E.E., 1955. Development and growth of hematopoietic tissues with a clinically practical method of growth analysys. Pediatrics 15, 733–751.
[9] Boyd P.A., 1984. Quantitative structure of the normal human placenta from 10 weeks of gestation to term. Early Hum. Dev. 9, 297–307.
[10] LoMauro A., Aliverti A., Frykholm P., et al., 2019. Adaptation of lung, chest wall, and respiratory muscles during pregnancy: preparing for birth. J. Appl. Physiol. 127, 1640–1650.
[11] Kouhkan S., Rahimi A., Ghasemi M., et al., 2015. Postural Changes during First Pregnancy. Br. J. of Med. And Med. Research 7, 744–753.
[12] Drąsutis J., 2017. Changes in breast morphological parameters, body size and shape, blood serum prolactin and lipids during pregnancy, multiple relationships of these indicators and morphological makers for health risk. Vilnius University Doctoral Dissertation.
[13] Maynard M.R., Long N.S., Moawad N.S., et al., The UF Family of hybrid phantoms of the pregnant female for computational radiation dosimetry. Phys. Med. Biol. 69, 4325–4343, 2014.