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ARTICLE

Assessment of radiation risk to pediatric patients undergoing conventional X-ray examinations

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Abstract – Increasing concern has been expressed in the literature that the knowledge of physicians regarding the radiation risk values incurred during different radiological examinations is inadequate. This study determined the amount of organ doses and the radiation risks involved in pediatric radiology in terms of the age and sex of patients. The X-ray examinations of the chest, abdomen, pelvis and skull in patients of six age groups (newborn, 1-, 5-, 10- and 15-year-old, and adult) were investigated. Exposure data of 480 patients were collected from four radiology departments and then Entrance Skin Exposure (ESE) values for standard patients in the six age groups as well as five X-ray examinations were measured. By using these practical data, the risk of exposure-induced cancer death (REID) values were estimated based on the risk models of the BEIR VII committee. It was shown that the differences in REID values in male and female patients were statistically significant for the chest and pelvis X-ray examinations. The X-rays of the abdomen, chest and pelvis have the highest REID values in 15-, 10- and 15-year-old patients, respectively. The results obtained can help physicians to make suitable decisions about the execution and justification of every X-ray examination in the different age groups. This information will help to prevent either overestimation or underestimation of radiation risks.

Keywords: pediatric / X-ray imaging / organ doses / radiation risk

1 Introduction

Radiological imaging is widely used in patient management. While radiological examinations undoubtedly help in the proper diagnosis of various diseases, their excessive use can lead to unnecessary exposure to radiation, the biggest long-term risk of which is cancer. In general, the benefits of the X-ray examinations should exceed the costs, which include the REID values to the patient and, less importantly, the financial costs.

It is a fundamental role of the physician to determine whether or not a proposed X-ray examination is justified. Knowledge of the approximate REID values will help physicians take the decision of performing an X-ray examination. This has also been reported in the literature. Dauer *et al.* (2011) explained that physicians' awareness is important in holistic benefit-and-risk discussions in shared medical decision-making. The importance of knowledge about the lifetime risk of inducing a fatal cancer for various pediatric examinations was also confirmed in Cook's study (Cook, 2001) for appropriate justification of requests. The REID values are comprehensible for physicians to determine that a proposed X-ray examination is justified and compare with other potential health risks including smoking, alcohol, car accidents, fire, pesticides, earthquakes, air travel and swimming (Mihai *et al.*, 2005). For example, a REID value of 10 per million is approximately equivalent to 1 return transatlantic flight (Cook, 2001).

Increasing concern has been expressed in the literature that despite the increased use of radiological examinations in clinical practice, the knowledge of physicians regarding the related REID values incurred during different radiological examinations is inadequate (Thomas *et al.*, 2006; Soye and Paterson, 2008; Keijzers and Britton, 2010).

A number of studies have reported radiation dose measurements from some X-ray examinations; however, their results were only limited to the presentation of entrance surface dose (ESD) or dose-area product (DAP) measurements or the effective dose (E) for some age groups (Huda, 2002; Hart and Wall, 2004; Hart *et al.*, 2009; Kiljunen *et al.*, 2009; Olowookere *et al.*, 2011). Nevertheless, the use of the effective dose to state the stochastic harm to patients from ionizing radiation is sometimes criticized (Valentin, 2007; McCollough *et al.*, 2010; Pradhan *et al.*, 2012). The effective dose is not expressed in terms of sex and age, while the REID values vary with age and gender (Clarke *et al.*, 1993). Previous studies have shown that for patients in the first decade of life, the risk is about 15%/Sv, while for adults in late middle age, the risk drops to 1% or 2%/Sv (Fig. 1). Girls are more radiosensitive than boys (Hall, 2002). Recently, it was suggested that the

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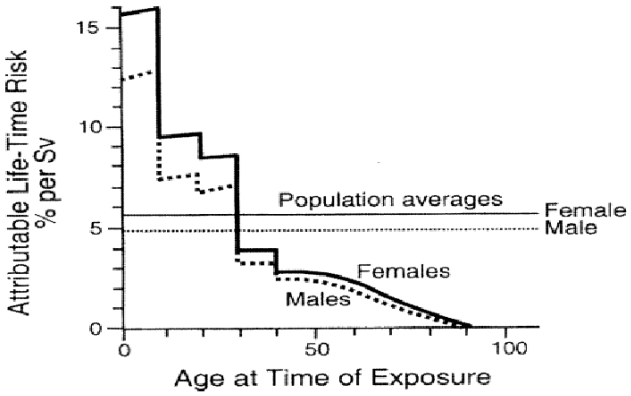

Fig. 1. The attributable lifetime risk from a single small dose of radiation at various ages at the time of exposure (Clarke *et al.*, 1993).

risk coefficients from the BEIR VII Report (Biological Effects of Ionizing Radiation, National Academy of Sciences) (BEIR, 2006) be used to perform risk estimates. The BEIR VII committee had derived risk models which took into account the organ-specific dose, the cancer site, sex, and age at the time of exposure.

Risk estimates have been reported in a few studies. Mazonakis *et al.* (2004) estimated the risk of fatal cancer induction to children undergoing skull radiography; Brindhaban and Eze (2006) performed this estimation for newborn and 1-year-old patients; and in Cook's study (Cook, 2001), the lifetime risk of developing a fatal cancer following X-ray exposure in childhood was generally shown. They estimated radiation-induced cancer values only for a few X-ray examinations and age groups.

The aim of the present study was: (a) to calculate organ doses and effective doses resulting from the commonly performed X-ray examinations; and (b) to estimate REID values for the patients, ranging from newborn to adults, as well as for male and female.

2 Materials and methods

2.1 X-ray examinations and exposure factors

The X-ray examinations most frequently utilized for disease assessment are chest (in the posteroanterior projection (PA)), abdomen (in the anteroposterior projection (AP)), skull (in the two AP and lateral (LAT) projections), and pelvis (in the AP projection). The patient exposure factors were determined based on the height and weight of standard patients in six age groups whose characteristics are shown in Table 1.

The exposure factors [X-ray tube voltage (kVp), tube current-time product (mAs) and radiation field size] associated with each X-ray examination are given in Table 2. The expert technologists employed in every department were asked to declare the suitable exposure factors which were used for X-rays of the standard patients whose characteristics are displayed in Table 1. This work was repeated for four X-ray machines available in the radiology departments of hospitals in Yazd. In total, for four X-ray machines, 480 patients' exposure data were collected for different X-ray examinations in six age groups. The following models of X-ray machines were used in this study: Varian, Siemens, Toshiba and Shimadzu, which are available all over the world. The radiographic equipment was calibrated based on recommendations of the National Council on Radiation Protection and Measurements (NCRP Report No. 99, 1988). Total filtration for the different X-ray units was measured at 80 kVp using an X-ray multimeter (model: Barracuda). Their total filtration ranged from 1.5 to 2.5 mm AL.

2.2 Entrance skin exposure measurements

Entrance Skin Exposure (ESE) values were measured using a solid-state dosimeter (6001 model, UNFORS), while the exposure factors related to the real patients were applied for every X-ray examination in the different X-ray machines. For ESE measurements, the dosimeter was placed at the source to skin distance (SSD) associated with every view without the patient present. The SSD values were determined for every view by considering the patient thickness (PT) or trunk thickness values shown in Table 1.

2.3 Organ doses, effective dose calculation and REID estimation

For simulation and dose calculation of different X-ray examinations, a Monte Carlo code named PCXMC (Tapiovaara and Siiskonen, 2008) developed by STUK (the Radiation and Nuclear Safety Authority in Finland) was used. The software incorporated pediatric and adult patient adjustable-size models, and allowed a free choice of the X-ray examination technique. Definition of the examination techniques (location and size of the radiation field and projection angle) was based on standard guidelines (*e.g.* Merrill's Atlas of Radiographic Positioning and Procedures (Frank *et al.*, 2013).

Briefly, real patients' data obtained from clinical work (input data of PCXMC for calculation) were as follows: the measured ESE, kVp, total filtration, and the examination technique (location and size of the radiation field and projection angle), which should be entered into the program for every X-ray examination. The output information of PCXMC was as follows: organ doses, effective doses and REID for all the X-ray examinations of the six age groups for male and female patients. The program was able to calculate the effective dose with both the present tissue-weighting factors of ICRP Publication 103 (Valentin, 2007) and ICRP Publication 60 (Mountford and Temperton, 1992).

The REID was computed using the calculated organ doses and their corresponding cancer estimates by the PCXMC program. This work was performed based on the risk models of the BEIR VII committee (BEIR, 2006) (on the assumption of a "linear non-threshold" (LNT) model). These models are sex- and age-dependent, so the risk coefficients related to every X-ray examination were extracted for every age group as well as each gender. Risk estimates were related to the excess of fatal cancers over those naturally occurring in the population. In other words, the perception of REID originates from cohort analysis methods. This was performed by comparison of death

Table 1. Standard measurements of the phantoms in PCXMC software (Eckerman *et al.*, 1996).

Age (y)	Height (cm)	Weight (kg)	Trunk width (cm)	Trunk thickness (cm)
Newborn	50.9	3.4	10.94	9.8
1	74.4	9.2	15.12	13.0
5	109.1	19.0	19.64	15.0
10	139.8	32.4	23.84	16.8
15	168.1	56.3	29.66	19.6
Adult	178.6	73.2	34.40	20.0

Table 2. The exposure factors of the different X-ray examinations related to the real patients.

Examination	Age (y)	kVp			mAs			Radiation field size (width × height) (cm^2)
		Mean	±SD	Range	Mean	±SD	Range	
Abdomen	0	45.0	5.8	40–50	20.5	5.2	16–25	12 × 13
	1	48.8	6.1	43–54	27.9	9.7	20–40	15 × 18
	5	56.3	8.4	48–64	33.4	4.5	30–40	19 × 24
	10	58.8	6.7	52–65	37.9	4.3	32–40	26 × 30
	15	62.3	6.7	56–68	45.0	5.8	40–50	30 × 37
	30	67.3	3.2	64–70	55.0	5.8	50–60	33 × 40
Chest (PA)	0	46.7	5.8	40–50	13.3	2.3	12–16	14 × 11
	1	51.0	5.2	45–54	16.3	7.5	12–25	18 × 14
	5	56.0	6.9	48–60	18.3	5.8	15–25	23 × 20
	10	60.3	7.2	52–64	20.3	4.0	18–25	27 × 24
	15	64.7	9.2	54–70	20.3	4.0	18–25	35 × 29
	30	71.0	8.7	61–76	24.3	0.6	24–25	37 × 33
Pelvis (AP)	0	45.0	5.8	40–50	20.5	5.2	16–25	13 × 9
	1	48.8	6.1	43–54	27.9	9.7	20–40	16 × 12
	5	56.3	8.4	48–64	33.4	4.5	30–40	21 × 14
	10	58.8	6.7	52–65	37.9	4.3	32–40	26 × 18
	15	62.3	6.7	56–68	45.0	5.8	40–50	30 × 23
	30	67.3	3.2	64–70	55.0	5.8	50–60	33 × 26
Skull (AP)	0	49.3	1.2	48–50	21.7	2.9	20–25	14 × 12
	1	51.0	1.7	49–52	40.0	1.2	38–40	15 × 16
	5	56.0	3.5	52–58	40.0	1.2	38–40	15 × 18
	10	58.3	2.9	55–60	46.7	5.8	40–50	17 × 20
	15	64.7	5.8	58–68	46.7	5.8	40–50	18 × 22
	30	67.3	4.6	62–70	53.3	11.5	40–60	19 × 23
Skull (Lat)	0	47.0	1.7	45–48	19.0	5.2	16–25	14 × 12
	1	48.7	2.3	46–50	26.7	11.5	20–40	16 × 16
	5	49.7	0.6	49–50	40.0	0.7	38–40	17 × 18
	10	53.7	1.5	52–55	40.0	1.2	38–40	19 × 20
	15	58.3	2.9	55–60	40.0	1.2	38–40	19 × 22
	30	62.0	3.5	58–64	46.7	5.8	40–50	25 × 23

rates in the exposed and unexposed cohorts. The null hypothesis was: "There is no difference between the exposed and unexposed groups". A positive REID value indicates excess deaths in the exposed group (in a population of 1 000 000 patients in the present study). A more thorough explanation of the calculation details of the program can be found in a technical program document (Tapiovaara and Siiskonen, 2008) and in previous studies (Chaparian and Aghabagheri, 2013; Chaparian *et al.*, 2014). In order to evaluate the risk of radiation-induced cancer death for an examination, the user needs to enter correct patient data for the "Age", "Gender" and mortality "Statistics" (Euro-American, Asian) of the patient. The Asian and Euro-American mortality data were from ICRP Publication 103 (Valentin, 2007).

3 Results

Table 3 summarizes the mean of the measured entrance skin exposure (mGy) and the effective dose values (μSv) for every X-ray examination for all age groups. This information is related to the four types of X-ray examinations.

The organs which receive the highest dose values in different X-ray examinations in all of the six age groups are shown in Tables 4–7. While the PCXMC program was able to calculate doses for 45 organs and tissues, including the active bone marrow, adrenals, brain, breasts, colon (upper and lower large intestine), extrathoracic airways, gall bladder, heart, kidneys, liver, lungs, lymph nodes, muscle, esophagus, oral mucosa, ovaries, pancreas, prostate, salivary glands, skeleton,

Table 3. Results of the measured entrance skin exposure (mGy) and calculated effective dose values (μSv) for abdomen, chest, pelvis and skull X-ray examinations in the different age groups.

X-ray examination	Age (y)	Entrance skin exposure (mGy)		Effective dose (μSv)		X-ray examination	Age (y)	Entrance skin exposure (mGy)		Effective dose (μSv)	
		Mean	±SD	Mean	±SD			Mean	±SD	Mean	±SD
Abdomen	0	0.321	0.138	64	21	Pelvis (AP)	0	0.321	0.138	39	14
	1	0.587	0.232	94	23		1	0.587	0.232	60	17
	5	1.088	0.145	193	30		5	1.088	0.145	115	15
	10	1.475	0.165	255	42		10	1.475	0.165	156	22
	15	2.202	0.480	334	82		15	2.202	0.480	214	50
	30	3.368	0.871	521	113		30	3.368	0.871	350	78
Chest (PA)	0	0.048	0.004	6	1	Skull (AP & Lat)	0	0.661	0.099	40	6
	1	0.081	0.023	8	1		1	1.283	0.152	58	6
	5	0.122	0.012	12	1		5	1.926	0.111	62	3
	10	0.170	0.008	17	2		10	2.581	0.182	65	5
	15	0.213	0.007	19	4		15	3.322	0.209	85	8
	30	0.321	0.029	34	8		30	4.389	0.405	109	13

Table 4. Mean organ doses (μGy) for abdomen X-ray examination in the different age groups.

Organ Dose (μGy)	Age groups					
	0	1	5	10	15	30
Active bone marrow	11	17	47	75	114	170
Adrenals	26	34	67	84	113	157
Colon (large intestine)	116	170	347	461	625	1013
Extrathoracic airways	120	203	405	550	748	1254
Kidneys	30	37	75	91	105	178
Liver	140	206	416	511	655	896
Lower large intestine	95	131	265	354	474	775
Ovaries	90	119	255	340	440	732
Pancreas	78	103	215	282	368	544
Prostate	118	156	295	441	624	980
Small intestine	107	160	331	424	573	957
Spleen	51	65	135	162	197	304
Stomach	164	266	547	729	960	1439
Testicles	26	34	62	102	146	152
Upper large intestine	131	200	409	540	739	1194
Urinary bladder	177	278	551	727	1038	1706
Uterus	108	173	325	431	577	938

skin, small intestine, spleen, stomach, testicles, thymus, thyroid, urinary bladder and uterus, only organs and tissues at risk which receive a considerable dose in different X-ray examinations are presented in these tables.

Figure 2 and Table 8 demonstrate the results of the REID (per million) due to the different X-ray examinations for male and female patients in all age groups. The REID values are the sum of the risks of the various cancers. The word "mean" refers to the average of the results attained for the four X-ray units used in this study. In other words, the different cancer risks and final REID related to every X-ray examination were calculated separately for every X-ray unit and then the means of the REID values are displayed in these figures.

Radiation risk is strongly dependent on the degree to which sensitive organs are positioned in the radiation field (Tabs. 4–7). The REID value for the abdomen is higher than that for other examinations because organs in the abdomen have higher radiosensitivity.

Table 5. Mean organ doses (μGy) for pelvis X-ray examination in the different age groups.

Organ Dose (μGy)	Age groups					
	0	1	5	10	15	30
Active bone marrow	11	13	35	46	67	112
Colon (large intestine)	81	114	218	296	384	668
Gall bladder	8	14	23	29	30	54
Lower large intestine	95	133	259	339	447	761
Ovaries	85	116	226	303	369	662
Prostate	134	196	365	516	739	1158
Small intestine	81	113	213	295	377	677
Testicles	330	571	1070	1479	2089	3163
Upper large intestine	69	99	187	264	337	598
Urinary bladder	178	283	578	761	1082	1807
Uterus	105	156	327	408	545	944

Table 6. Mean organ doses (μGy) for chest X-ray examination in the different age groups.

Organ Dose (μGy)	Age groups					
	0	1	5	10	15	30
Active bone marrow	5	6	10	17	25	48
Adrenals	9	12	24	29	33	58
Breasts	8	10	14	18	21	26
Heart	9	9	15	20	21	40
Liver	4	5	8	11	15	25
Esophagus	10	11	19	22	30	52
Spleen	4	6	12	14	15	29
Thymus	4	5	7	9	9	18
Thyroid	7	8	10	15	17	30

Table 7. Mean organ doses (μGy) for skull X-ray examination in the different age groups.

Organ Dose (μGy)	Age groups					
	0	1	5	10	15	30
Active bone marrow	94	123	98	113	100	107
Brain	211	269	307	435	539	696
Extrathoracic airways	303	508	481	898	856	1034
Oral mucosa	350	535	628	1197	1074	1391
Salivary glands	326	488	601	818	1045	1379
Thyroid	309	442	542	641	728	1030

Table 8. Results of the REID values (per million) due to the different X-ray examinations for male and female patients in the different age groups.

X-ray examination	Abdomen				Chest				Pelvis				Skull (AP & Lat)			
	Male		Female		Male		Female		Male		Female		Male		Female	
Age (y)	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
0	8.33	2.78	7.94	2.64	0.93	0.21	1.90	0.42	4.25	1.51	2.43	0.80	5.19	0.71	6.30	0.85
1	11.67	2.93	11.35	2.79	1.10	0.16	2.25	0.31	5.99	1.73	3.34	0.78	6.52	0.64	7.83	0.76
5	20.38	3.04	20.03	3.04	1.49	0.12	3.00	0.24	8.85	1.12	5.43	0.90	5.05	0.28	5.93	0.33
10	22.23	3.51	22.00	3.52	1.66	0.20	3.32	0.40	9.65	1.33	5.98	1.01	3.95	0.30	4.62	0.35
15	24.15	5.89	23.85	5.83	1.63	0.35	3.03	0.65	10.94	2.53	6.76	1.67	4.13	0.38	4.92	0.46
30	21.85	4.76	20.63	4.50	1.66	0.38	3.03	0.70	10.56	2.34	6.89	1.48	3.12	0.39	3.66	0.45

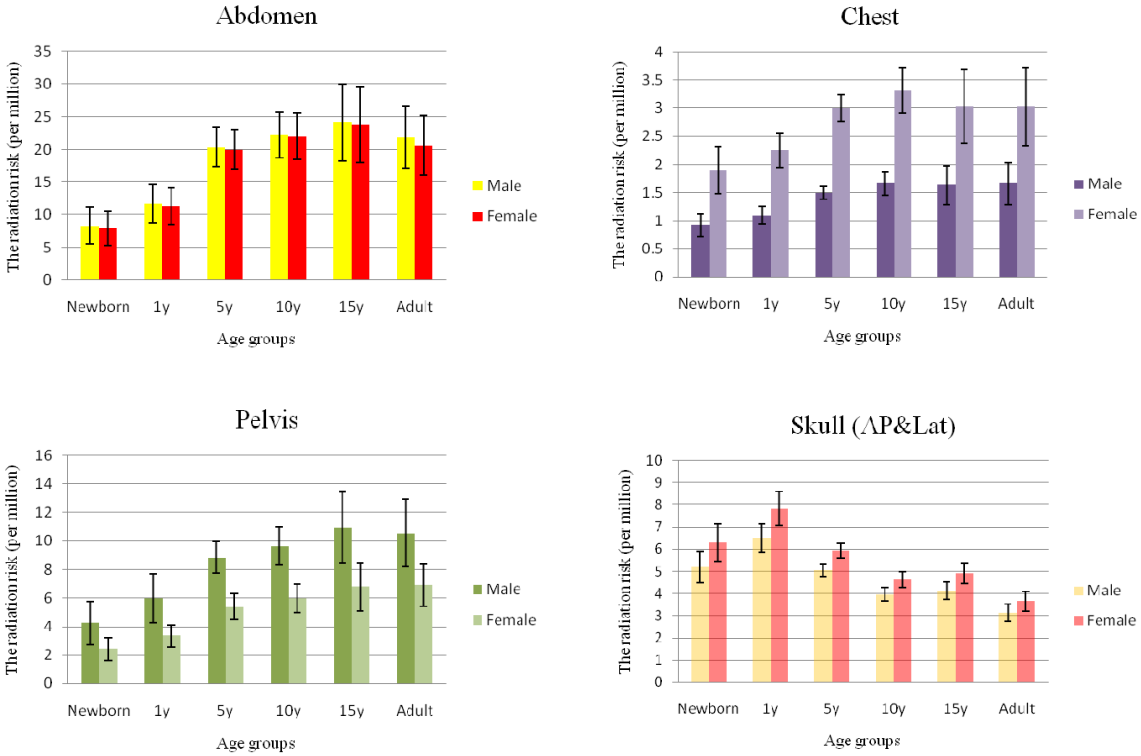

Fig. 2. The mean (±SD) values of the REID (per million) from the X-ray examinations in the different age groups of male and female patients.

4 Discussion

In this study, radiation risks from the various X-ray examinations were expressed as the risk of radiation-induced cancer death (REID) values per million. Also, the differences in radiation risk between different age groups as well as in male and female patients were surveyed. This type of presentation is comprehensible for physicians to determine whether or not a proposed X-ray examination is justified and compare with other risks such as smoking. While the main objective of this study was to obtain the radiation risks involved in pediatric radiology, in order to compare and validate the results of this study with other studies, the results were also obtained for adult patients.

The REID values have been estimated in a few studies. Hence, for validation of the results of the present study, the effective dose values obtained in this study (Tab. 3) were compared with those of other studies. While the calculated effective doses in this investigation for abdomen radiography of newborn and 1-year-old patients were 64 and 94 μSv, respectively, these were 62 and 90 in Huda's (2002) study, respectively. Also, the effective dose obtained for this radiography was 521 μSv for adults, which was relatively similar to the value of 530 μSv calculated by Hart and Wall (2004). The calculated effective dose for chest radiography of adults was 34 μSv in this study, which was similar to the findings of Huda's study (Huda, 2002). Also, the effective dose for skull radiography was 109 μSv for adults, which was consistent with that reported by Olowookere *et al.* (2011). The reasons for some discrepancies between different research works can be attributed to the use of different X-ray machines and exposure factors for every X-ray examination. Another reason for these differences may be due to the use of different weighting factors [ICRP Publication 103 (Valentin, 2007) and ICRP Publication 60 (Clarke *et al.*, 1993)] for calculation of the effective dose.

Comparison of the REID values in this study with other studies was difficult, because only limited age groups or

examinations were evaluated in the previous studies. However, there was relatively good agreement between the REID values obtained in the present study and the results obtained by Cook (2001) and Mazonakis *et al.* (2004). Some discrepancies could be explained by mismatching of age groups and use of different risk estimation methods.

The lifetime cancer mortality risk of patients from the various X-ray examinations (Tab. 8) should not be considered negligible because, according to the literature, a risk of death of more than 1 in a million may not be generally ignored (Perlmutter *et al.*, 1998). Furthermore, repeating the X-rays as a result of either improper selection of exposure parameters or patient motion, especially in children, will increase the cancer risk.

The REID values can be used for easy comparisons, *e.g.* between different X-ray examinations and age groups, and between male and female patients. As shown in Figure 2, there was no statistically significant correlation between the corresponding REID values and the sex of patients for the abdomen and skull X-ray examinations. Conversely, it was shown that the difference in REID values between the two genders was statistically significant for the chest and pelvis X-ray examinations. This may be explained by the fact that the above risk estimates were based on the different organ doses (Tabs. 4–7) and the radiation sensitivity of some organs such as the breasts, gonads and prostate are different in male and female patients.

Table 3 shows that for all X-ray examinations, the effective dose increases with increasing age, but on the other hand, according to the literature (Fotakis *et al.*, 2003), for children the radiation risk per unit dose is 2 to 3 times higher than the average population. Considering the two facts above, new and exciting results were extracted in this study. As shown in Figure 2 and Table 8, the X-rays of the abdomen, chest and pelvis have the highest REID values in 15-, 10- and 15-year-old patients, respectively. Also, the radiography of the skull has the highest REID values in 1-year-old patients, which is consistent with the recent report of the ICRP (Khong *et al.*, 2013) that did not justify skull radiography for an infant or child with epilepsy or headaches. The results of this study showed that in most of the X-ray examinations except skull radiography, the REID values do not necessarily increase by decreasing age.

The major limitation of this study was the large range of age and size of patients from newborn to adult. Essentially, variety of patients (in terms of age, height, weight and thickness) is a problem encountered by all patient studies. To solve this problem, six standard age groups were chosen, representing newborn, 1-, 5-, 10- and 15-year-old, and adult patients (Tab. 1). These selections of standard groups have the advantage of matching the patient mathematical phantoms which are often used in Monte Carlo simulation programs and also in other studies. Obviously, the results of this study are applicable to the standard body sizes shown in Table 1. The findings may be slightly different if the patients in every age group are thinner or fatter.

Another limitation of the present study was the different random and systematic uncertainties embedded in estimates of cancer deaths induced by medical radiation. Other potential health risks such as smoking are also associated with large uncertainties. Also, the report of the BEIR VII committee (BEIR, 2006) explained that limitations in epidemiological data for radiation-induced cancer contribute to the uncertainty of risk estimation. However, it suggests that the risk estimates should be considered with a healthy skepticism, with more emphasis on the magnitude of the risk. Some studies stated that predictions of cancer incidence and deaths in patient populations exposed to effective doses below 50 mSv for single procedures or 100 mSv for multiple procedures over short time periods are highly speculative. However, they also confirmed the justification of the procedures for minimizing avoidable unnecessary radiation exposure (AAPM, 2011; Pradhan, 2013). While the public should not be scared of necessary imaging, physicians should try to minimize the dose and dose distribution to As Low As Reasonably Achievable (ALARA). Therefore, the aim of the present study was to help physicians with justification of required X-ray examinations.

5 Conclusions

On the whole, the results of this study showed that the use of the entrance surface dose (ESD) or effective dose (E) cannot be an accurate indicator for physicians judging the radiation risk of an X-ray examination. Therefore, the corresponding REID values from common radiological examinations for six age groups were obtained. It was shown that the difference in REID values between the two genders was statistically significant for the chest and pelvis X-ray examinations. The X-rays of the abdomen, chest and pelvis have the highest REID values in 15-, 10- and 15-year-old patients, respectively. This information will help to prevent either overestimation or underestimation of radiation risks. The physicians who underestimate the risks of radiation and order too many X-ray examinations can be concerned by knowing the REID values. On the other hand, the physicians who overestimate the risks of radiation and have an excessive fear of requesting these tests can reduce their concern based on this information and benefit from the advantages of using this method for diagnosis of diseases reasonably. The mean radiation risk values for X-ray examinations in every age group can be used as a guide for the risk *vs.* benefit of performing the radiography.

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