Organ dose and risk assessment in paediatric radiography using the PCXMC 2.0

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Abstract. Abdominal and chest radiographs are the most common examinations in paediatric radiology. X-ray examination of children attracts particular interest, mainly due to the increased risk for the expression of delayed radiogenic cancers as they have many years of expected life remaining. This study aims to calculate the organ dose and estimate the radiation Risk of Exposure Induced cancer Death (REID) to paediatric patients, using the PCXMC 2.0 Monte Carlo code. Patient data and exposure parameters were recorded during examinations of 240 patients, separated in four age groups undergoing chest or abdomen examinations. The organs received the highest dose in all patient groups were liver, lungs, stomach, thyroid, pancreas, breast, spleen in chest radiographs and liver, lungs, colon, stomach and ovaries, uterus (for girls) and prostate (for boys) in abdomen radiographs. The effective dose for the chest was $0.49 \times 10^{-2} - 1.07 \times 10^{-2}$ mSv, while for the abdomen $1.85 \times 10^{-2} - 3.02 \times 10^{-2}$ mSv. The mean REID value was $1.254 \times 10^{-5}$ for the abdomen and $0.645 \times 10^{-5}$ for the chest.

1. Introduction
Abdominal and chest radiographs are the most common examinations in paediatric radiology. X-ray examination of children attracts particular interest, mainly due to the increased risk for the expression of delayed radiogenic cancers, as they have many years of expected life remaining. Additionally, their smaller sizes bring all organs within or closer to the useful x-ray field, resulting to a higher overall exposure per radiograph [1].

Entrance surface dose (ESD) is one of the dosimetric quantities used in radiography and is useful to determine the level of patient doses, though it is not directly related to risk [2]. The evaluation of risk to paediatric patients requires the dose for various tissues and organs. One common method for evaluating organ doses is based on measurements using thermoluminescence dosimeters (TLD). TLD dosimetry, however, is laborious and time consuming [3-4]. Another method for estimating organ dose is Monte Carlo (MC) simulation. Monte Carlo simulation is a method applied extensively. The PCXMC code was developed at the Medical Radiation Laboratory of the Finnish Radiation and Nuclear Safety Authority for calculating patient doses in diagnostic radiology utilized relative simple measurements [5].

This study aims to calculate the mean value of the organ and effective doses, using the Monte Carlo PCXMC 2.0 code and estimate the radiation risk for paediatric patients in routine radiographic examinations. The calculation of the dose to each organ separately, in combination with the effective dose, provides an estimate of radiation risk.

2. Materials and methods
2.1. Measurements
Exposure parameters (tube load, tube voltage, tube current, Field Of View (FOV), Focus Skin Distance (FSD) and patient data (sex, age, weight, and height) were recorded for each examination at
the Karamandaneio Children Hospital of Patras, using the GE Model MS 18S radiology unit with tube filtration 3.5 mm Al. In this study, 120 paediatric patients underwent chest examination and 120 abdominal examinations. The chest radiographs were posterior-anterior and the abdomen radiographs anterior-posterior projection. No special preparation took place before examinations. Children were selected so that their anatomical characteristics (weight and height) to be representative of age groups (1, 5, 10, 15 years old) according to the requirements of the code used. The nominal anatomical data were based on the mathematical hermaphrodic phantom models of Christy and Eckerman [6-9].

2.2. Monte Carlo simulation
The PCXMC 2.0 code was used to calculate the dose of each organ separately and the effective dose of chest and abdomen x-ray examinations. All doses were calculated based on the exposure and patient data recorded. Photons were emitted isotropically from a point source into the solid angle specified by the FSD and FOV [6-9]. The simulations were made using Intel ® Core™ 2 Duo processor of 2.66 GHz CPU powered by Asus and 4 GB installed memory (RAM). The number of x-ray photons involved in each simulation was $2 \times 10^6$ in order to assure a low relative statistical uncertainty of 0.1%. The time required for each simulation was 20 to 30 minutes.

2.3. Effective doses and risk assessment.
The effective dose, for each radiograph examination, was computed according to the equation[10]:

$$E = \sum_{T} W_{T} \left[ \frac{H_{T}^{M} + H_{T}^{F}}{2} \right]$$

where $W_{T}$ is the tissue weighting factor and $H_{T}^{M}, H_{T}^{F}$ the equivalent doses for tissue T of male and female.

For the assessment of cancer risk resulting from an exposure to ionizing radiation [Risk of Exposure Induced cancer Death (REID)], the BEIR VII mathematical model was used, for all age groups. The REID values were calculated using the formula[7-8]:

$$REID_{C} (e, D) = \int_{T}^{\infty} \left[ \mu_{c}(t|e, D) - \mu_{c}(t) \right] S(t|e, D) dt$$

where $\mu_{c}(t|e, D)$ is the mortality rate at age t due to death cause c, given that the subject was alive at the age of exposure e and the corresponding dose at the age was D, $\mu_{c}(t)$ is the background mortality rate related to the death because c, $S(t|e, D)$ is the conditional probability that the subject is alive at age t, given a dose D at the age of exposure e.

3. Results and discussion
The patient data and the exposure parameters for chest and abdomen radiographs are presented in Table 1 and 2, respectively.

### Table 1. Patients data and exposure parameters for chest radiographs.

| Age (y) | weight (kg) | height (cm) | FSD (cm) | Tubevoltage (kVp) | Tubeload (mAs) |
|---------|-------------|-------------|----------|-------------------|---------------|
|         | Range Mean  | Range Mean  | Range Mean | Range Mean        | Range Mean    |
| 1       | 6.80-13     | 9.60        | 63-100   | 76.70             | 122           |
| 5       | 12.50-22    | 16.70       | 89-120   | 100.70            | 151           |
| 10      | 31-38       | 30.80       | 95-150   | 129.70            | 147           |
| 15      | 42-76       | 52.20       | 140-178  | 156.40            | 158           |


Table 2. Patients data and exposure parameters for abdomen radiographs.

| Age (y) | weight (kg) | height (cm) | FSD (cm) | Tubevoltage (kVp) | Tubeload (mAs) |
|--------|-------------|-------------|----------|-------------------|----------------|
|        | Range       | Mean        | Range    | Mean              | Range          | Mean          | Range    | Mean          |
| 1      | 8-13.50     | 10.26       | 62-90    | 79.60             | 118            | 70-80        | 75.50    | 3.21-12.50   | 6.21         |
| 5      | 14-26       | 19.40       | 92-120   | 111.00            | 151            | 70-80        | 74.40    | 3.89-17.20   | 7.86         |
| 10     | 27-39       | 32.23       | 120-145  | 135.60            | 150            | 70-80        | 76.60    | 3.95-18.25   | 10.04        |
| 15     | 40-61       | 49.20       | 145-165  | 151.10            | 160            | 70-80        | 75.50    | 8.89-22.60   | 15.43        |

Table 3. Organ doses in chest examinations.

| Organ | Dose (mGy) x 10^{-2} |
|-------|----------------------|
|       | 1 y  | 5 y  | 10 y | 15 y |
| Liver | 4.10 | 3.23 | 3.28 | 2.66 |
| Lungs | 4.71 | 4.66 | 6.07 | 5.84 |
| Stomach | 4.23 | 7.82 | 2.10 | 1.61 |
| Thyroid | 4.57 | 1.35 | 1.00 | 0.61 |
| Pancreas | 4.04 | 3.12 | 3.12 | 2.50 |
| Breast | 1.96 | 1.77 | 2.42 | 1.00 |
| Spleen | 3.15 | 2.98 | 2.95 | 2.35 |

Table 4. Organ doses in abdomen examinations.

| sex   | Organ | Dose (mGy) x 10^{-2} |
|-------|-------|----------------------|
|       | 1 y  | 5 y  | 10 y | 15 y |
| Liver | 1.61 | 1.40 | 0.96 | 1.91 |
| Lungs | 0.98 | 0.59 | 0.59 | 0.52 |
| Stomach | 3.91 | 3.89 | 3.31 | 3.31 |
| Colon | 3.33 | 3.20 | 3.03 | 3.74 |
| girls | Ovaries | 3.07 | 3.03 | 3.50 | 3.03 |
| Uterus | 3.35 | 3.36 | 3.66 | 3.29 |
| boys  | Prostate | 3.09 | 3.25 | 3.34 | 3.28 |

Table 5. Mean Effective dose for chest and abdomen examinations.

| Age (y) | Mean Effective Dose (mSv) x 10^{-2} |
|---------|-------------------------------------|
|         | chest | abdomen |
| 1       | 0.94  | 3.02    |
| 5       | 1.07  | 1.26    |
| 10      | 0.49  | 2.11    |
| 15      | 0.98  | 1.85    |
Table 6. Mean REID values for all patient groups for both examinations.

|          | REID x10^{-5} |
|----------|---------------|
| Chest    | 0.645         |
| Abdomen  | 1.254         |

Tables 3-6 present the organ dose, effective dose and the REID values, according to ICRP 103, for each examination and age group. The dose contribution analysis for all age groups indicates that some organs received greater dose amounts, such as liver, lungs, stomach, thyroid, pancreas, breast, spleen in chest radiographs and liver, lungs, colon, stomach and ovaries, uterus (for girls), prostate (for boys) in abdomen radiographs. The dose of the other organs was negligible.

4. Conclusions
The organs received the highest doses in all patient groups studied were liver, lungs, stomach, thyroid, breast, pancreas, spleen in chest radiography and liver lungs, colon, stomach and ovaries, uterus (for girls) and prostate (for boys) in abdomen radiography. The value of mean effective dose was up to four times higher for abdomen compared to chest. The value of REID for girls was slightly greater than boys for each examination. The mean REID value was almost double (1.254x10^{-5}) for abdomen compared to chest (0.645x10^{-5}). The risk was extremely low for both chest and abdomen examinations for all patient groups studied.

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