Radiation Measurements 89 (2016) 68–73

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Evaluation of medical exposure and exposure by the public in a typical scenario of examinations using mobile X-ray equipment through the Monte Carlo simulation

Felipe A. Santos [a, *], Diego C. Galeano [a], William S. Santos [b], Albérico B. Carvalho Júnior [a]

[a] Department of Physics, Center of Exact Sciences and Technology, Federal University of Sergipe, UFS, Marechal Rondom Street, São Cristóvão, Brazil
[b] Nuclear Energy Research Institute, University of São Paulo, USP, Almeida Prado Street, São Paulo, Brazil

HIGHLIGHTS

- A computational scenario involving mobile X-ray equipment in hospitals were modeled.
- Evaluation of medical exposure and exposure by the public was made by CC_E (E/ESD).
- A pair of the anthropomorphic simulators was inserted into the input file MCNPX.
- Analyze the influence in CC_E for the different types of fields used in examinations.
- Monitoring the reduction of CC_E's with increasing distance between the beds.

ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form
7 March 2016
Accepted 9 March 2016
Available online 10 March 2016

Keywords:
Mobile X-ray equipment
Monte Carlo simulation
Conversion coefficient
Effective dose

ABSTRACT

In this work irradiation scenarios that simulated chest and abdomen examinations involving mobile X-ray equipment in hospitals were modeled with the purpose of calculating conversion coefficient for effective dose (CC_E), normalized to entrance surface dose (ESD), applied to patients and public individuals. These coefficients can easily be used in this practice. Patients and public individuals were represented by a pair of anthropomorphic phantoms inserted in the MCNPX 2.7.0 radiation transport code. One of the phantoms (patient) was irradiated with the direct beam simulating examinations of the chest and abdomen, each with two fields of irradiation, ideal (IF) and extrapolated (EF). Using the software SPECGEN X-ray spectra from 60 to 100 kVp at 10 kVp intervals were generated and used in this work. The other phantom (public individual) was positioned 50–200 cm from the patient. In relation to the CC_E calculated in the patient, the average increase obtained between the irradiation fields was 62.4% for the chest examinations, and for the same conditions the CC_E was calculated for abdomen examinations and found to be 8.0%. Increasing the distance between public individual and patient, reductions of up to 81.7% in the CC_E in abdomen examinations and 83.4% in chest examinations were observed. Through the assessment of CC_E of these scenarios, it is possible to measure the damages relating to this practice for both patients and public individuals.

1. Introduction

Clinical applications of mobile X-ray equipment are very common. Several advances in medical imaging can be used for diagnosing acute emergencies diseases by means of rapid diagnostic imaging, such as cardiovascular and thoracic abnormalities, emphysema, hemothorax, or cardiopulmonary resuscitation (Henschke et al., 1997; Graat et al., 2006). The mobile X-ray equipment is often used in general infirmary, intensive care units and surgery rooms. When the mobile X-ray machine is used, the radiation protection must be enforced for the general public and radiation workers (Bhagwanjee and Muckart, 1996; Trotman-Dickenson, 2003; Simpson et al., 1998).

The use of mobile X-ray equipment is well established in hospitals. Moreover, there are already protocols for securing the quality of service in relation to the dose and image quality (Tuohy et al., 1995). There are several studies about the radiation doses

* Corresponding author.
E-mail address: santosfa@outlook.com (F.A. Santos).

http://dx.doi.org/10.1016/j.radmeas.2016.03.005
1350-4487/

Table 1
Variations of scenarios in this work.

Examinations type	Irradiation field (cm^2)	Voltage (kVp)	Distance between phantoms (cm)
Chest/Abdomen	Ideal 35 × 43 and Extrapolated 55 × 55	60	50/100/150/200
		70	50/100/150/200
		80	50/100/150/200
		90	50/100/150/200
		100	50/100/150/200

related to the use of the mobile X-ray equipment in hospital infirmaries (Burrage et al., 2003; Smans et al., 2008; Santos and Maia, 2012) but everything that has been made until now related to these studies is experimental. A study with chest examination simulation was developed with an acrylic phantom in a Brazilian hospital. The results show that for most cases the professional who follows recommendations of radioprotection remains with values of effective dose below the recommended limits (Santos and Maia, 2012). Computer simulations, through the Monte Carlo method, have been used in some works in the radiodiagnostic area, mainly in interventional radiology (IR) (Mah et al., 2011; Clairand et al., 2008; Jarvinen et al., 2008; McCafrey et al., 2012; Koukorava et al., 2014; Santos et al., 2014). However, these works use Monte Carlo Method to simulate beams in IR (Mah et al., 2011), for estimating doses in dosimeters and for comparing with the experimental methods (Clairand et al., 2008; Jarvinen et al., 2008), in order to evaluate types of materials that are used to ensure the security levels for procedures using high temporal resolution (McCaffrey et al., 2012). Some papers seek to produce a real scenario in IR irradiation (Koukarava et al., 2014; Santos et al., 2014).

Direct measurements of dose in organs and tissues are very complicated, and in most cases, impossible to be performed. There are some alternatives to solving this problem, like the use of physical anthropomorphic phantoms that allow the insertion of detectors for direct measurement of dose in organs (Cerqueira et al., 2011), or the estimated doses through computer simulation. In such cases the most common technique is the Monte Carlo method (MC), which uses a computational anthropomorphic phantom to represent the individual exposed (Santos et al., 2014). The creation of more realistic scenarios provides the acquisition of dose values in typical situations where the patient, professional and public individuals were exposed. Because of MC method and the advent of computers, the use of this technique has become more accessible in Medical Physics (Yorijaz, 2009). By knowing that an accurate calculation of radiation doses is a difficult task to be experimentally achieved, the use of MC simulation proved to be adequate to estimating the absorbed doses in organs and tissues of patients and public individuals.

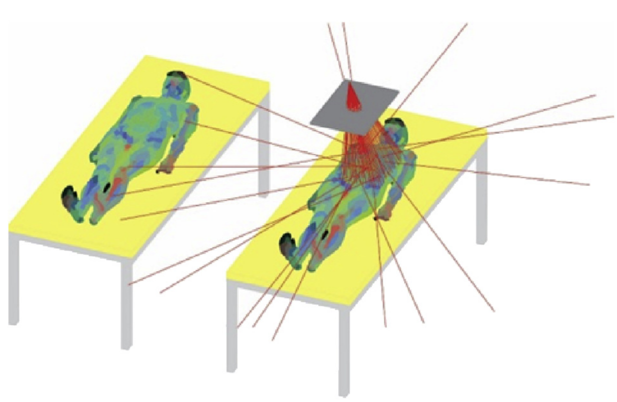

Fig. 1. Viewing example of the computer scenario.

The establishment of radiation protection and radiation safety with the use of mobile X-ray equipment is the main focus of our study. In this sense, this research aims to creating a real computational scenario for the practice of radiographic examinations performed in an infirmary using a pair of anthropomorphic computer simulators (patient and individual public). The goal is to estimate conversion coefficients (CCs) for effective dose (E) normalized to entrance surface dose (ESD) in a patient during chest and abdomen examinations for an ideal and an extrapolated field of irradiation. Additionally, we evaluated the influence of these procedures in CCs to public individuals that are restrained to a bed close to the examination equipment.

2. Materials and methods

The radiation transport code used was the MCNPX 2.7.0 (Pelowitz, 2011). This code can handle the transport and interaction of neutrons, photons, electrons and many other particles in a wide range of energies. Through this code it is possible to model complex irradiation scenarios and to achieve important applications in medical physics, as this area needs highly detailed scenarios in order to represent a rather realistic situation for the radiation exposure. The scenarios generated aimed to reproducing a typical scenario of radiological examinations that are performed in hospital beds, and for this purpose, two standard anthropomorphic phantoms (AM - Adult Male and AF – Adult Female) of ICRP 110 were used to calculate the effective dose (ICRP, 2009). In order to accomplish the duplication of the AM and AF reference phantom, the number of identification numbers (ID's) were reduced using the ImageJ (ImageJDisclaimer, 2004) software. This simplification was based on different ID's belonging to the same material. For example, the phantom had one ID for the left lung and another one for the right lung, but the simplified anthropomorphic phantoms used in this study possessed an ID for the entire lung. After the simplification the duplication of the phantom was performed using the same software. By modifying the IDs, a phantom with the same anatomical features of the original, but with different IDs, was generated. After simplification and duplication of the phantoms, they were converted into repeated structures and inserted in the form of an input file of the MCNPX code. In relation to the objects of the irradiation scenario, beds with polyurethane foam mattresses (density = 0.021 g/cm^3, composition: H (4.1%), C (54.4%), N (12.1%), O (29.4%)) and brackets stainless steel 302 (density = 7.86 g/cm^3, composition: C (0.140%), Si (0.930%), P (0.042%), S (0.028%), Cr (18%), Mn (1.860%), Fe (70%), Ni (9%)) were introduced (Mcconn et al., 2011).

In order to develop a realistic collimation system of the X-ray tube, a lead plate with a square section in the middle was created. For dealing with situations commonly found in these environments, different scenarios were elaborated. Simulations were made for examinations of the chest and abdomen considering and for each exam an ideally collimated field (IF) and an extrapolated field (EF). The technical parameters used in the computational simulation were obtained from the literature: peak voltages of 60–100 kVp at 10 kVp intervals, anode angle of 17°, tungsten

Table 2
Conversion coefficients of effective dose per entrance surface dose to patient as a function of the type of examination and tube voltage.

Irradiation field	Voltage (kVp)	E/ESD (mSv/mGy)											
		Chest			Abdômen			Chest			Abdômen		
		Male	Female	Average	Male	Female	Average	Male	Female	Averag	Male	Female	Average
Ideal (IF)	60	0.27	0.06%	0.28	0.07%	0.28	0.05%	0.65	0.07%	0.70	0.06%	0.67	0.05%
	70	0.29	0.06%	0.31	0.06%	0.30	0.05%	0.69	0.07%	0.76	0.06%	0.72	0.05%
	80	0.30	0.07%	0.33	0.06%	0.32	0.05%	0.71	0.07%	0.80	0.06%	0.76	0.05%
	90	0.32	0.06%	0.36	0.06%	0.34	0.05%	0.73	0.06%	0.83	0.06%	0.78	0.05%
	100	0.35	0.06%	0.40	0.06%	0.38	0.05%	0.74	0.06%	0.87	0.06%	0.80	0.05%
Extrapolated (EF)	60	0.43	0.07%	0.46	0.07%	0.44	0.05%	0.69	0.07%	0.75	0.07%	0.72	0.05%
	70	0.46	0.07%	0.50	0.06%	0.48	0.05%	0.73	0.07%	0.82	0.07%	0.77	0.05%
	80	0.49	0.07%	0.54	0.07%	0.51	0.05%	0.76	0.07%	0.87	0.07%	0.81	0.05%
	90	0.52	0.06%	0.59	0.06%	0.56	0.05%	0.79	0.06%	0.90	0.07%	0.85	0.05%
	100	0.57	0.06%	0.67	0.06%	0.62	0.05%	0.80	0.06%	0.96	0.06%	0.88	0.05%

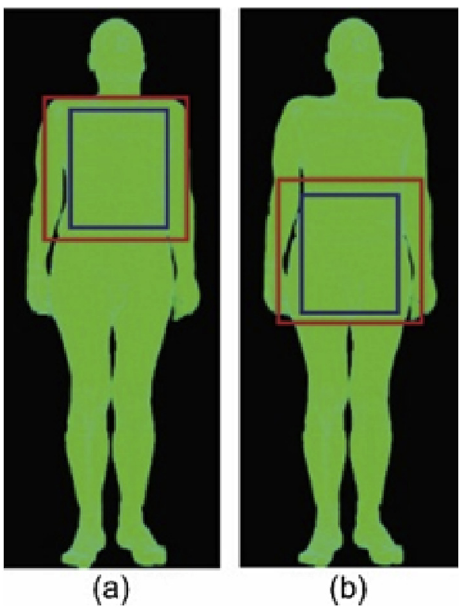

Fig. 2. Irradiation fields of (a) examination of the chest and (b) examination of the abdomen.

target material and beam filtration of 2.5 mm Al. Additionally, the FSD (Focus Skin Distance) was 90 cm and the patient was irradiated in AP projection. The spectra were generated using the software SPECGEN (Tucker et al., 1991). Besides these parameters, others information of the simulation procedures are presented in Table 1.

Fig. 1 shows a three-dimensional representation of the processed scenarios. The patient is the phantom that receives the primary beam and needs examination. The phantom beside the patient was regarded as an individual of the public, that is, the one that receives the scattered radiation from the patient examination. For each irradiation field and applied voltage, the distances between the phantoms (50, 100, 150 and 200 cm) were varied. The values of 50–200 cm are the distances between the patient's right arm to the left arm of the public individual.

In order to calculate the conversion coefficients (CC_E) to effective dose (E) per entrance surface dose (ESD) a scenario without anthropomorphic phantoms was created. In such simulation a beam of radiation strikes an atmospheric air cell of 6 cm^3 placed at the same position of the patient. The effective dose values calculated in this work were normalized by the air absorbed dose in the air cell multiplied by backscatter factor of 1.4 to calculate ESD (Henriques et al., 2014). Thus, by calculating the conversion coefficients and the experimental measurement of ESD at the same conditions of these scenarios, it is possible to evaluate the effective dose and the possible damage related to this practice. The calculation of radiation doses to the patient and public individuals organs were made using the MCNPX tally *F8. For each set of cells (representing organs or tissues) in which the *F8 command was used, a value that represents the total energy (in MeV) deposited was given. For the calculation of air absorbed doses in the cells the F6 tally was used. This measure provides the total energy divided by the mass of the cell (MeV/g) and is used for conditions of electronic equilibrium. The values of cut-off energy to photons and electrons, cross-section, type of interaction and variance reduction technique were kept in their MCNPX default values. In all the simulations an i7 processor with 2.8 GHz and 6 GB of RAM computer was used. We took 24 h to render each scenario irradiation considering 100 million (10^8) runs.

3. Results and discussions

In this study, the CC_E (E/ESD) calculated from examinations of the chest and abdomen irradiation field for patient and public individual using mobile X-ray equipment in hospital room were obtained. The CC_E to patients are presented in Table 2.

The highest values of CC_E in abdomen scenarios are due to the most relevant organs for the calculation of effective dose are in this region of examination, as the large intestine, stomach, gonads, bladder, liver and thyroid. In diagnostic examinations which involve the use of ionizing radiation it is recommended to optimize examination to the maximum. For this purpose, in the present study, the irradiation field was varied to evaluate the CC_E considering the case of an ideal collimated radiation field and the case of an extrapolated field. Fig. 2 shows the regions of the primary beam collimated to the patient phantom. In this Figure, the difference between the ideal field (IF), the minimum field, and the extrapolated field (EF), the larger one, is presented. The dimensions of the fields correspond to the dimensions of the image device sensitive area behind the patient.

Table 3
Percentage increase of the conversion coefficients for effective. dose (E/ESD) in examinations of the abdomen and chest.

Examinations	Tube voltage (kVp)				
	60	70	80	90	100
Abdomen	6.6%	7.4%	7.7%	8.2%	9.6%
Chest	60.3%	61.1%	62.2%	62.9%	64.5%

Table 4
Other works in the literature.

	Tube voltage (kVp)	E/ESD (mSv/mGy)
Rill et al., 2003 – chest	60–99	0.14
Paydar et al., 2011 – chest	66–110	0.15
Lee et al., 2005 – chest	92–132	0.23
Lee et al., 2005 – abdomen	70–90	0.18

Table 3 shows the percentage increase in the CC_E due to the change of the irradiation field.

The increases in the CC_E for the patient due to increase in the field of view were expected, because a larger area of the phantom is achieved by direct beam, and more X-ray photons deposit energy in parts of the phantom which were previously not affected. The extrapolation of the field shows an average increase in the CC_E of 7.9% in examinations of the abdomen and 62.2% in examinations of the chest. This difference percentage between these two examinations is justified because, although the CC_E in examinations of the abdomen are larger, the extrapolation of the field in chest examinations affect more radiosensitive tissues, which did not occur in the ideal field. For examinations of the abdomen, the extrapolation promotes a lower percentage increase in CC_E because most radiosensitive organs are already being affected by the direct beam radiation, even with an ideal collimated field. It causes only damage to the patient with no benefit in enhancing image quality. Thus, the basic principle of optimization of radiation protection, which says that the practice should seek to reduce the radiation dose as much as possible, is not being fulfilled in this type of procedure.

Comparison with other studies in the literature is not easy. Many studies estimate the effective dose without calculating ESD, or vice versa. Nevertheless, a few papers relating both quantities for examinations in patients. The Table 4 shows average values of E/ESD obtained from these papers.

In this work, the average E/ESD to patient was 0.32 mSv/mGy (IF- chest examination), 0.52 (0.32 mSv/mGy (EF- chest examination), 0.75 (IF- abdomen examination) and 0.81 (EF- abdomen examination).

This difference regarding to literature values is due to differences between simulators used and the realism of scenarios. In general, the presented studies use mathematical simulators or hermaphrodite whereas this work uses the references anthropomorphic simulators of ICRP 110. Besides, this work contains a pair of simulators in the same scenario and a table that promotes backscatter. In the literature works, the absence of other simulator and objects in the scenarios contribute to differences in effective doses.

Table 5
Percentage increase in CC_E between the IF and the EF inpublic individual of the chest and abdomen examinations.

Tube Voltage (kVp)	Distance (cm)	Percentual increase (%)	
		Chest	Abdomen
60	50	73.4	75.5
	100	73.2	83.4
	150	68.8	67.9
	200	67.9	72.9
70	50	74.6	75.1
	100	74.9	72.3
	150	68.8	66.0
	200	69.2	63.2
80	50	74.8	79.8
	100	74.7	68.3
	150	68.3	71.2
	200	67.1	65.4
90	50	76.9	77.8
	100	76.9	72.7
	150	71.5	67.3
	200	68.4	61.1
100	50	75.5	73.9
	100	76.6	67.4
	150	72.3	66.5
	200	71.9	64.8

For calculating the CC_E in public individual it is important to analyze the influence on the increase of the irradiation field and the differences in the results. The behavior of the CC_E for the public individual can be seen in Fig. 3. The graphs were elaborated from the CC_E depending on distance and examination type. The results for public individuals are in appendix A. It shows all CC_E's to AM, AF, the effective dose as mean value and all the uncertainties calculated in simulations. CC_E's obtained in this study present errors lower than 10% (see Table 2 and Appendix A). The Monte Carlo method provides reliability in their simulations when the coefficient of variation is less than 10% (Briesmeister, 1986).

From the graphs of Fig. 3, it can be seen that the curves EF are shifted to higher energy values. This increase in the CC_E of the public individual is attributed to the increase in scattering, due to the increased scattering center as can be seen in Fig. 2. From Table 5 it is possible to verify the increase in the CC_E for public individual.

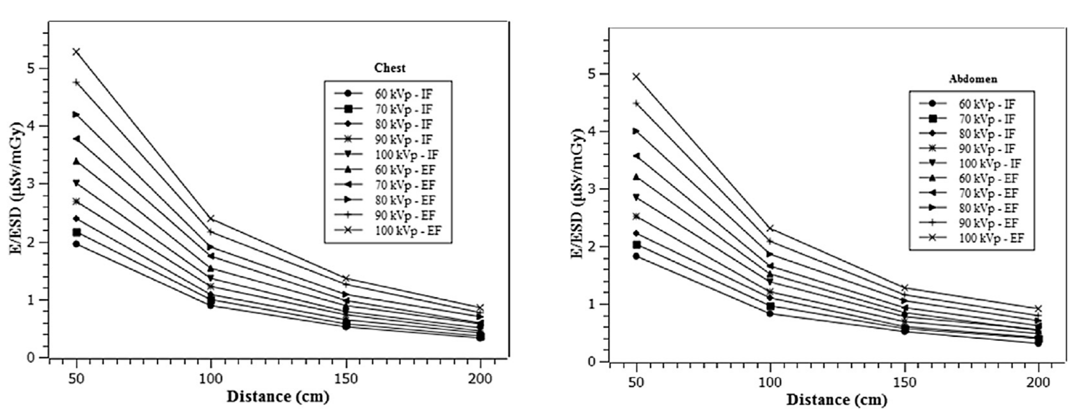

Fig. 3. CC_E to the public individual from chest and abdomen examinations.

Due to the increase in the irradiation field, the assessment of the percentage increase in the CC_E dose becomes even more relevant, because the public individual also receives a higher dose. By analyzing the percentage differences between the IF and the EF for public individuals, and considering the closest position to the patient (50 cm), the average increase of was 72.3% for chest, and 70.6% for abdomen examinations.

Analyzing the average CC_E calculated for public individual in this work is possible also observe the importance of the distance between the patient and the public individual in infirmaries. In relation to the public individual that is 50 cm from the patient in the chest and abdomen examination, there is a reduction of 54.5% (chest) and 52.8% (abdomen). To the public individual at 150 cm, the reduction is 73.7% (chest) and 72.3% (abdomen). To the public individual at 200 cm, the reductions in CC_E's are 83.4% (chest) and 81.7% (abdomen).

4. Conclusion

For patients the average percentage difference in the conversion coefficients for effective dose calculated between the ideal and extrapolated field was 7.9% for abdomen and 62.3% for chest examinations. For public individuals, the extrapolation of the field also results in an increase of CC_E. For abdomen and chest examinations we obtained 70.6% and 72.3% of increase, respectively. With this, the need for optimization of field size collimation during the examination becomes even more relevant since in both patient and public individual a high dose increase is observed due to the extrapolation of the field. With respect to the values of CC_E to the public individual positioned at 200 cm and at 50 cm the work revealed that at a distance of 200 cm, the CC_E is reduced on average 81.7% to abdomen examination and 83.4% to chest examination. For environments where there is no possibility of maintaining an appropriate distance between the patient and the public individual, the use of mobile barriers can be adopted to ensure the safety levels of the locations. The conversion coefficients in this work were calculated to make practical the conversion between entrance surface dose and effective dose. In this way the values of effective dose and the possible damage caused by ionizing radiation can both be better estimated, making possible to take appropriate action based on the reference values for effective dose.

Acknowledgments

We would like to thank the Higher Education Personnel Training Coordination (CAPES) and National Institute of Science and Technology (INCT) for their support financial.

Appendix A

Table A.1
Conversion coefficients of effective dose (E) per entrance surface dose (ESD) to public individuals to chest examination.

Irradiation field	Voltage (kVp)	Chest - E/ESD (μSv/mGy)											
		50 cm			100 cm			150 cm			200 cm		
		Male	Female	Average	Male	Female	Average	Male	Female	Average	Male	Female	Average
Ideal (IF)	60	1.75 1.01%	2.16 1.43%	1.95 0.91%	0.80 1.37%	0.97 1.96%	0.89 1.24%	0.48 1.88%	0.57 2.38%	0.53 1.55%	0.31 2.45%	0.36 2.42%	0.34 1.73%
	70	1.93 1.00%	2.39 1.40%	2.16 0.90%	0.89 1.42%	1.10 1.90%	1.00 1.23%	0.51 1.93%	0.63 2.29%	0.57 1.53%	0.33 2.48%	0.39 2.30%	0.36 1.69%
	80	2.12 1.04%	2.68 1.42%	2.40 0.92%	0.98 1.51%	1.19 1.93%	1.08 1.26%	0.56 2.07%	0.72 2.33%	0.64 1.59%	0.38 2.22%	0.45 2.36%	0.42 1.63%
	90	2.35 1.02%	3.04 1.46%	2.69 0.94%	1.09 1.43%	1.36 2.01%	1.23 1.28%	0.64 1.96%	0.81 2.38%	0.73 1.58%	0.42 2.38%	0.49 2.48%	0.46 1.73%
	100	2.68 1.02%	3.32 1.56%	3.00 0.98%	1.20 1.45%	1.52 2.13%	1.36 1.35%	0.69 1.99%	0.89 2.57%	0.79 1.69%	0.44 2.36%	0.55 2.65%	0.50 1.81%
Extrapolated (EF)	60	3.12 0.77%	3.65 1.13%	3.39 0.70%	1.40 1.12%	1.67 1.52%	1.54 0.97%	0.83 1.44%	0.95 1.78%	0.89 1.17%	0.52 1.82%	0.62 1.87%	0.57 1.31%
	70	3.44 0.77%	4.11 1.09%	3.77 0.69%	1.59 1.10%	1.89 1.41%	1.74 0.92%	0.87 1.48%	1.07 1.71%	0.97 1.15%	0.55 1.87%	0.66 1.81%	0.60 1.30%
	80	3.70 0.79%	4.69 1.11%	4.20 0.71%	1.70 1.14%	2.09 1.46%	1.90 0.95%	0.95 1.55%	1.22 1.75%	1.08 1.19%	0.63 1.74%	0.77 1.84%	0.70 1.28%
	90	4.12 0.78%	5.41 1.16%	4.76 0.74%	1.91 1.12%	2.42 1.55%	2.17 1.00%	1.10 1.49%	1.39 1.81%	1.25 1.21%	0.70 1.81%	0.84 1.88%	0.77 1.31%
	100	4.50 0.78%	6.03 1.22%	5.27 0.77%	2.06 1.12%	2.74 1.63%	2.40 1.05%	1.18 1.51%	1.54 1.95%	1.36 1.28%	0.77 1.80%	0.94 1.95%	0.85 1.35%

Table A.2
Conversion coefficients of effective dose (E) per entrance surface dose (ESD) to public individuals to abdomen examination.

Irradiation field	Voltage (kVp)	Abdomen - E/ESD (μSv/mGy)											
		50 cm			100 cm			150 cm			200 cm		
		Male	Female	Average	Male	Female	Average	Male	Female	Average	Male	Female	Average
Ideal (IF)	60	1.66 0.97%	1.99 1.46%	1.83 0.91%	0.76 1.45%	0.89 1.89%	0.83 1.22%	0.46 1.92%	0.55 2.45%	0.51 1.59%	0.29 2.34%	0.34 2.59%	0.31 1.77%
	70	1.86 0.92%	2.23 1.33%	2.04 0.84%	0.86 1.48%	1.07 1.83%	0.96 1.21%	0.52 1.88%	0.62 2.40%	0.57 1.56%	0.35 2.53%	0.42 2.51%	0.39 1.79%
	80	2.02 0.95%	2.44 1.40%	2.23 0.88%	0.98 1.46%	1.24 1.86%	1.11 1.22%	0.56 1.88%	0.67 2.43%	0.61 1.58%	0.38 2.40%	0.46 2.55%	0.42 1.77%
	90	2.28 0.95%	2.77 1.47%	2.52 0.91%	1.09 1.46%	1.32 1.92%	1.21 1.24%	0.62 1.89%	0.76 2.53%	0.69 1.63%	0.45 2.42%	0.54 2.69%	0.49 1.84%
	100	2.56 0.94%	3.13 1.59%	2.85 0.97%	1.25 1.46%	1.52 2.09%	1.38 1.32%	0.69 1.90%	0.85 2.76%	0.77 1.74%	0.50 2.45%	0.60 2.81%	0.55 1.90%
Extrapolated (EF)	60	2.86 0.71%	3.55 1.12%	3.21 0.69%	1.36 1.09%	1.68 1.47%	1.52 0.95%	0.77 1.44%	0.94 1.86%	0.85 1.21%	0.48 1.78%	0.60 1.98%	0.54 1.36%
	70	3.15 0.71%	4.01 1.11%	3.58 0.69%	1.49 1.11%	1.82 1.42%	1.66 0.93%	0.85 1.43%	1.04 1.70%	0.94 1.14%	0.56 1.91%	0.71 1.83%	0.63 1.32%
	80	3.49 0.73%	4.52 1.11%	4.01 0.70%	1.66 1.11%	2.07 1.45%	1.87 0.94%	0.94 1.48%	1.15 1.78%	1.05 1.19%	0.62 1.86%	0.77 1.90%	0.70 1.34%
	90	3.92 0.72%	5.05 1.17%	4.48 0.73%	1.86 1.10%	2.31 1.56%	2.09 0.99%	1.04 1.45%	1.27 1.87%	1.16 1.22%	0.71 1.85%	0.88 1.96%	0.80 1.36%
	100	4.38 0.75%	5.52 1.25%	4.95 0.77%	2.04 1.14%	2.58 1.62%	2.31 1.04%	1.15 1.49%	1.40 1.96%	1.28 1.27%	0.81 1.88%	1.01 2.10%	0.91 1.44%

References

Bhagwanjee, S., Muckart, D.J., 1996. Routine daily chest radiography is not indicated for ventilated patients in a surgical ICU. Intensive Care Med. 22, 1335–1338.

Briesmeister, J.F., 1986. MCNP – a General Monte Carlo Code for Neutron and Photon. Los Alamos National Laboratory, LA, p. 7396.

Burrage, J.W., Rampant, P.L., Beeson, B.P., 2003. Scatter and transmission doses from several pediatric X-ray examinations in a nursery. Pediatr. Radiol. 33, 704–708.

Cerqueira, R.A.D., Conceição, B.M., Teixeira, C.H.C., Mota, C.D., Rodrigues, T.M.A., Maia, A.F., 2011. Development of an anthropomorphic thorax phantom for image quality control measurements in diagnostic radiology. Rev. Bras. Fis. Med. 4, 39–42.

Clairand, I., Struelens, L., Bordy, J., Daures, J., Debroas, J., Denozières, M., Donadille, L., Gouriou, J., Itié, C., Vaz, P., d'Errico, F., 2008. Intercomparison of active personal dosemeters in interventional radiolog. Radiat. Prot. Dosim. 129, 340–345.

Graat, M.E., Choi, G., Wolthuis, E.K., Korevaar, J.C., Spronk, P.E., Stoker, J., Vroom, M.B., Schultz, M.J., 2006. The clinical value of daily-routine chest radiographs in a mixed medical-surgical intensive care unit is low. Crit. Care 10, R11.

Henriques, L.M.S., Cerqueira, R.A.D., Santos, W.S., Pereira, A.J.S., Rodrigues, T.M.A., Carvalho Júnior, A.B., Maia, A.F., 2014. Characterization of an anthropomorphic chest phantom for dose measurements in radiology beams. Radiat. Phys. Chem. 95, 296–298.

Henschke, C.I., Yankelevitz, D.F., Wand, A., Davis, S.D., Shiau, M., 1997. Chest radiography in the ICU. Clin. Imaging 21, 90–103.

Publication 110 ICRP, 2009. International Commission on Radiological Protection Adult Reference Computational Phantoms.

ImageJDisclaimer, 2004 . Last Acess: dez/2015. Available in: http://rsbweb.nih.gov/ij/disclaimer.html.

Jarvinen, H., Buls, N., Clerinx, P., Miljanic, S., Nikodemová, D., Ranogajec-Komor, M., Struelens, L., d'Errico, F., 2008. Comparison of double dosimetry algorithms for estimating the effective dose in occupational dosimetry of interventional radiology staff. Radiat. Prot. Dosim. 131, 80–86.

Koukorava, C., Farah, J., Struelens, L., Clairand, I., Donadille, L., Vanhavere, F., Dimitriou, P., 2014. Efficiency of radiation protection equipment in interventional radiology: a systematic Monte Carlo study of eye lens and whole body doses. J. Radiol. Prot. 34, 509–528.

Lee, S.C., Wang, J.N., Liu, S.C., Jiang, S.H., 2005. Effective dose evaluation for chest and abdomen X-ray tests. Radiat. Prot. Dosim. 116, 613–619.

Mah, E., He, W., Huda, W., Yao, H., Selby, B., 2011. Monte Carlo modeling of the scatter radiation doses in IR. Med. Imaging 2011:Physics Med. Imaging 7961, 79613H-1-H-11.

McCaffrey, J.P., Tessier, F., Shen, H., 2012. Radiation shielding materials and radiation scatter effects for interventional radiology (IR) physicians. Med. Phys. 39, 4537–4548.

Mcconn, R.J., Gesh, C.J., Pagh, R.T., Rucker, R.A., Williams, R.G., 2011. Compendium of Material Composition Data for Radiation Transport Modeling. Pacific Northwest National Laboratory.

Paydar, R., Takavar, A., Kardan, M.R., Babakhani, A., Deevband, M.R., Saber, S., 2012. Patient effective dose evaluation for chest X-ray examination in three digital radiography centers. Iran. J. Radiat. Res. 10, 139–143.

Pelowitz, D.B., 2011. MCNPX User's Manual. Los Alamos Nacional Laboratory.

Rill, L.N., Brateman, L., Arreola, M., 2003. Evaluating radiographic parameters for mobile chest computed radiography: phantoms, image quality and effective dose. Med. Phys. 30, 2727–2735.

Santos, W.S., Maia, A.F., 2012. Evaluation of personal doses associated with the use of mobile X-rays in a Brazilian hospital. Radiat. Prot. Dosim. 150, 188–191.

Santos, W.S., Carvalho Júnior, A.B., Hunt, J.G., Maia, A.F., 2014. Using the Monte Carlo technique to calculate dose conversion coefficients for medical professionals in interventional radiology. Radiat. Phys. Chem. 95, 177–180.

Simpson, P.H., Martin, C.J., Darragh, C.L., Abel, R., 1998. A study of chest radiography with mobile X-ray units. Br. J. Radiol. 71, 640–645.

Smans, K., Struelens, L., Smet, M., Bosmans, H., Vanhavere, F., 2008. Patient dose in neonatal units. Radiat. Prot. Dosim. 131, 143–147.

Trotman-Dickenson, B., 2003. Radiology in the intensive care unit (Part I). J. Intensive Care Med. 18, 198–210.

Tucker, D.M., Barnes, G.T., Hakraborty, C.A., 1991. A semipirical model for generating tungsten target x-ray spectra. Med. Phys. 18, 211–218.

Tuohy, B., Tuohy, G., Cooney, P., Moran, B., Malone, J.F., 1995. Quality assurance programme applied to mobile X ray equipment. Radiat. Prot. Dosim. 57, 241–244.

Yorijaz, H., 2009. Monte Carlo method: principles and applications in medical physics. Rev. Bras. Fis. Med. 3, 141–149.