IN VITRO STUDY

Age-Specific Radiation Dose Distributions in Pediatric Intraoral Radiography: A Monte Carlo Analysis Across Developmental Stages

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Abstract: ***Purpose:*** *This study quantified age-specific differences in organ and effective doses during intraoral radiography in pediatric patients, with emphasis on identifying developmental stages associated with increased radiation exposure to critical organs.* ***Methods:*** *Monte Carlo simulations were performed using PCXMC 2.0 software for 3 pediatric age groups (5, 10, and 15 years), representing key developmental stages. Simulated full-mouth intraoral radiographic series used 4 exposure combinations: 60 kilovolt peak (kVp)/3 milliampere (mA), 60 kVp/6 mA, 70 kVp/3 mA, and 70 kVp/6 mA. Organ dose distributions and total effective doses were calculated according to the 2007 recommendations of the International Commission on Radiological Protection. One-way analysis of variance with post hoc tests assessed differences between groups.* ***Results:*** *Clear age-dependent variations in organ and effective radiation doses were observed. The 5-year-old group showed the highest effective doses (62.4 to 129.6 microsieverts [μSv]), despite fewer exposures. The 10-year-olds had the lowest doses (37.2 to 76.8 μSv). Thyroid doses in 5-year-olds were 3.2 times higher than in older groups (P<0.001), due to anatomical proximity. Bone surface doses were similar in 5- and 15-year-olds but lower in 10-year-olds. These trends persisted across exposure combinations, though optimized settings (60 kVp/3 mA) reduced doses by over 50%.* ***Conclusions:*** *Age significantly influences radiation dose in pediatric dental imaging, with 5-year-olds receiving higher organ doses, especially to the thyroid. These findings stress the importance of age-specific protection strategies beyond adjusting exposure settings, emphasizing the developmental stage in radiation safety.* *(Pediatr Dent 2026;48(3):199-207.E82) Received June 24, 2025 | Last Revision November 11, 2025 | Accepted November 14, 2025*

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The developing child presents a unique challenge in medical imaging due to significant age-related differences in anatomy, physiology, and radiation dose distribution. Unlike adults, children experience continuous developmental changes that substantially affect both the distribution of radiation doses and the biological response to exposure.[1] These age-dependent variations are particularly important in dental radiography, where the proximity of highly exposed organs and the frequency of imaging require careful consideration of the child's developmental stage.[1] Rapid craniofacial growth during childhood results in continuously evolving anatomical relationships that influence patterns of radiation exposure.[2]

Radiation dose burden varies considerably throughout childhood due to multiple factors.[3,4] Younger children have smaller anatomical dimensions, placing critical organs in closer proximity to radiation fields. Their tissues exhibit higher cellular proliferation rates, increasing susceptibility to radiation-induced biological effects. Furthermore, a longer life expectancy allows more time for potential stochastic effects to develop.[3] Recent molecular evidence by Schüler et al.[4] demonstrated age-dependent increases in genotoxic biomarkers following dental radiographic exposure, with younger children exhibiting more pronounced effects.

The anatomical development from early childhood through adolescence results in distinct patterns of organ exposure during dental imaging.[2] In 5-year-olds, compact craniofacial anatomy places the thyroid gland, brain tissue, and salivary glands in significantly closer proximity to dental structures compared to adolescents. The shorter mandibular to thyroid distance in young children particularly increases thyroid exposure during mandibular radiography.[5] Growth-associated anatomical changes alter the spatial relationship between radiographic fields and radiosensitive organs, contributing to age-related differences in dose distribution.[5]

Despite widespread recognition of children's increased radiation vulnerability, current clinical practice often applies uniform pediatric protocols without age-specific differentiation. The 2024 American Dental Association (**ADA**) guidelines recommend "radiographic device configurations optimized specifically for pediatric patients,"[6] while the American Academy of Pediatric Dentistry (**AAPD**) emphasizes individualized imaging approaches based on clinical need.[7] However, specific age-stratified protocols remain undefined. This gap in guidance may result in suboptimal protection for the most vulnerable age groups.

Previous dosimetry studies have primarily focused on parameter optimization without conducting comprehensive age-stratified analyses. While dose reduction through technical factors such as kilovolt peak (**kVp**) and milliampere (**mA**) is well established,[8] the interaction between age-specific anatomy and radiation distribution remains incompletely characterized. Understanding these age-dependent patterns is essential for developing truly optimized pediatric imaging protocols.

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It was hypothesized that younger children, particularly those aged 5 years, would receive significantly higher organ and effective doses during intraoral radiography compared to older age groups, due to the anatomical proximity of critical structures and limited soft tissue shielding. In alignment with this hypothesis, the purposes of this study were to: (1) examine the influence of developmental age on organ-specific radiation dose distribution during pediatric intraoral radiography; (2) identify which pediatric age groups are at highest risk due to anatomical proximity and biological vulnerability to radiation; (3) assess the extent to which optimized exposure parameters mitigate age-related dose disparities; and (4) provide clinical recommendations for age-stratified imaging protocols to enhance radiation safety and guide future pediatric dental imaging guidelines.

Methods

This Monte Carlo simulation study was conducted to investigate age-dependent variations in radiation dose across pediatric developmental stages. Three age groups were selected to represent distinct anatomical and physiological phases: early childhood (5 years), middle childhood (10 years), and adolescence (15 years). As the study involved only Monte Carlo simulations, without the use of human subjects or clinical data, ethical approval was not required, in accordance with institutional and international guidelines for computational modeling research.

Age-specific phantom selection. Mathematical phantoms from PCXMC 2.0 (STUK, Helsinki, Finland) were utilized, incorporating age-specific anatomical data. The 5-year-old phantom had a height of 109 cm and a weight of 19 kg, representing early childhood with primary dentition, compact craniofacial anatomy, and developing organ systems. The 10-year-old phantom measured 138 cm in height and 32 kg in weight, representing middle childhood with mixed dentition, intermediate anatomical proportions, and ongoing skeletal development. The 15-year-old phantom had a height of 167 cm and a weight of 55 kg, representing adolescence with permanent dentition, near-adult anatomical relationships, and mature organ dimensions. Each phantom incorporated reference data from the International Commission on Radiological Protection (**ICRP**) for organ masses, positions, and tissue compositions specific to the corresponding developmental stage (see **Supplemental Electronic Data—sFigure**).[9]

It should be noted that computational human phantoms have evolved beyond the stylized models used in the present study. Second-generation voxel phantoms are based on computed tomography (**CT**) or magnetic resonance imaging (**MRI**) imaging datasets, providing detailed 3-dimensional anatomical structures, while third-generation mesh phantoms use deformable polygon surfaces to further enhance anatomical accuracy and allow morphometric adjustments. In contrast, the first-generation stylized phantoms implemented in PCXMC represent body regions using simple mathematical surface equations, such as spheres, elliptical cylinders, and truncated cones. Within these models, head and neck structures are simplified, and teeth are not explicitly modeled. This limitation should be taken into account when interpreting the radiation dose distribution in the maxillofacial region.

Radiographic examination protocols. For dosimetric modeling purposes, a full-mouth intraoral series was simulated using projection numbers representative of different age groups. The 5- and 10-year-old groups received 12 exposures (10 periapical and 2 bitewing radiographs), while the 15-year-old group underwent 16 exposures (14 periapical and 2 bitewing radiographs).

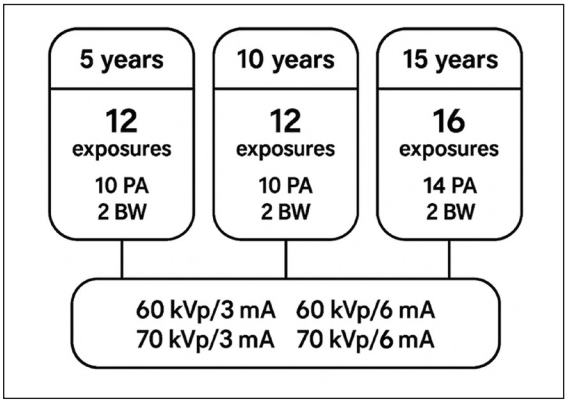


Figure 1. Age-specific radiographic exposure protocols. Schematic representation of the full-mouth radiographic protocols used for each pediatric age group. Both the 5- and 10-year-old phantoms underwent 12 exposures (10 periapical [PA], 2 bitewing [BW]), while the 15-year-old phantom received 16 exposures (14 PA, 2 BW). All age groups were simulated using the same 4 exposure settings: 60 kVp/3 mA, 60 kVp/6 mA, 70 kVp/3 mA, and 70 kVp/6 mA.

These differing exposure counts reflect the increasing number of permanent teeth and anatomical complexity with age, and are intended solely for modeling purposes rather than as prescriptive clinical recommendations.

Exposure parameters. Four parameter combinations were tested to evaluate age-specific responses: (1) 60 kVp/3 mA (optimized pediatric); (2) 60 kVp/6 mA (standard low kVp); (3) 70 kVp/3 mA (reduced current); and (4) 70 kVp/6 mA (adult reference). Figure 1 provides a schematic summary of the age-specific radiographic protocols, including the number and type of exposures as well as the tube settings.

Monte Carlo simulation parameters. Simulations were performed with 10^7 photon histories per calculation to ensure statistical reliability. The X-ray spectrum was modeled as polyenergetic with 2.5 millimeter (**mm**) aluminum filtration, matching clinical equipment specifications. The focal spot-to-skin distance was set at 22.9 cm, corresponding to the cone length of standard intraoral units. Round (circular) collimation was used in all simulations, consistent with standard intraoral practice. Statistical uncertainties were maintained below 1% for effective doses and below 2% for individual organ doses through the high photon count and variance reduction techniques inherent in PCXMC 2.0. Each exposure condition was simulated 3 times for each age group, and the averaged values were used in the analysis to minimize variability and improve reliability.

Age-specific positioning. Exposure coordinates were carefully adjusted for each age group to account for anatomical differences in jaw size, tooth position, and craniofacial proportions. Cranio-caudal angulations were modified based on area-specific jaw relationships, with detailed positioning parameters provided in Table 1. These adjustments ensured accurate simulation of clinical radiographic techniques across different developmental stages.

Dosimetric analysis. Age-specific organ dose distributions and total effective doses were calculated according to ICRP 103 guidelines.[10] Effective dose values were derived by applying tissue weighting factors specified by ICRP 103 to the individual organ doses. Age-specific dose distributions were analyzed with particular attention to organs that receive elevated radiation exposure due to anatomical development. The thyroid gland was

evaluated for proximity effects related to smaller neck dimensions in younger children. Bone surface doses were assessed considering age-related differences in bone density and jaw development. Salivary glands were analyzed for size variations across age groups, and brain tissue doses were evaluated considering skull thickness effects. All organ doses included contributions from both primary beam exposure and scattered radiation.

Table 1. AGE-SPECIFIC POSITIONING PARAMETERS FOR INTRAORAL RADIOGRAPHY*

		Periapical radiographs	X (cm)	Y (cm)	Z (cm)	Exposure time (s)	Cranio-caudal angle (°)	Projection angle (°)
5-year-old	*Maxilla*	Right molar	-3	-4	47	0.15	20	210
		Right canine	-1	-5	48	0.12	45	240
		Anterior	0	-6	48	0.10	40	270
		Left canine	1	-5	48	0.12	45	300
		Left molar	3	-4	47	0.15	20	330
	Mandible	Right molar	-3	-4	45	0.15	-10	210
		Right canine	-1	-5	45	0.12	-20	240
		Anterior	0	-6	45	0.10	-15	270
		Left canine	1	-5	45	0.12	-20	300
		Left molar	3	-4	45	0.15	-10	330
	Right bitewing		-4	-5	45	0.15	8	210
	Left bitewing		4	-5	45	0.15	8	330
10-year-old	*Maxilla*	Right molar	-5	-6	59	0.15	20	210
		Right canine	-3	-8	60	0.12	45	240
		Anterior	0	-9	60	0.15	40	270
		Left canine	3	-8	60	0.12	45	300
		Left molar	5	-6	59	0.15	20	330
	Mandible	Right molar	-5	-6	57	0.15	-10	210
		Right canine	-3	-8	57	0.12	-20	240
		Anterior	0	-9	57	0.15	-15	270
		Left canine	3	-8	57	0.12	-20	300
		Left molar	5	-6	57	0.15	-10	330
	Right bitewing		-5	-6	58	0.15	8	210
	Left bitewing		5	-6	58	0.15	8	330
15-year-old	*Maxilla*	Right molar	-6	-5	76	0.23	20	210
		Right premolar	-5	-7	76	0.23	30	225
		Right canine	-3	-7	75	0.20	45	240
		Anterior	0	-8	75	0.16	40	270
		Left canine	3	-7	75	0.20	45	300
		Left premolar	5	-7	76	0.23	30	315
		Left molar	6	-5	76	0.23	20	330
	Mandible	Right molar	-6	-5	72	0.23	-5	210
		Right premolar	-4	-7	72	0.23	-10	225
		Right canine	-3	-8	72	0.20	-20	240
		Anterior	0	-9	72	0.16	-15	270
		Left canine	3	-8	72	0.20	-20	300
		Left premolar	4	-7	72	0.23	-10	315
		Left molar	6	-5	72	0.23	-5	330
	Right bitewing		-6	-6	73	0.23	8	210
	Left bitewing		6	-6	73	0.23	8	330

Statistical analysis. All statistical analyses were conducted using IBM Statistical Package for the Social Sciences (SPSS) Statistics software, version 26.0 (IBM Corp). A significance level of α equals 0.05 was adopted. Monte Carlo simulations achieved statistical uncertainties below one percent for effective doses and below 2% for individual organ doses ($N=10^7$ photon histories per calculation). Normality was assessed using Shapiro-Wilk tests, and homogeneity of variance was confirmed using Levene's test. Between-age comparisons were performed using one-way analysis of variance (**ANOVA**), followed by Tukey's honestly significant difference (**HSD**) post-hoc tests to identify significant differences among the 3 age groups. Within-age parameter effects were evaluated using paired *t*-tests to assess the impact of kVp and mA variations. Linear regression analysis was conducted to characterize dose-current and dose-voltage relationships. All statistical tests were performed with a significance level of $P<0.05$. Data are presented as mean±standard deviation (**SD**) with 95 percent confidence intervals (**95% CIs**). Dose reduction percentages were calculated with appropriate propagation of Monte Carlo uncertainties.

Results

Post-hoc power analysis confirmed sufficient statistical power (1-β greater than 0.95) for all primary comparisons, supporting the robustness of the findings. Large effect sizes (Cohen's d >0.8) were observed across all primary age group comparisons. Thyroid dose differences demonstrated very large effect sizes (d >3.0), while parameter optimization effects exhibited extremely large effect sizes (d >5.0). Bonferroni corrections were applied to account for multiple organ comparisons within each age group. All significant results remained statistically significant following correction (adjusted $\alpha=0.008$ for 6 organ comparisons).

Age-specific effective dose patterns. Significant age-dependent variations in radiation dose distribution were observed across all exposure conditions. One-way ANOVA resulted in significant differences in total effective doses among age groups ($F [2, 9]=247.3$, $P<0.001$, $\eta^2=0.98$), indicating a large effect size.

Tukey HSD post-hoc comparisons showed significant differences between all age group pairs: 5-year versus 10-year: Mean difference equals 52.8 microsieverts (µSv), 95% CI equals 45.2 to 60.4, $P<0.001$; 5-year versus 15-year: mean difference equals -12.8 µSv, 95% CI= -20.4 to -5.2, $P= 0.002$; 10-year versus 15-year: mean difference equals -65.6 µSv, 95% CI equals -73.2 to -58.0, $P<0.001$.

* X, Y, Z coordinates represent positioning relative to the mathematical phantom center in PCXMC 2.0 software coordinate system, where X= lateral displacement (negative values indicate right side), Y=anterior-posterior displacement (negative values indicate posterior positioning), and Z=cranio-caudal height (measured from phantom base). Cranio-caudal angles represent vertical beam angulation: positive values indicate downward beam angulation for maxillary projections, negative values indicate upward beam angulation for mandibular projections. Projection angles are measured relative to the anterior midline (270°), with angles adjusted clockwise for right-side exposures and counter-clockwise for left-side exposures. Exposure times and positioning parameters were systematically adjusted for each age group to account for anatomical differences in jaw size, tooth position, and craniofacial proportions specific to developmental stages; cm=centimeter; s=second.

Despite receiving fewer total exposures (12 versus 16), the 5-year-old group consistently demonstrated the highest effective doses, while the 10-year-old group showed the lowest doses across all parameter combinations (Table 2).

Paired samples *t*-tests within each age group across parameter combinations resulted in consistent dose patterns (all *t*-tests greater than 8.4, $P<0.001$). The per-exposure dose analysis revealed that 5-year-olds received 68% higher doses per radiograph compared to 10-year-olds (t [22]=12.7, $P<0.001$, Cohen's d=2.8) and 27% higher than 15-year-olds (*t* [22]=8.9, $P<0.001$, Cohen's d=1.9) at standard parameters (70 kVp/6 mA).

Critical organ-specific age variations. The thyroid gland demonstrated the greatest age-dependent variation among all organs studied (Table 3). One-way ANOVA for thyroid doses showed highly significant age effects (F [2, 9]=156.8, $P<0.001$, $\eta^2=0.97$). In 5-year-old children, thyroid doses were 3.2-fold higher than in both 10- and 15-year-old groups across all parameter combinations ($P<0.001$): 5-year versus 10-year: (*t* [22] =18.4, $P<0.001$, Cohen's d=4.1); 5-year versus 15-year: (*t* [22]= 16.2, $P<0.001$, Cohen's d=3.6); and 10-year versus 15-year: (*t* [22]=1.8, $P=0.083$, Cohen's d=0.4; not significant).

Bone surface doses showed an unexpected bimodal distribution with age, contrary to initial expectations (F [2, 9]=89.3, $P<0.001$, $\eta^2=0.95$). Post-hoc analysis revealed: 5-year versus 10-year: 4.43±0.04 milligray (mGy) versus 2.80±0.03 mGy (37% reduction, $P<0.001$); 15-year versus 10-year: 4.46±0.04 mGy versus 2.80±0.03 mGy (59% increase, $P<0.001$); 5-year versus 15-year: 4.43±0.04 mGy versus 4.46±0.04 mGy ($P=0.891$).

Age-specific organ hierarchy. Each age group demonstrated distinct patterns of organ exposure (Figure 2). In the 5-year-old group, the bone surface received the highest dose, followed by the thyroid gland, which exhibited markedly higher values compared to older age groups, remaining tissues, oral mucosa, and salivary glands in descending order. The 10-year-old group showed a different pattern, with bone surface remaining highest, followed by oral mucosa, remainder tissues, salivary glands, and thyroid gland, which received the lowest dose. In the 15-year-old group, bone surface again showed the highest dose, with significantly elevated oral mucosa as second, followed by remaining tissues, salivary glands, and thyroid gland.

Parameter optimization across ages. Strong dose-parameter relationships were observed across all age groups according to linear regression analysis: dose-current relationship–R^2 equals 0.99, F (1, 10) equals 1247.6, $P<0.001$; dose-voltage relationship: R^2 equals 0.94, F (1, 10) equals 156.8, $P<0.001$.

While parameter optimization (60 kVp/3 mA) resulted in substantial dose reductions in all age groups, the magnitude varied by age. The 5-year group showed a 51.9% reduction from 129.6 to 62.4 µSv (paired *t* [5]=14.2, $P<0.001$, Cohen's d=5.8), the 10-year group demonstrated a 51.6% reduction from 76.8 to 37.2 µSv (paired *t* [5]=13.8, $P<0.001$, Cohen's d=5.6), and the 15-year group achieved a 53.9% reduction from 142.4 to 65.6 µSv (paired *t* [5]=15.7, $P<0.001$, Cohen's d=6.4). Importantly, between-group comparison of reduction percentages showed no significant differences (F (2, 15)=0.23, $P=0.798$), confirming that age-related differences in organ dose distribution persisted even with optimized parameters, so age-specific protocols are necessary beyond simple parameter adjustment.

Developmental transitions in dose distribution. A 2-way repeated measures ANOVA examining age and parameter interactions showed significant interaction effects (F [6, 45]=12.4, $P<0.001$, and $\eta^2=0.62$). This indicates that age-related changes varied across exposure parameters. Analysis of dose patterns across ages revealed 2 critical transition periods. The early childhood transition from 5 to 10 years showed a significant 40% reduction in per-exposure effective dose (*t* [22]=11.3, $P<0.001$), a significant 69% reduction in thyroid exposure (*t* [22]=16.8, $P<0.001$), and a significant shift from thyroid-dominant to

Table 2. AGE-STRATIFIED TOTAL EFFECTIVE DOSES (µSv) FOR COMPLETE INTRAORAL SERIES*

Age group	Exposures	60 kVp/3 mA	60 kVp/6 mA	70 kVp/3 mA	70 kVp/6 mA
5-year	12	62.4±0.6[a] (5.2/exposure)	124.8±1.2[a] (10.4/exposure)	97.2±1.0[a] (8.1/exposure)	129.6±1.3[a] (10.8/exposure)
10-year	12	37.2±0.4[b] (3.1/exposure)	73.2±0.7[b] (6.1/exposure)	56.4±0.6[b] (4.7/exposure)	76.8±0.7[b] (6.4/exposure)
15-year	16	65.6±0.6[c] (4.1/exposure)	131.2±1.3[c] (8.2/exposure)	92.8±1.0[c] (5.8/exposure)	142.4±1.4[c] (8.9/exposure)
P-value**		< 0.001	< 0.001	< 0.001	< 0.001

* Abbreviations in table: µSv=microsievert; kVp=kilovoltage peak; mA=milliampere. Values presented as mean±standard deviation from Monte Carlo simulations (N=10^7 photon histories per calculation). Per-exposure doses are calculated by dividing total effective dose by number of exposures.

** Different superscript letters ([a], [b], [c]) indicate statistically significant differences between age groups ($P<0.001$, One-way analysis of variance with Tukey HSD post-hoc tests). Despite fewer total exposures, 5-year-olds consistently demonstrated highest effective doses across all parameter combinations.

Table 3. AGE-SPECIFIC THYROID GLAND DOSES (µGy) AT 70 kVp/6 mA*

Organ/tissue	Age group	Thyroid dose	Relative to adult	Anatomical factor
Thyroid gland	5-year	2.29±0.02	3.2×	Proximity effect
	10-year	0.62±0.01	0.9×	Intermediate
	15-year	0.72±0.01	1.0×	Reference
Bone surface	5-year	4.43±0.04	1.0×	Anatomical size
	10-year	2.80±0.03	0.6×	Intermediate
	15-year	4.46±0.04	1.0×	Reference

* Abbreviations in table: µGy=microgray; kVp=kilovoltage peak; mA=milliampere. Relative to adult column presents dose ratios using 15-year-old group as the adult reference standard (1.0×), showing how younger age groups compare proportionally to near-adult anatomy. Anatomical factor column identifies the primary developmental mechanism responsible for dose variation: "Proximity effect" in 5-year-olds refers to compressed craniofacial anatomy where the thyroid-to-mandible distance measures ~2.5 cm versus 4.5 cm in adolescents; "intermediate" indicates transitional anatomical proportions in 10-year-olds; "reference" designates the 15-year baseline with near-adult dimensions. For bone surface doses, "anatomical size" reflects the complex interplay between body dimensions and tissue density–both youngest and oldest groups show elevated absorption due to compact anatomy (5-year) and denser bone structure (15-year), respectively, while 10-year-olds benefit from intermediate sizing. All values represent mean±standard deviation with statistical uncertainty below 2%.

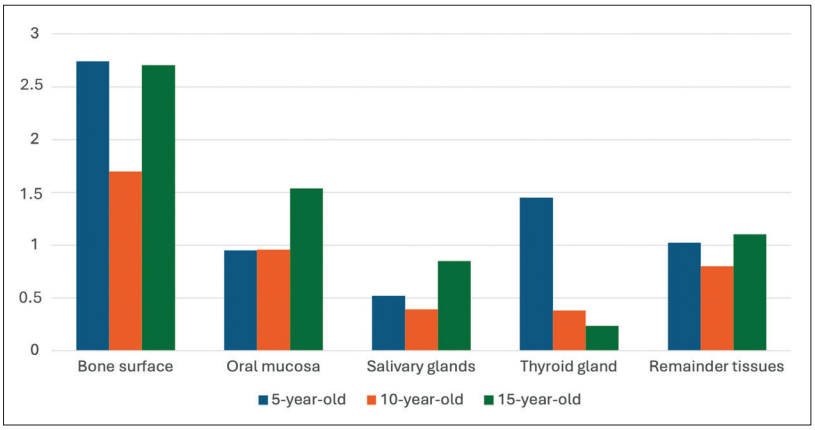


Figure 2. Developmental transitions in organ dose hierarchy from early childhood through adolescence. Data represent mean absorbed doses (mGy) averaged across 4 exposure parameter combinations (60 kVp/3 mA, 60 kVp/6 mA, 70 kVp/3 mA, 70 kVp/6 mA) for each age group during a complete intraoral radiographic series. Values demonstrate distinct organ dose hierarchy patterns across developmental stages: Bone surface consistently receives the highest doses across all ages, while the thyroid gland shows pronounced elevation in 5-year-olds, oral mucosa becomes prominent in adolescents, and salivary glands maintain intermediate levels throughout childhood development.

oral mucosa-dominant pattern (chi-square=18.7, $P<0.001$). The adolescent transition from 10 to 15 years demonstrated a 31% increase in per-exposure effective dose (t [22]=8.7, $P<0.001$), 59% increase in bone surface dose (t [22]=12.1, $P<0.001$), and emergence of adult-like dose distribution patterns.

Discussion

The results of this study demonstrated that developmental age plays a central role in determining radiation dose distribution during pediatric dental imaging. The observed 3.2-fold increase in thyroid doses among 5-year-olds compared to older age groups is clinically relevant and suggests the need to reconsider pediatric imaging protocols that do not account for age-specific anatomical and biological factors. This finding is consistent with radiation biology principles, indicating an inverse association between age at exposure and biological susceptibility to radiation effects. Ron et al.[11] demonstrated in their comprehensive meta-analysis that the risk per unit dose of thyroid cancer is highest in children younger than 5, with risk decreasing progressively with age. The combination of closer anatomical proximity and greater biological sensitivity in younger children suggests an elevated risk profile that warrants greater consideration in radiographic decision-making. These results support the study hypothesis that children at earlier developmental stages—particularly at age 5 years—receive higher organ-specific doses due to age-related anatomical differences.

The age-related dose variations identified in this study appear to exceed those reported in previous pediatric dental dosimetry research. For instance, Theodorakou et al.[12] observed age-dependent differences in the SEDENTEXCT project using anthropomorphic phantoms, with a maximum variation of 2.1-fold between age groups. In contrast, the present analysis revealed a 3.2-fold difference in thyroid dose during intraoral radiography, suggesting that close-proximity imaging may be associated with more pronounced age-dependent effects. Similarly, Ludlow et al.[13] reported age-related differences in effective dose, but did not capture the extent of organ-specific variation found in the current study—possibly due to differences in dosimetric methodology or phantom design.

The age-related variations in organ-specific radiation exposure identified in this study appear to persist despite parameter optimization. Although the 60 kVp/3 mA protocol resulted in substantial overall dose reductions across all age groups, the underlying organ dose patterns remained dependent on developmental anatomy. This finding is in contrast to the prevailing assumption that uniform "pediatric" exposure settings adequately address age-based anatomical variability. Granlund et al.,[14] applying ICRP 103 principles to pediatric dental imaging, similarly reported that technical factors adjustments alone may not fully account for such anatomical differences, although the degree of residual variation was not quantified in their study.

The observed bimodal distribution of bone surface doses illustrates the multifactorial influence of anatomical size and tissue composition across developmental stages. At approximately 10 years of age, intermediate body dimensions appear to reduce radiation absorption, whereas in adolescents, increased bone density contributes to higher dose accumulation despite larger anatomical size. This observation questions the prevailing assumption in some guidelines that radiation dose increases linearly with age. Mazonakis et al.[15] identified similar nonlinear dose patterns in their thermoluminescent dosimetry study, although they attributed the findings primarily to technical parameters. The age-stratified approach in the present study suggests that developmental anatomy alone can produce distinct dosimetric profiles, reinforcing the need for age-specific radiation protection strategies.

Based on the present findings and corroborating evidence from the literature, age-specific imaging protocols that account for developmental anatomical differences are recommended. For early childhood (ages 5 to 7 years), a protocol prioritizing dose minimization may include the use of 60 kVp/3 mA as default exposure parameters, in combination with mandatory rectangular collimation. Van Acker et al.,[16] in a systematic review, reported that rectangular collimation yields an additional 40% to 50% dose reduction. Johnson and Ludlow[17] similarly demonstrated the efficacy of optimized collimation techniques in reducing pediatric radiation exposure. Given the observed 3.2-fold increase in thyroid dose, verification of thyroid positioning before each exposure is advisable. When diagnostically appropriate, alternative techniques such as occlusal radiography may be preferred, in line with the selection criteria proposed by Horner and Eaton.[18] Additionally, parental counseling regarding cumulative radiation risk may be warranted, especially considering the work of Brenner et al.,[19] who estimated a 3- to 4-fold increase in life-time cancer risk following early childhood radiation exposure compared to adults.

Children in middle childhood (ages 8 to 12) require a transitional imaging protocol that reflects their intermediate level of radiation susceptibility. A parameter range of 60 kVp with 3 to 4 mA provides an optimal balance between dose reduction and diagnostic image quality. This recommendation is consistent with the European Academy of Paediatric Dentistry (**EAPD**) guidelines,[20] which demonstrated sufficient diagnostic performance at reduced exposure levels. While standard collimation becomes acceptable due to larger anatomical dimensions in this age group, minimizing repeat exposures should remain a priority. The use of digital sensors is strongly recommended,

as studies by White and Mallya[21] indicate a 50% to 60% reduction in radiation dose compared to F-speed film, without compromising image quality in pediatric populations.

Adolescents (ages 13 to 17) may be managed using a modified adult protocol that applies 60 to 65 kVp and 4 mA, reflecting their near-adult anatomical characteristics while adhering to dose optimization principles. The similarity in bone surface doses between 15-year-olds and adults observed in the current study supports the validity of this approach. Nonetheless, strict justification for prescribing a full-mouth series remains essential to avoid unnecessary radiation exposure. Detailed protocol recommendations are provided in Table 4, offering clinical decision-making guidance across common scenarios, while Table 5 presents age-specific dose reference values for incorporation into quality assurance programs.

Table 4. AGE-SPECIFIC CLINICAL DECISION MATRIX*

Clinical scenario	5-7 years	8-12 years	13-17 years
Caries screening	Selective imaging only	Bitewings priority	Standard protocol
Orthodontic assessment	Defer if possible	Limited series	Complete assessment
Trauma evaluation	Single views preferred	Focused imaging	As indicated
Endodontic treatment	Minimize working films	Standard protocol	Adult approach

* Clinical recommendations based on age-specific radiation sensitivity patterns and anatomical vulnerability. Early childhood (5-7 years) requires maximum protection due to 3.2-fold thyroid dose elevation. Middle childhood (8-12 years) represents transitional period with intermediate risk. Adolescents (13-17 years) may follow modified adult protocols while maintaining strict justification principles. These guidelines should be integrated with individual clinical assessment and current professional standards.

Table 5. AGE-STRATIFIED TOTAL EFFECTIVE DOSE REFERENCE VALUES FOR COMPLETE SERIES

Age group (years)	Protocol (kVp/ 6 mA)	Total effective dose (µSv)*	Relative to adult standard (%)**	Clinical recommendation
5-7	60	62.4 (61.2-63.6)	44	Optimal protocol
	60	124.8 (122.4-127.2)	88	Acceptable if needed
	70	97.2 (95.2-99.2)	68	Alternative option
	70	129.6 (127.0-132.2)	91	Avoid if possible
8-12	60	37.2 (36.4-38.0)	26	Optimal protocol
	60	73.2 (71.8-74.6)	51	Acceptable
	70	56.4 (55.2-57.6)	40	Alternative option
	70	76.8 (75.4-78.2)	54	Standard pediatric
13-17	60	65.6 (64.4-66.8)	46	Optimal protocol
	60	131.2 (128.6-133.8)	92	Dense bone cases
	70	92.8 (90.8-94.8)	65	Alternative option
	70	142.4 (139.6-145.2)	100	Adult reference

* Abbreviations in table: µSv=microsievert; kVp=kilovoltage peak; mA=milliampere. Values presented as mean (95% confidence interval).

** Adult standard reference=70 kVp/6 mA in 15-year group (142.4 µSv).

While the ADA recommends pediatric-specific imaging configurations, its guidelines do not incorporate age-based stratification, which is identified in this study as a critical factor.[6] This gap is not limited to US-based standards; the guidelines of the EAPD similarly categorize pediatric patients as a single group.[22] However, the findings of this study indicate that such generalized classifications overlook substantial variations in organ-level radiation dose across different stages of childhood. Awareness of this issue is increasing internationally; for instance, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[23] has recommended age-specific dose coefficients, and ICRP Publication 135[24] has introduced age-dependent diagnostic reference levels (**DRLs**). The dose data provided in this study support the application of these recommendations in pediatric dental radiology to enhance the precision and safety of exposure protocols.

When compared to standard adult protocols, the age-specific differences in radiation dose become even more evident. A 5-year-old child imaged using adult parameters (70 kVp/6 mA) receives a thyroid dose equivalent to that of 3.2 adult examinations, despite undergoing only 75% of the total number of exposures. This disparity exceeds the 2-fold variation predicted by conventional scaling models, highlighting the need to consider not only exposure parameters but also developmental anatomical characteristics when designing pediatric imaging protocols. Similar conclusions were reported by Morant et al.[25] in their comparative phantom study, which demonstrated that extrapolating pediatric dose estimates from adult data systematically underestimates organ doses—especially for superficially located organs such as the thyroid.

The reliability of the Monte Carlo simulation approach is supported by a broad body of literature demonstrating high concordance with physical dosimetry. Lee[26] recently reviewed Monte Carlo applications in medical imaging and reported uncertainty levels below 5% for validated codes such as PCXMC. Tapiovaara and Siiskonen[27] further validated the use of radiology in dentistry by comparing it to thermoluminescent dosimetry, observing organ dose discrepancies within 10%. In the present study, effective dose estimates achieved an uncertainty level of less than 1%, which surpasses previously reported benchmarks and reinforces the credibility of the dosimetric data. Nevertheless, clinical validation of age-specific imaging protocols remains essential. Future investigations should prioritize the assessment of diagnostic image quality across pediatric age groups, utilizing methodologies such as those outlined by Martinez-Beneyto et al.,[28] to identify additional opportunities for dose optimization tailored to developmental stages.

Recent surveys have identified substantial knowledge deficits that hinder the adoption of age-specific imaging protocols in pediatric dental practice. Mitsea et al.[29] reported that 68% of pediatric dentists lacked awareness of optimal exposure parameters, while Sheikh et al.[30] found that 82% were unable to identify the kVp settings on their imaging equipment. These educational gaps are further compounded by technological limitations; Snel et al.[31] noted that 40% of surveyed dental clinics did not possess pediatric-specific exposure configurations. The age-stratified guidance proposed in this study may serve as a framework to bridge this knowledge to practice divide; however, successful implementation will depend on targeted professional education and systematic upgrades to radiographic equipment.

Establishing DRLs should be considered a priority in light of the present findings. DRLs are dose levels for typical examinations of standard-sized patient groups that should not be

exceeded without justification during standard procedures when good practice is applied.[24] Unlike CT imaging, where DRLs are defined using the CT Dose Index, in intraoral dental radiography, DRLs are typically expressed in terms of patient entrance surface dose or dose-area product (**DAP**).[32] For pediatric dental radiography specifically, the International Atomic Energy Agency and European guidelines recommend using patient entrance dose measured in μGy or the more practically measurable DAP in milligray square centimeter ($mGy \cdot cm^2$).[33] Some facilities also use incident air kerma at the patient entrance point as the reference quantity.[34] Existing DRLs frequently rely on broad pediatric age categories, which appear insufficient to capture the distinct dose variations identified across developmental stages. The European Commission's Radiation Protection Report 185[35] recommends stratified age bands of less than 1, 1 to 5, 5 to 10, and 10 to 15 years for DRL formulation, which correspond closely with the dosimetric phases observed in this analysis. Implementation of age-stratified DRLs could enhance the effectiveness of quality assurance frameworks and facilitate the broader adoption of optimized, age-appropriate imaging protocols.

Recognizing early childhood as a developmental period characterized by increased radiation-related risk carries important public health implications. With an estimated 10 million pediatric dental radiographs performed annually in the United States alone, the implementation of age-specific imaging protocols has the potential to reduce cumulative radiation exposure in this sensitive population. Based on ICRP risk coefficients, the observed 3.2-fold increase in thyroid dose for 5-year-olds corresponds to approximately 10 excess thyroid cancer cases per million examinations under standard adult parameters, compared to 3 per million with optimized pediatric settings. Although the absolute risk per individual remains low, the population-level impact is considerable. The cumulative nature of radiation risk—supported by biomarker studies from Schüler et al.[4] showing persistent genetic alterations following dental radiographic procedures—further highlights the need for minimizing exposure during early developmental stages.

While this study focused on organ-level absorbed dose and effective dose values derived from validated Monte Carlo simulations, future work may benefit from incorporating threshold-based comparisons to further contextualize clinical risk. As highlighted in recent literature, assessing whether radiation exposures in pediatric dental imaging approach or exceed biologically meaningful thresholds—particularly for radiosensitive organs such as the thyroid—may provide additional insight into patient vulnerability. However, such thresholds are not currently well established for low-dose dental radiography, and translating dosimetric data into biological risk estimates would require integration with epidemiological or biomarker data. Future studies that combine dosimetric modeling with biological outcomes may, therefore, yield a more nuanced interpretation of pediatric radiation risk.

This study offers several important strengths. To date, no previous research has comprehensively modeled age-specific radiation dose distributions in pediatric intraoral radiography using validated Monte Carlo simulations across multiple developmental stages. The use of anatomically accurate mathematical phantoms in conjunction with exposure parameters to specific modeling enabled detailed organ-level dose estimation, extending beyond conventional effective dose analysis. Statistical rigor—through adequate power, effect size evaluation, and correction for multiple comparisons—further enhances the reliability of the findings. Notably, these data were translated into age-stratified clinical protocol recommendations, directly addressing a critical gap in existing pediatric dental imaging guidelines. Nonetheless, several limitations should be acknowledged. The analysis was based on mathematical phantoms and simulated exposures rather than patient-specific anatomical data or clinical images. While PCXMC has been validated for dental applications, individual anatomical variation within age groups remains unaccounted for. In addition, the study relied on first-generation stylized phantoms, in which anatomical structures are represented using simplified mathematical equations and teeth are not explicitly modeled. More advanced voxel- and mesh-based phantoms may provide higher anatomical fidelity and could potentially improve dose estimations in the maxillofacial region. Additionally, diagnostic image quality was not evaluated, leaving uncertainty regarding whether the proposed low-dose protocols ensure adequate clinical performance in all scenarios. Although thyroid positioning and collimation were realistically modeled, factors such as operator technique and patient motion were not incorporated and may influence real-world dose delivery.

It is important to emphasize that the radiographic protocols modeled in this study, including 12 exposures for 5- and 10-year-olds and 16 exposures for 15-year-olds, do not reflect routine clinical practice. Full-mouth intraoral series are rarely prescribed in young children and are typically reserved for specific indications, such as extensive caries, trauma, or developmental anomalies. In adolescents, although a full-mouth series may occasionally be justified, current pediatric radiographic selection criteria emphasize individualized prescription based on clinical necessity rather than routine use.[6,7,36] Therefore, the exposure numbers utilized in this Monte Carlo simulation were selected solely to standardize dosimetric modeling across age-specific phantoms and should not be interpreted as representative of real-world radiographic frequency. The organ dose values presented here illustrate relative age-based differences under controlled experimental conditions and are intended to inform radioprotection strategies, not to suggest that pediatric patients typically undergo this number of exposures in clinical practice.

Conclusions

Based on the findings of this study, the following conclusions can be drawn:

1. Developmental age is the primary determinant of radiation dose distribution in pediatric intraoral radiography. Younger children, especially those aged 5 years, received significantly higher organ doses due to anatomical proximity and increased biological vulnerability to radiation.
2. The thyroid gland showed the greatest age-related dose variation, with 5-year-olds receiving up to 3.2-fold higher exposure than older age groups. These findings emphasize the importance of careful attention to thyroid exposure in younger patients from a radiation-safety standpoint.
3. Age-dependent differences in organ dose distribution persisted regardless of exposure protocol, demonstrating that anatomical factors substantially influence dose independent of technical optimization.
4. Consideration of age-adapted imaging approaches may support optimization of radiation protection in pediatric patients. Protocol design should consider developmental anatomy and apply individualized exposure parameters, collimation, receptor selection, and established pediatric radiographic selection criteria.

5. The present dosimetric data contribute to the evidence base supporting continued refinement of pediatric radiographic guidance, including consideration of developmental factors when planning and performing intraoral imaging.

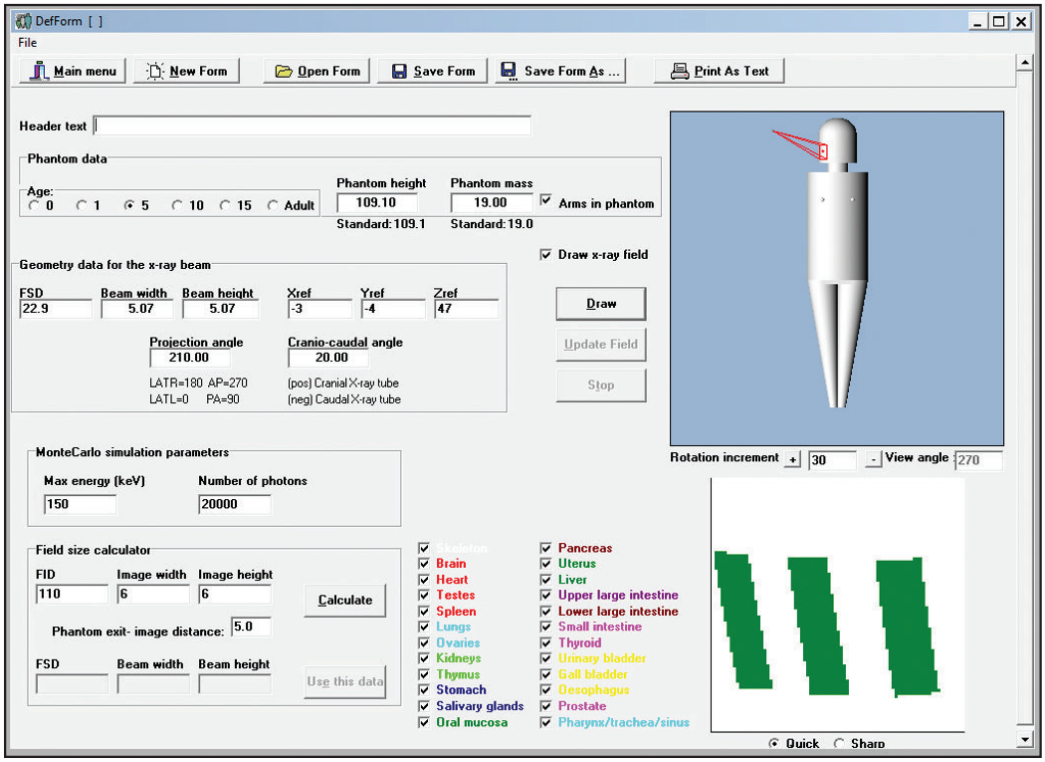
Disclaimer. The authors declare no conflicts of interest.

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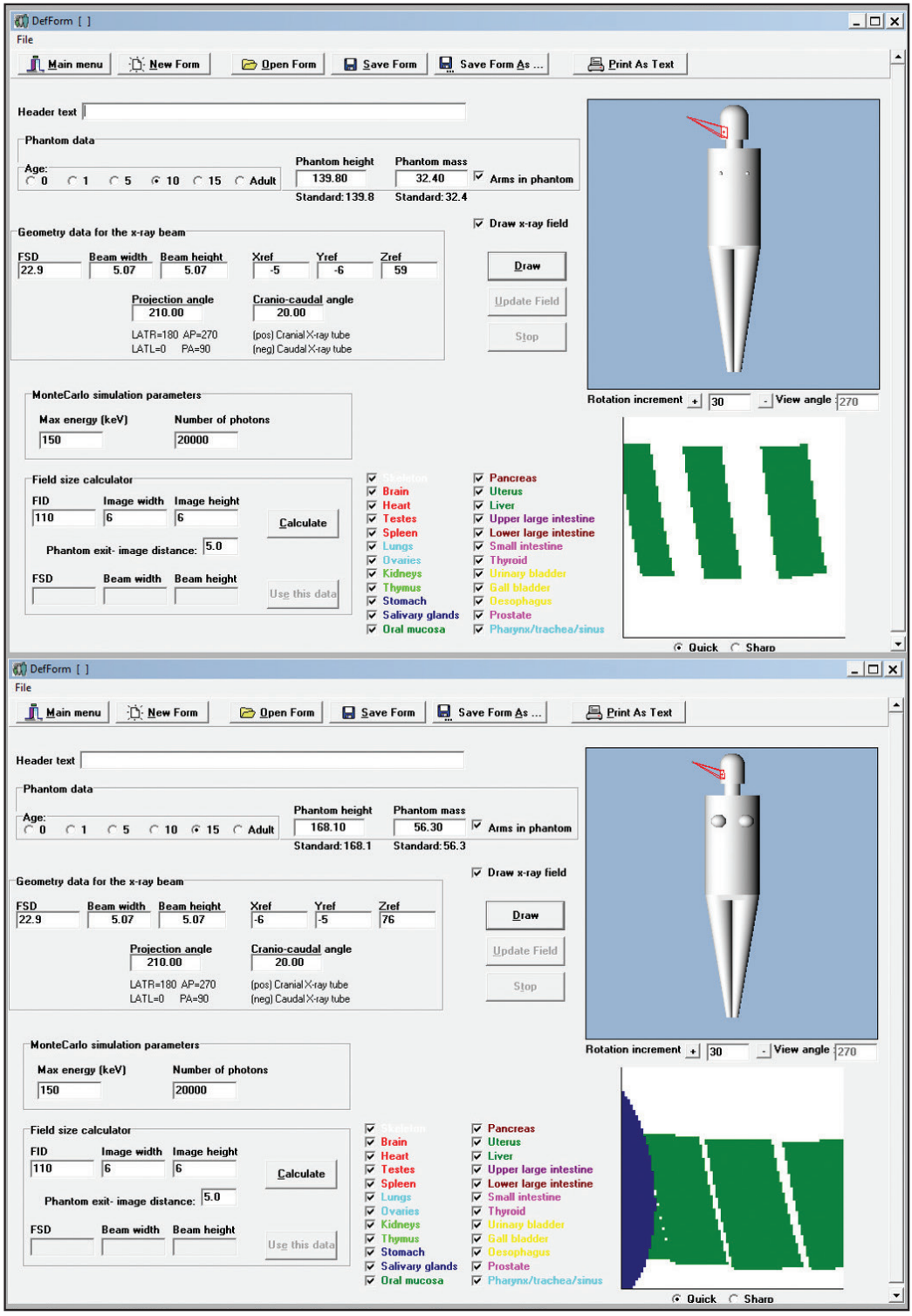
Supplemental Electronic Data—sFigure



(a) 5-year-old children

sFigure. Stylized age-specific hermaphroditic phantoms used in PCXMC 2.0 simulations for 5-, 10-, and 15-year-old children. These mathematical phantoms reflect pediatric anatomical proportions and incorporate organ definitions from the International Commission on Radiological Protection (ICRP) reference data, enabling simulation of intraoral radiographic exposures at different developmental stages. The phantoms are presented from top to bottom in the order of 5, 10, and 15 years.

sFigure continued on the next page.



(b) 10-year-old children

(c) 15-year-old children

sFigure. Stylized age-specific hermaphroditic phantoms used in PCXMC 2.0 simulations for 5-, 10-, and 15-year-old children. These mathematical phantoms reflect pediatric anatomical proportions and incorporate organ definitions from the International Commission on Radiological Protection (ICRP) reference data, enabling simulation of intraoral radiographic exposures at different developmental stages. The phantoms are presented from top to bottom in the order of 5, 10, and 15 years.