Calculation of photon enamel dose coefficients for retrospective EPR dosimetry

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1. Introduction

Electron paramagnetic resonance (EPR) dosimetry with tooth enamel, which is one of the most reliable methods to reconstruct doses for retrospective dosimetry, is recommended by the International Atomic Energy Agency (IAEA) to be used in radiological accidents and radioepidemiological studies [1]. The enamel absorbed doses measured by EPR can be used to estimate the radiation risk, by converting them into organ/tissue absorbed doses or effective doses. Accordingly, Takahashi et al. [2–4] and Ulanovsky et al. [5] produced datasets of enamel dose conversion factors for external photon exposures in idealized irradiation geometries by performing Monte Carlo simulations coupled with mathematical and/or voxel phantoms. However, the complex structure of tooth enamel was not defined in the mathematical and voxel phantoms due respectively to the simplicity and limited voxel resolutions, which might cause unreliable dose calculations for weakly-penetrating radiations (e.g., low-energy photons).

To overcome these limitations, the present study developed detailed teeth models including inner tooth structures (i.e., enamel, dentin, pulp, and cementum) in high-quality mesh format. The developed teeth models were then incorporated into the head of the adult and pediatric mesh-type reference computational phantoms (MRCPs) of the International Commission on Radiological Protection (ICRP), which were recently developed to address the limitations of the older voxel phantoms in dose calculations. Finally, the enamel dose coefficients were calculated for mono-energetic photons by performing Geant4 Monte Carlo radiation transport simulation [6]. To evaluate the dosimetric impact of the mesh-type teeth models, the calculated results were then compared with the values given in the previous study [5].

2. Materials and Methods

2.1 Development of mesh-type teeth models

The mesh-type teeth models were developed for newborn, 1-, 5-, 10-, 15-year-old, and adult male and female, defining both the erupted and unerupted teeth. Prior to the development of the teeth models, the target masses of each tooth were first calculated considering the eruption period and reference total teeth mass of each age [7, 8]. Then, the inner tooth structures were defined in each tooth. For this, the masses and densities of enamel, dentin, pulp, and cementum were decided referring to various scientific literature [9-15].

The mesh-type teeth models were constructed using the high-quality polygon-mesh models for permanent and deciduous teeth (http://dk.kisti.re.kr; https://www.turbosquid.com/3d-models/primary-teeth-dentition-max/953912) by scaling each tooth to match the target mass. Each tooth was placed in the cranium and mandible of the adult and pediatric MRCPs considering the location and eruption period of each age. The inner tooth structures were then manually modeled referring to scientific literature [7] and under the guidance of the anatomists. Finally, for the calculation of enamel dose coefficients, each tooth enamel was again separated into buccal and lingual enamels.

2.2 Geant4 Monte Carlo simulation

Geant4 (version 10.06.p01) [6] Monte Carlo simulations were performed to calculate enamel doses per particle fluence (i.e., fluence-to-enamel dose conversion coefficients) for six external idealized irradiation geometries (i.e., antero-posterior (AP), postero-anterior (PA), left-lateral (LLAT), right-lateral (RLAT), rotational (ROT), and isotropic (ISO)) for monoenergetic parallel beams of photons in the energy range of 0.01–10 MeV. The MRCPs in the tetrahedral mesh format were implemented in the Geant4 Monte Carlo radiation transport code by using G4Tet class. The physics library of G4EMLivermorePhysics was used to transport photons, and a secondary cut value of 1 μm was applied. The statistical relative errors of the calculated enamel doses were less than 5%.

3. Results and Discussion

In the present study, a total of 396 age-specific mesh-type tooth models (i.e., newborn: 20, 1-year: 28, 5-year: 48, 10-year: 38, 15-year: 32, and adult: 32 for male and female) were individually developed and incorporated into the head of the adult and pediatric MRCPs. Note that the 5- and 10-year-old MRCPs have large number of teeth when compared to other phantoms, which is because both the erupted and

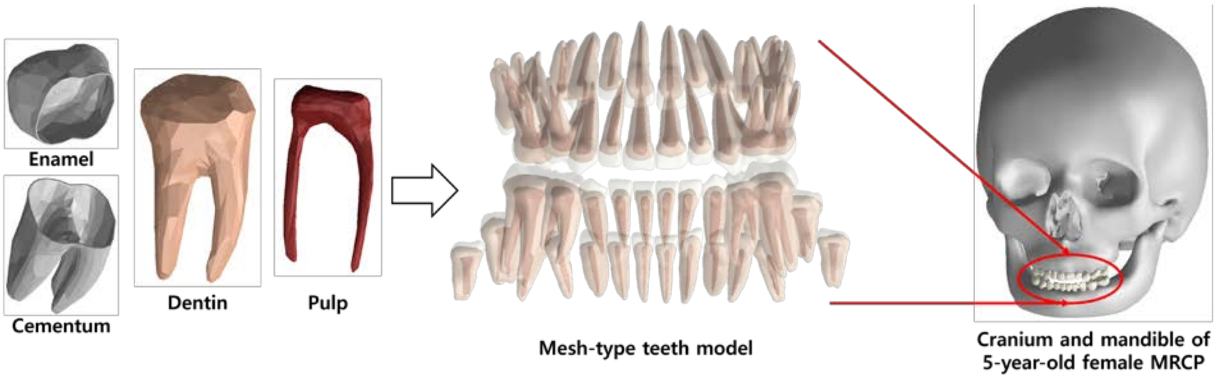

Figure 1. Mesh-type teeth models incorporated into the 5-year-old female MRCP.

unerupted teeth were defined in the present study. Figure 1 shows the developed mesh-type teeth models for 5-year-old female as an example. As shown in figure 1, the teeth models are properly located at the cranium and mandible, each tooth comprising enamel, dentin, pulp, and cementum.

In order to compare the enamel doses with the values given in Ulanovsky et al. [5], the enamel doses per particle fluence were converted to the enamel dose conversion coefficients (Gy Gy^{-1}), which are the ratio of enamel absorbed dose and air kerma. Figure 2 shows the dose conversion coefficients for front and left/right enamel (Figure 2(a): buccal; Figure 2(b): lingual

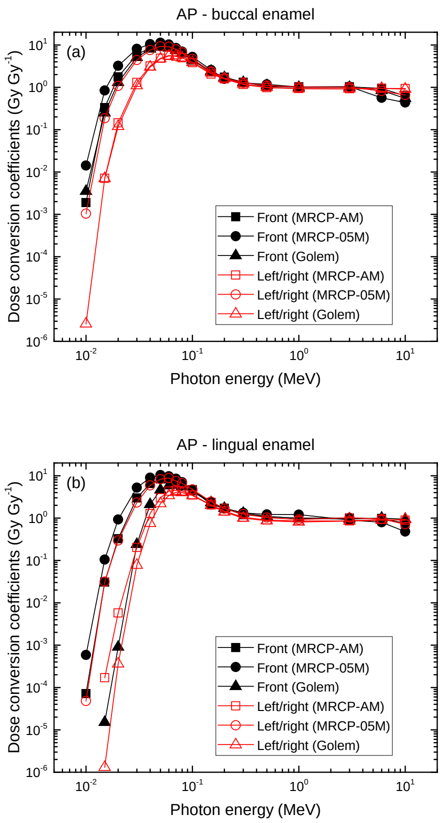

Figure 2. Dose conversion coefficients (Gy Gy^{-1}) of front and left/right enamel for adult male, 5-year-old male and those of ulanovsky et al. [5]: (a) buccal and (b) lingual enamel.

enamel) calculated by using the adult male and 5-year-old male MRCPs and those calculated by using Golem voxel phantom [5] for AP external irradiation geometry as an example. When comparing the values of the adult male MRCP with those of the Golem phantom, for all the considered energies, the values between them were not significantly different for buccal enamel; the differences are within ~50%. For lingual enamel, however, the values of the adult male MRCP was significantly greater than those of the Golem phantom at energy ranges less than 50 keV, the maximum difference being a factor of ~2000 and ~130 at 15 keV for front and left/right enamel, respectively. These results are due to the fact that the lingual enamel, which is located at the tongue side of the teeth, are shielded by dense materials for the Golem phantom. Enamel of the Golem phantom is thicker than that of the MRCPs due to the limited voxel resolution (i.e. $2.08 \times 2.08 \times 8$ mm^3) and unlike the MRCPs, only dentin is defined at the inner side of the enamel, of which the density is ~2 times higher than pulp. As a result, at low energy photons, the lingual enamel dose of the Golem phantom is underestimated by the shielding effect.

When comparing the results of the 5-year-old male MRCP with those of the Golem phantom, the differences are greater than those of adult male. For buccal enamel, the maximum differences are by a factor of ~3 and ~300 at 10 keV for front and left/right enamel, respectively. The differences are even greater for lingual enamel, the maximum difference being a factor of ~7000 and ~24000 at 15 keV for front and left/right enamel, respectively. These results are due to the fact that the average distance of the enamel from the skin surface in AP direction for 5-year-old male is closer than adult male about 1 and 3 cm for front and left/right enamel, resulting in additional shielding effect.

4. Conclusion

In the present study, the age-specific enamel dose coefficients were calculated for use in EPR retrospective dosimetry for external photon exposures. For this, the age-specific mesh-type teeth models were developed based on the calculated masses of each tooth structures and then were incorporated into the adult and pediatric MRCPs. The results of the present study show that the mesh-type teeth model provides similar enamel dose values with the values of the previous research [5] for high energy photons and more reliable dose values for low energy photons. In the near future, the full dataset of enamel dose coefficients will be established using the mesh-type teeth models coupled with adult and pediatric MRCPs and distributed to the public.

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