ANALYSIS OF DOSE AND RISK ASSOCIATED WITH THE USE OF TRANSMISSION X-RAYS BODY SCANNER USING MONTE CARLO SIMULATION

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Abstract
Aiming to reduce possible awkward situations arising from the process of searching visitors at Brazilian penitentiary units, the government has invested in the use of X-ray body scanners. Although the use of body scanners is relevant from the point of view of security in prison units, the use of such devices has an associated risk due to the use of ionizing radiation. Considering the foregoing, the proposal of this study was to conduct, through simulations with the Monte Carlo MCNPX code, an evaluation of the values of radiation doses received by visitors to the Penitentiary Complex of Nelson Hungria undergoing X-ray body scans. The absorbed dose and effective dose values obtained using simulations such as the Monte Carlo MCNPX code showed that the visitors receive dose values below the limits recommended for members of the public, thus showing that the use of these scanners can be an alternative to be used in place of pat-down and intimate searches on visitors.

Key words: body scanner, X-ray, MCNP, penitenciary, monte carlo

1. Introduction:

The entry of illegal items such as mobile phones, weapons and drugs is today one of the most severe and complex problems to be resolved in the Brazilian penitentiary system. To prevent the inflow of such objects, prison employees and visitors are submitted to a thorough pat-down search. If they are suspected of having concealed illegal items in their body cavities, there is also an intimate search.

With the purpose of reducing possible awkward situations arising from the search process, the Brazilian government has invested in the use of new technological solutions, of which one of the main ones has been the use of transmission x-ray body scanners, allowing users to identify objects concealed under the clothing and inside body cavities.

1.1 Transmission X-ray body scanner of the Penitentiary Complex of Nelson Hungria:

One of the first Brazilian prison units to use the x-ray body scanner instead of pat-down and intimate searches has been the Penitentiary Complex of Nelson Hungria, located in the state of Minas Gerais, in Brazil.

The x-ray body scanner installed in this prison unit allows employees to scan individuals by means of the transmission technique (Interagency Steering Committee on Radiation Standards, 2008). In this scanning system the x-rays cross the human body, similar to medical radiology, and the photons that emerge from the individual's body sensitize an imaging detector positioned diametrically opposite the radiation beam. These systems use narrow fan-shaped X-ray beams and a linear matrix of digital detectors to obtain the image. The main specifications of the equipment used at the Penitentiary Complex of Nelson Hungria are presented in Table 1.

Table 1. Specifications of the equipment used at the Penitentiary Complex of Nelson Hungria

Parameters	Specifications
manufactuturer	NuchtechCompanyLimited
Model	BI2002
Type of Scanner	Transmission X-ray body scanner
Serial Number	TFN CD III 10002
Scan Time	12 segundos
Beam Type	Estreito com colimação em leque
Voltage	95 kV(5,6 mA), 115 kV(5,7 mA) e 120 kV (5,8 mA)
Filtration	0,1 mm de Cu

To perform a scan at the Penitentiary Complex of Nelson Hungria, the individual is positioned in the antero-posterior (AP) projection, where he or she remains immobile while a narrow fan-shaped X-ray beam is moved vertically, as illustrated in Figure 1.

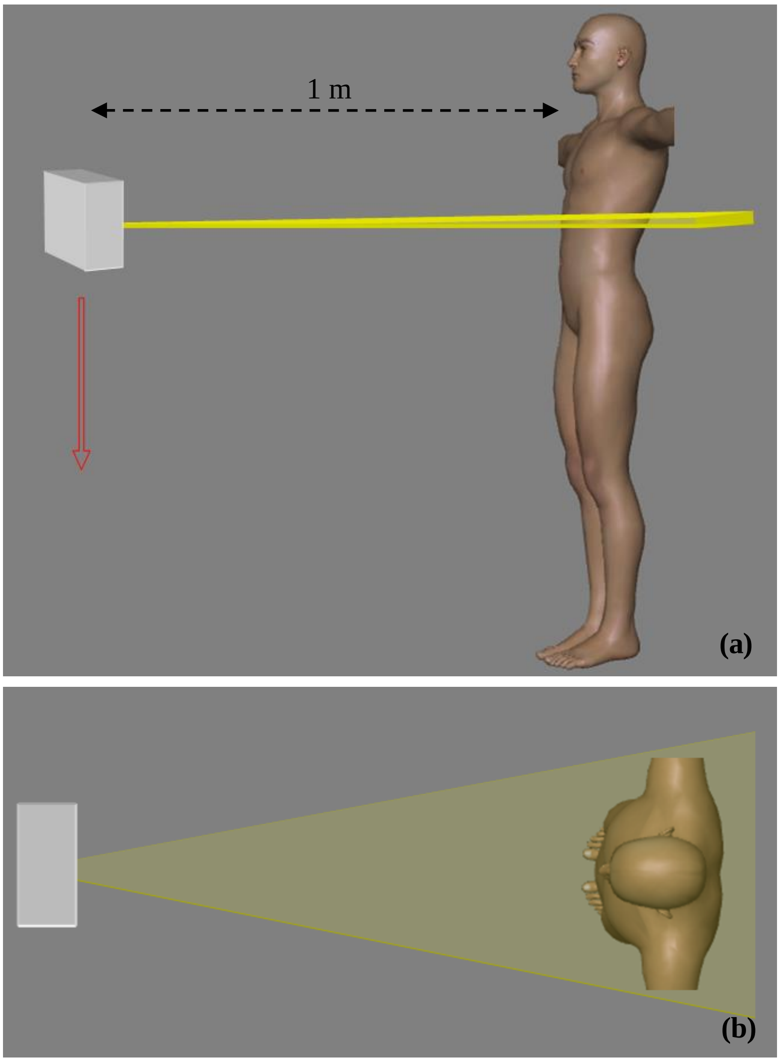


Figure 1: Scanning of individuals. In (a) lateral view of the scan and in (b) superior view of the scan.

Although the application of X-ray body scanners is relevant from the point of view of security at prison units, the use of such scanning devices involves a difficult and polemical decision by the authorities that needs to be made based on comprehensive and rigorous technical studies, especially as refers to the risk associated with the use of ionizing radiation as a security device in the screening of humans.

As regards the investigation of the potential health risks associated with the use of X-ray body scanners, until now few studies have been published in the literature presenting values of effective dose and ambient dose equivalent associated with these practices (Hupe and Ankerhold, 2006; Rez, Metzger and Mossman, 2010), and none of these provide estimates of values of doses absorbed in the organs of individuals.

Considering the foregoing, the aim of this study is to perform, through simulations with the Monte Carlo MCNPX code, an estimate of the radiation doses received by visitors to the Penitentiary Complex of Nelson Hungria, submitted to X-ray body scanning. The effective dose values provided in this study will be calculated using the International Commission on Radiological Protection (2007) and the male voxel MAX (Kramer et al., 2003), and female voxel FAX (Kramer et al., 2004) phantoms.

2. Computer Modeling

Computer modeling was carried out with the Monte Carlo MCNPX code, version 2.5 (Pelowitz, 2005). The male voxel MAX (Male AdultvoXel) and female voxel FAX (FemaleAdultvoXel) phantoms were used to represent the human body [Kramer et al., 2003, 2004]. The MAX and FAX phantoms are illustrated in Figure 2.

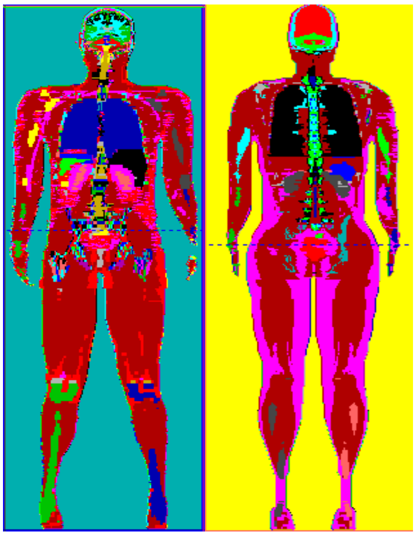
(a)  (b)

Figura 2: Voxel phantoms. In (a) MAX and in (b) FAX.

The parameters presented in Table 1 were adopted to model the X-ray beam of the Nutech BI 2002 body scanner.

The X-ray spectra used in the computer simulations were obtained through the spectrum generation software SRS-78 (Cranley et al., 1997). Figures 5 and 6 present the X-ray spectra and the radiation field used. The final radiation field was modeled so as to represent the radiation field incident on an individual during a complete scan. To obtain the final radiation field we simulated 338 fan-beam collimated point sources separated by a distance of 0.52 cm from one another, as shown in Figure 6 (a). During the modeling, all the radiation reaching the collimators was disregarded.

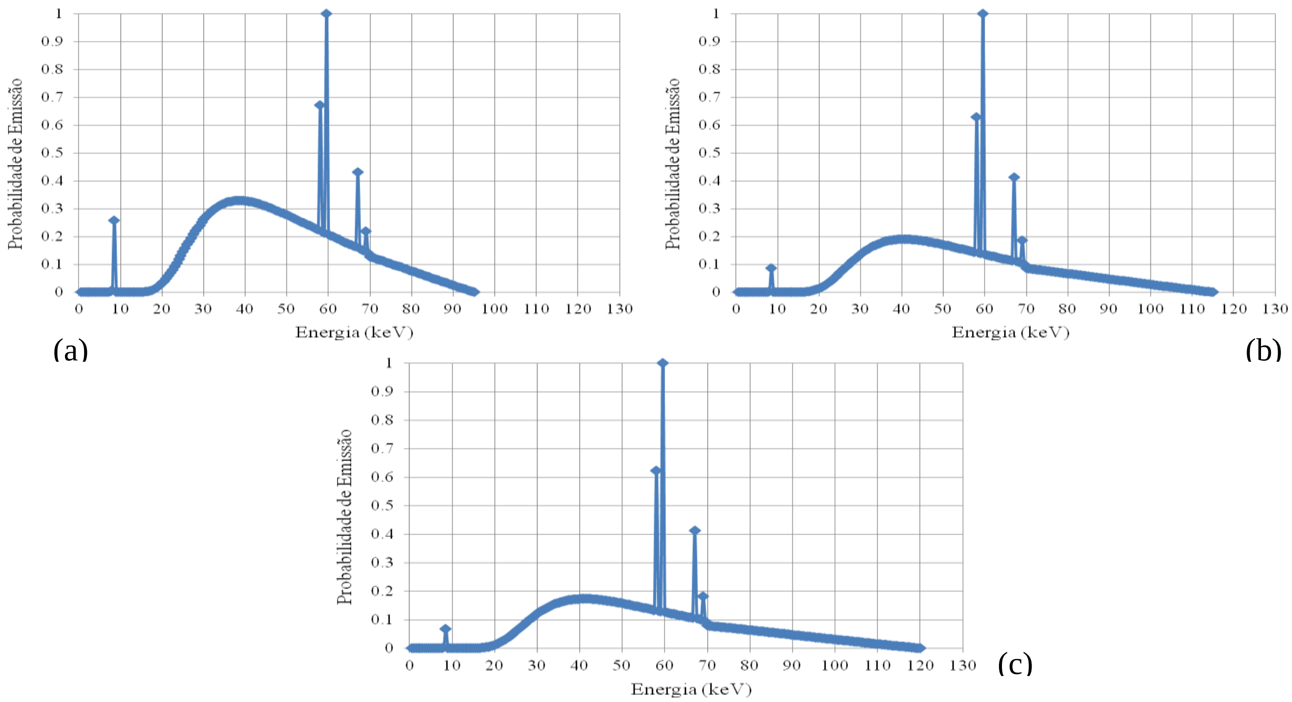


Figure 5:X-ray spectra used in the simulations obtained through the spectra generation software SRS-78. In (a) Spectrum obtained with 95 kV, in (b) Spectrum obtained with 115 kV and in (c)

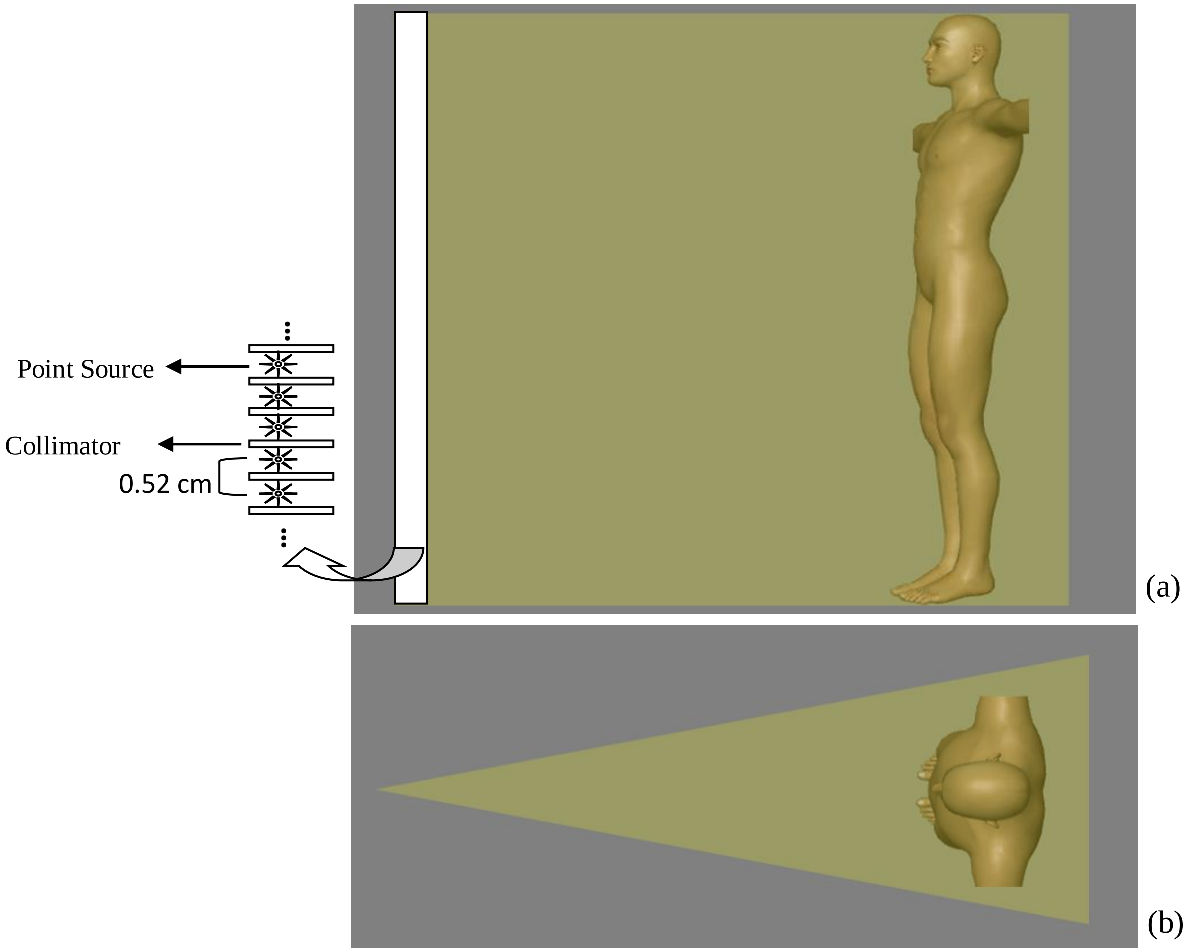


Figure 6: Radiation field used in the simulations. In (a) lateral view of the radiation field and in (b) superior view of the radiation field.

In this study we evaluated dose values considering individuals positioned at a distance of 1 meter from the radiation source in the antero-posterior projection.

2.1 CALCULATION OF THE ABSORBED DOSE

To estimate the dose absorbed in the organs of the scanned individuals, the energy deposited by radiation in the organs and tissues of the phantoms in voxels was obtained using the **F8* command of MCNPX. This command makes it possible to obtain the energy deposited in a set of voxels that form an organ or tissue of the phantoms. The obtainment of the absorbed dose was achieved by dividing the energy deposited in the organ or tissue by its respective mass value (m), according to the equations below (Correa et al., 2008; Correa et al., 2010):

$$D_T\,(\text{rads}) = \frac{*\,F8(\text{MeV})}{m}(1{,}602\text{x}10^{-6}\,\text{erg/MeV})\left(\frac{1}{100\text{erg/g/rad}}\right) \quad \textbf{(1)}$$

$$D_T\,(\text{rads}) = \frac{*\,F8}{m}1{,}602\text{x}10^{-8} \quad \textbf{(2)}$$

$$D_T\,(\text{Gy}) = \frac{*\,F8}{m}1{,}602\text{x}10^{-10} \quad \textbf{(3)}$$

where m is the mass of the organ or tissue for which we wish to estimate the absorbed dose.
The absorbed dose values (D_T) were normalized by the value of absorbed dose in the air (D_{ar}), thus calculating the normalized absorbed dose (D_n). To calculate the absorbed dose in the air we used tally F5 and fluency conversion factors for a dose of International Commission on Radiological Protection (1987).

2.2 EFFECTIVE DOSE CALCULATION

The effective dose was calculated following the recommendations of International Commission on Radiological Protection (2007) and using the absorbed dose values normalized. In International Commission on Radiological Protection (2007) the absorbed dose values are calculated considering the female anatomy and the male anatomy, according to the diagram illustrated in Figure 7.
The effective dose normalized by the absorbed dose in air, was calculated through the equation:

$$E_n = \sum_T w_T \left[\frac{H_{Tn}^M + H_{Tn}^F}{2}\right] \quad \textbf{(4)}$$

where w_T is a weighting factor provided by International Commission on Radiological Protection (2007) which introduces radiosensitivity for stochastic effects of organs or tissues, and H_{Tn}^M and H_{Tn}^F are the normalized equivalent dose values considering the male and female anatomy, respectively, defined as:

$$H_{Tn}^M = \sum_R \left(\frac{D_T^M}{D_{ar}}\right) w_R \qquad H_{Tn}^F = \sum_R \left(\frac{D_T^F}{D_{ar}}\right) w_R \quad \textbf{(5)}$$

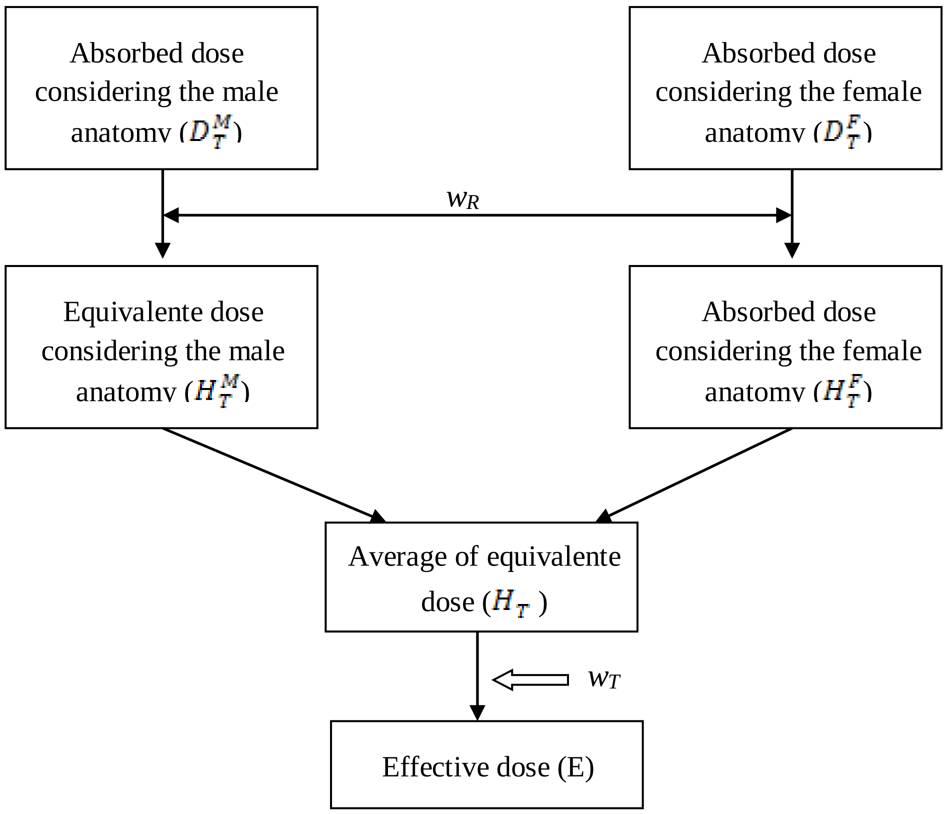


Figura 7: Diagram illustrating calculation of Effective Dose.

2.3 ESTIMATE OF THE ABSORBED AND EFFECTIVE DOSE DURING THE SCAN

The effective dose (E) and the dose absorbed in the organ (D) for a complete scan were obtained through Equations 6 and 7.

$$E(\mu Sv)=E_n.\boldsymbol{X} \quad \textbf{(6)}$$

$$D(\mu Sv)=D_n.\boldsymbol{X} \quad \textbf{(7)}$$

Where ***X*** is equivalent to the values of absorbed dose in the air during a complete scan, obtained experimentally through a Radcal Corporation model 9015 dose meter, with model 10x5-1800 ionization chamber.

To measure dose in the positioning of the scanned individual the ionization chamber was positioned in the center of the radiation beam at a height of 56 cm and at a distance of 1.00 m from the focal spot of the X-ray tube, as shown in Figure 3.

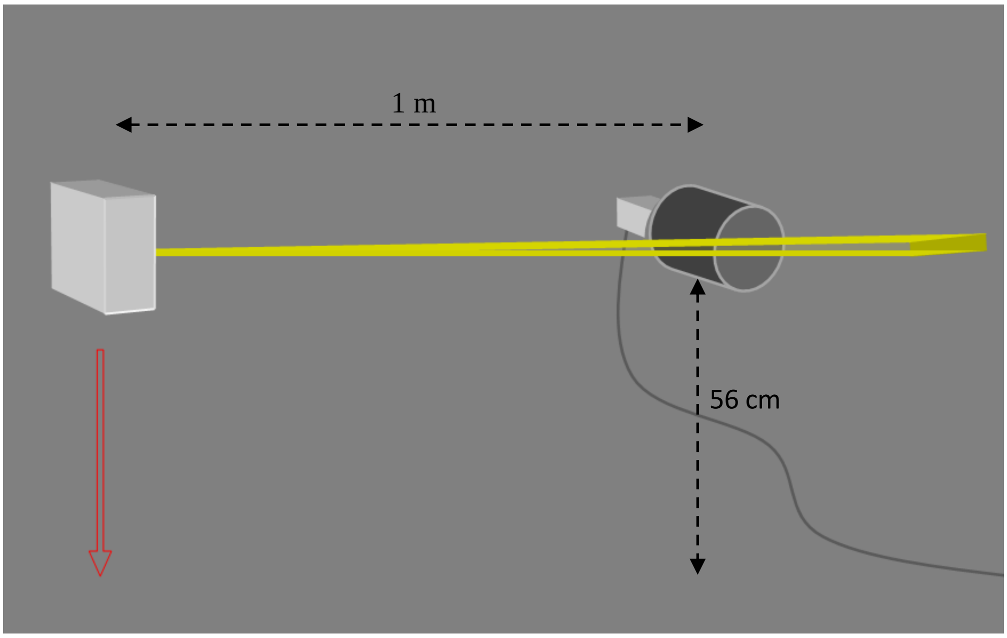


Figure 3: Positioning of the ionization chamber for performance of the dose measurements.

Air dose rate values were measured through the ionization chamber. These dose rate values were multiplied by the full scan time (12 seconds), providing the dose absorbed in the air. The values of dose rate and dose absorbed in the air in a scan are presented in Tables 2 and 3 respectively.

Table 2: Dose rate values measured during inspection of the Nutech BI2002 body scanner.

Local	**Taxa de dose (nGy/s)**		
	95 kV	**115 kV**	**120 kV**
Indivíduo escaneado	39.8±4.0	132.7±19.3	241.5±48.5

Table 3: Values of dose absorbed in the air during a 12-second scan in the Nutech BI 2002 body scanner.

Local	**Taxa de dose (μGy)**		
	95 kV	**115 kV**	**120 kV**
Indivíduo escaneado	0.48 ± 0.05	1.59 ± 0.23	2.9 ± 0.58

3.RESULTS

Tables 4 and 5 present the absorbed dose values in the organs and tissues obtained with the FAX and MAX voxel phantoms for a full 12-second scan.

Tabela 4: Absorbed dose obtained with the female phantom FAX.

Órgão	Dose absorvida (µGy)		
	95 kV	**115 kV**	**120 kV**
Bexiga	0.32	1.26	2.38
Cérebro	0.13	0.50	0.95
Cólon	0.34	1.31	2.45
Mama	0.43	1.56	2.91
Fígado	0.27	1.06	2.00
Pulmões	0.23	0.87	1.63
Esôfago	0.18	0.75	1.42
Testículo	0.25	0.98	1.89
Medula óssea	0.33	1.33	2.50
Pele	0.31	1.09	2.03
Estômago	0.33	1.30	2.44
Tireóide	0.40	1.49	2.78
Superfície óssea	0.41	1.56	2.91
Média do Corpo Inteiro	0.24	0.92	1.73
Restante	0.21	0.81	1.53

Tabela 5: Absorbed dose obtained with the female phantom MAX.

Órgão	Dose absorvida (µGy)		
	95 kV	**115 kV**	**120 kV**
Bexiga	0.29	1.15	2.19
Cérebro	0.12	0.48	0.90
Cólon	0.27	1.06	2.00
Fígado	0.22	0.87	1.64
Pulmões	0.23	0.92	1.74
Esôfago	0.18	0.73	1.40
Testículo	0.56	2.01	3.75
Medula óssea	0.38	1.49	2.82
Pele	0.29	1.04	1.93
Estômago	0.23	0.93	1.75
Tireóide	0.37	1.39	2.63
Superfície óssea	0.45	1.71	3.21
Média do Corpo Inteiro	0.25	0.97	1.82
Restante	0.21	0.80	1.50

Through Tables 4 and 5 it can be seen that the highest values of dose absorbed in the organs and tissues were received by individuals scanned with a radiation beam obtained with 120 kV.
As regards gender, the magnitudes of the absorbed doses do not exhibit major differentiation. It was also verified that the absorbed dose values in scanned individuals are below 3.5 µGy.
Table 6 presents the effective dose values obtained in this evaluation.

Tabela 6: Effective dose calculated according to ICRP 103.

Dose Efetiva (µSv)		
95 kV	**115 kV**	**120 kV**
0.28	1.06	2.00

Analyzing the effective dose values it was verified that the highest dose values were once again received by individuals scanned with a radiation beam generated with 120 kV. It was also observed that all the effective dose values were no higher than 2.00μSv. Comparing the effective dose values found in this evaluation with the values received by individuals submitted to chest radiodiagnosis exams, which are around 30 μSv (Ullman et al., 2006; Correa et al, 2008), it can be verified that the effective dose received by visitors to the Penitentiary Complex of Nelson Hungria is around 15 times lower than those received in chest examinations.
Through the results found in this evaluation it can also be verified that the values of absorbed dose and effective dose received by visitors are below the annual dose limits for members of the public of 1 mSv (International Commission on Radiological Protection, 1991). Taking the administrative control effective dose limit for members of the public of 0.250 mSv per year (for exposures arising from a single practice), recommended by NCRP (National Council on Radiation Protection and Measurements, 1993) as a reference, it is observed that it is possible to perform up to 125 scans without reaching the annual dose limit recommended by NCRP.
Considering that visits to the Penitentiary Complex of Nelson Hungria occur twice a week, it is verified that an assiduous visitor to the unit will receive no more than 0.208 mSv per year (considering that one year contains approximately 52 weeks), a value that is also below the annual administrative control effective dose limit recommended by NCRP.

4.CONCLUSION

The absorbed dose and effective dose values obtained using simulations such as the Monte Carlo MCNPX code showed that visitors to the Penitentiary Complex of Nelson Hungria receive dose values below the limits recommended for members of the public, thus showing that the use of X-ray body scanners can be an alternative for use in place of pat-down and intimate searches of visitors.
However, it is worth emphasizing that it is imperative to have this practice carried out under strict regulatory control, in order to guarantee that this equipment is operating appropriately, submitting any individuals exposed to low values of radiation exposure.

References

Correa, S.C.A., Souza, E.M., Silva, A.X., Yoriyaz, H. and Lopes, R. T. (2008) 'AP and PA Thorax Radiographs: Dose Evaluation using the FAX Phantom', *International Journal of Low Radiation*, Vol. 5 No. 3, pp.237-255

Correa, S.C.A., Souza, E.M., Silva, A.X., Yoriyaz, H. and Lopes, R. T. (2010) 'Dose and Risk Evaluation in Thoracic Radiology using Male and Female Voxels Phantoms', *International Journal of Low Radiation*, Vol. 7 No. 2, pp.81-97

Cranley, K., Gilmore, B.J., Fogarty, G.W.A. and Desponds, L. (1997) Catalogue of Diagnostic X-Ray Spectra and Other Data. Institute of Physics and Engineering in Medicine., IPEM Report 48, York, UK: Institute of Physics and Engennering in Medicine.

Hupe, O. and Ankerhold, U. (2006) 'Determination of Ambient and Personal Dose Equivalent for Personal and Cargo Security Screening', *Radiation Protection Dosimetry*, Vol. 121 No 4, pp.429-437.

International Commission on Radiological Protection. (1987) Data for Use in Protection Against External Radiation, ICRP Publication 51, Oxford: Pergamon Press.

International Commission on Radiological Protection. (1991) Recommendations of the International Commission on radiological protection. ICRP Publication 60, Oxford: Pergamon Press.

International Commission on Radiological Protection. (2003) Basic Anatomical and physiological data for use in radiological protection: reference values. ICRP Publication 89, Oxford: Pergamon Press.

International Commission on Radiological Protection. (2007) Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, Oxford: Pergamon Press.

Interagency Steering Committee on Radiation Standards. (2008) Guidance for Security Screening of Humans utilizing Ionizing Radiation. Report 2008-1, United States.

Kramer, R., Vieira, J.W., Khoury, H.J., Lima, F.R.A. and Fuelle, D. (2003) 'All about MAX: a Male Adult Xoxel Phantom for Monte Carlo Calculation in Radiation Protection Dosimetry', *Physics in Medicine and Biology*, Vol. 48, pp.1239-1262

Kramer, R., Khoury, H.J., Vieira, J.W., Loureiro, E.C.M., Lima, V.J.M., Lima, F.R.A. and Hoff, G. (2004) 'All about FAX: a Female Adult Xoxel Phantom for Monte Carlo Calculation in Radiation Protection Dosimetry', *Physics in Medicine and Biology*, Vol. 49, pp.5203-5216

Pelowitz, D.B. (2005) Ed. MCNPX^{TM} User's Manual. Version 2.5.0., Los Alamos National Laboratory report LA-CP-05-0369.

Ullman, G., Sandborg, M., Dance, D.R., Hunt, R.A., Carlsson, G.A. (2006). 'Towards Optimization in Digital Chest Radiography using Monte Carlo Modelling'. *Phys. Med. Biol.* Vol. 51, pp. 2729-2743.