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Radiology and mammography standard X-ray spectra simulated with the Monte Carlo method

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ABSTRACT

Six standard beams described in the TRS-457 (IAEA): RQR 5, 8, M1, M2, M3, M4 were simulated using the EGSnrc Monte Carlo code. Each spectrum was created by an X-ray tube simulated in BEAMnrc, and attenuation curves were obtained using the application egs_kerma. The quality of each beam was evaluated by the 1st and 2nd half-value layers, the homogeneity coefficients and the mean energies. All beams presented quality parameters compatible with those described in TRS-457 (IAEA).

Keywords: **EGSnrc, TRS-457, HVL.**

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1. INTRODUCTION

Ionizing radiation is found in several sectors of modern society, from scientific and industrial applications to the medical use, and it corresponds to a great improvement in the quality of life and services. An important medical application is the diagnostic radiology, a non-invasive imaging technique that has the potential to early detect several diseases.

Some examples of medical applications of ionizing radiation are the radiographs, computed tomography scans and the mammography, all using X-ray beams. Those techniques are largely applied because of their high diagnostic capacity. Mammography beams are usually produced by an X-ray tube with high voltage from 25 kV to 35 kV; radiography and computed tomography beams are produced using higher voltages, from 40 kV to 150 kV [1].

In order to produce radiation beams that are capable to deliver accurate results, all equipment should be tested and their quality ensured. To this end, the use of radiation detectors previously calibrated in certified laboratories is necessary [2]. Hospitals and clinics should periodically send their radiation detectors to certified laboratories that return the equipment calibrated depending on the energy at they are usually used.

The TRS-457 [1] is a document published by the International Atomic Energy Agency used for the implementation of X-ray beams in calibration laboratories. It presents standard characteristics for different series of radiation beams, including conventional radiology (RQR) and mammography (RQR M). Some of those characteristics are the high voltage applied in the tube, the half-value layers and the homogeneity coefficients. It is up to the laboratory to calibrate detectors in radiation beams with similar characteristics to the ones described in the TRS-457.

It is possible to simulate an X-ray tube and to test the performance of radiation detectors with the simulated spectra using the Monte Carlo method or other computational codes. Those simulations are also important before the construction of the radiation detector because the influence of certain materials may be evaluated in the project [3].

Recent published research papers demonstrate the use of Monte Carlo simulations to obtain X-ray spectra, to test radiation detectors or to perform dosimetry studies [4,5]; however, when a study aims to develop or characterize radiation detectors used in calibration laboratories, it is interesting to use simulated standard X-ray spectra, because the research involving these beams may improve the quality of the calibrations performed in laboratories [6].

The objective of this work was to simulate radiology and mammography standard radiation beams, following the quality parameters established in the TRS-457 [1], using the Monte Carlo code EGSnrc v2020 [7].

2. MATERIALS AND METHODS

The simulations were divided into two steps using the software included in the default installation package of EGSnrc: first, the radiation beams were simulated using the BEAMnrc [8] to obtain each spectrum; then the attenuation curve of each beam was obtained using egs_kerma [9]. All simulations were performed in a computer Intel® Core™ i3-5005U Dual CPU 2.00 GHz, and the time of each simulation was about 1 h to 3.5 h.

2.1. Simulation of the X-ray spectra

The BEAMnrc uses the EGSnrc code of radiation transport and allows the simulation of X-ray tubes with some input parameters, such as: the material of the anode, known as target; angulation of the target; additional filtration; and others.

An X-ray tube was simulated, with the objective to create X-ray beams with the quality parameters described in TRS-457. A cylindrical electron beam with radius of 0.1 cm was accelerated, in the vacuum, towards the target with an angulation of 11˚ for radiology beams and 15˚ for mammography beams. The X-ray beams were produced by the deacceleration of electrons (*Bremsstrahlung*) and by electron transitions in the anode (characteristic X-rays).

The following standard beams were simulated: RQR 5, RQR 8, RQR M1, RQR M2, RQR M3 and RQR M4. In the simulation of RQR 5 and 8 the target was of metallic tungsten, with density 19.3 g/cm^3, and the additional filtration was of metallic aluminum, with density 2.6989 g/cm^3. For the beams RQR M1, M2, M3 and M4 the anode and additional filtration were made with molybdenum, with density 10.22 g/cm^3. Filters were placed 4 cm distant from the target, and the space out of the X-ray tube was filled with air, with density 0.0012048 g/cm^3. The spectra were obtained from the planar fluence of photons normalized by the energy interval that are crossing a circle of 15 cm radius, in the air, and 75 cm distant from the target, using the BEAM Data Processor [10]. The incidence angle of photons was not considered in the calculation of fluence. Figure 1 shows a simulation scheme of the geometry used in BEAMnrc.

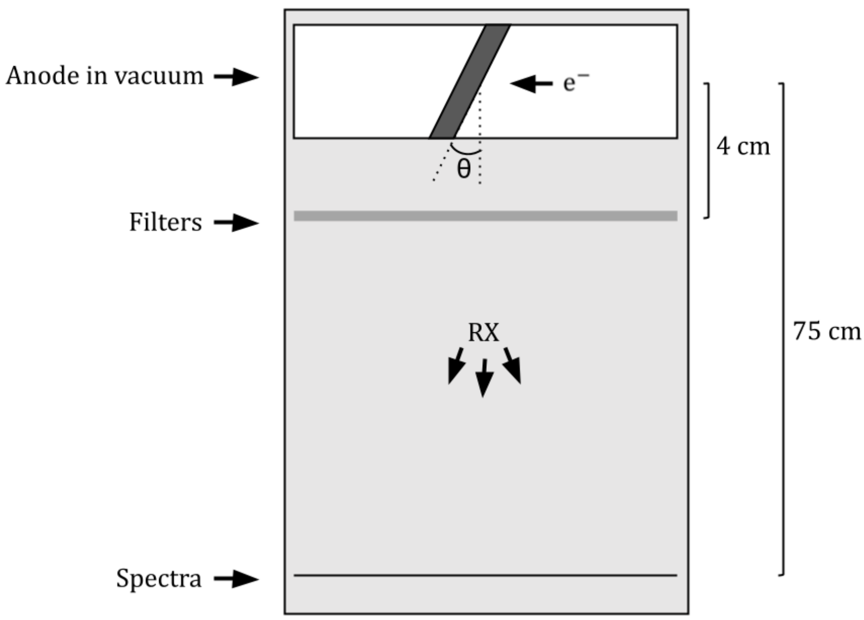

Figure 1: *Scheme of the simulations performed in the BEAMnrc. For the RQR spectra a tungsten anode with $\theta = 11^\circ$ and aluminum filters were used. For the RQR-M spectra a molybdenum anode with $\theta = 15^\circ$ and molybdenum filters were used.*

Every spectrum simulation was performed with $3x10^7$ histories, with photons and electrons being transported until the 1 keV energy threshold. The radiation transport parameters used in the simulations were the default configuration of BEAMnrc, with the following exceptions: the XCOM cross sections for the photoelectric effect and the NIST cross sections for Bremsstrahlung were used; Compton and Rayleigh scatter were activated; the IK option was selected for the Electron Impact Ionization; the KM option was selected for the Bremsstrahlung angular sampling; and the variance reduction techniques Directional Bremsstrahlung Splitting (DBS) and Bremsstrahlung Cross Section Enhancement (BCSE) were applied to increase the calculation efficiency [8]. Atomic relaxations and spin effects were also activated.

The mean energy $\bar{E}$ was calculated for each spectrum by Equation 1:

$$\bar{E} = \sum_{i=1}^{k} E_i \Phi_i \qquad (1)$$

where E_i is the energy interval value in the spectrum and Φ_i the relative fluence.

2.2. Quality evaluation of the X-ray spectra

For the evaluation of the simulated spectra, the EGSnrc application egs_kerma was used, with the objective to determine the air kerma in a detector volume defined by the user. For each spectrum, quality parameters were determined to verify if they respect the recommendations of the TRS-457 [1]. This evaluation was performed using attenuation curves of each spectrum, obtained by the decrease of the air kerma measured in the detector volume in function of the increase of the thickness of the attenuator filter between the radiation source and the detector.

It is necessary to reproduce a good geometry to obtain each curve, where the beam is collimated enough to irradiate only the sensible volume of the detector, producing minimum scatter [1]. Therefore, an air volume of 0.6 cm^3 was used simulating a radiation detector, attenuation filters of aluminum of different thicknesses, and a lead collimator, with density 11.35 g/cm^3.

Each radiation source of the RQR and RQR M beams was modeled using an isotropic photon source, with the spectra generated in Section 2.1, at a distance of 100 cm and collimated to irradiate the detector. Attenuation filters of aluminum were placed 5 cm distant from the source, between the detector and the source. Besides that, a lead collimator was placed between the filters and the detector, 10 cm from the source, and the scattered radiation produced by the filter was collimated, in order to detect the maximum of the direct beam with the minimum of scattered radiation. The visualization of geometries can be performed using the egs_view software [7]. Figure 2 shows a simulation scheme of the geometry used in egs_kerma.

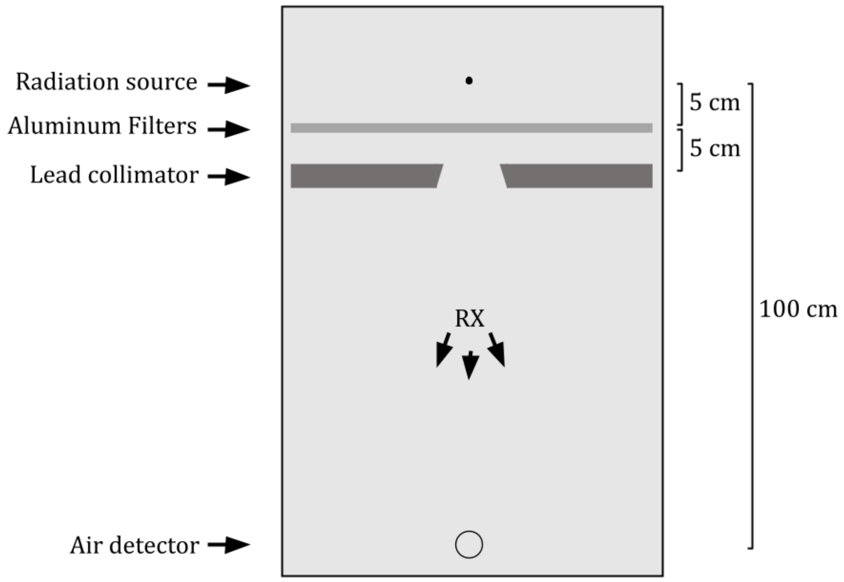

Figure 2: *Scheme of the simulations performed in the egs_kerma. Aluminum filters of different thicknesses were used to obtain the attenuation curves of the RQR and RQR-M beams.*

For each beam, irradiations were simulated with aluminum filters of different thicknesses, and the objective was to determine the necessary thickness of aluminum that decreases the initial intensity of the beam to a half, the first half-value layer, 1st HVL; and to a quarter, the second half-value layer, 2nd HVL. With the air kerma measured in the detector for each thickness of aluminum filter, the attenuation curve was created with the relative air kerma data by a non-linear fit in the software GNUPLOT.

The X-ray spectra considered in this work are polyenergetic, where the low-energy photons are attenuated faster than the high-energy ones. In this case, the non-linear fit of the intensity of the beam should be more complex and different from Equation 2, known as the Beer-Lambert Law, that states the exponential attenuation of monoenergetic beams:

$$I(x) = I_0 e^{-\mu x} \tag{2}$$

where I_0 is the initial intensity of the beam, μ its linear attenuation coefficient and $I(x)$ the intensity of the beam in function of the thickness x.

For polyenergetic beams, Yu et al. proposed in 1997 [11] the Equation 3, an alternative model of attenuation:

$$I(x) = I_0 e^{\left(\frac{a_1 x}{1 + a_2 x}\right)} \quad (3)$$

where a_1 and a_2 are constants calculated numerically in the attempt to reproduce the attenuation of photons of different energies in the beam. Equation 3 was the model that best fitted the data obtained in this work.

The simulation of the attenuation curves used 5×10^7 and 1×10^8 histories for the radiology and mammography beams, respectively; electrons and photons were transported until 10 keV. The radiation transport parameters of the simulations were the default configuration of egs_kerma and they were similar to the BEAMnrc configuration, with the following exceptions: the MCDF-XCOM renormalized photoelectric cross sections were used and no variance reduction techniques were applied in this section.

3. RESULTS AND DISCUSSION

3.1. Simulation of the X-ray spectra

The spectra were obtained with the additional filtration necessary to achieve the quality parameters described in the TRS-457 [1], detailed in Section 3.2. The RQR 5 and RQR 8 spectra were obtained, respectively, with additional filtration of 3.0 mm and 3.9 mm of aluminum. The RQR M1 and M2 spectra were obtained with additional filtration of 0.02 mm of molybdenum, and the RQR M3 and M4 spectra with additional filtration of 0.03 mm of molybdenum.

In Figure 3 are shown the radiology spectra RQR 5 and RQR 8. It is possible to verify that in the RQR 8 spectrum there are peaks of characteristic X-rays produced by the tungsten anode in 57, 59, 66 and 69 keV. Both RQR 5 and RQR 8 presented the expected shape of each spectrum.

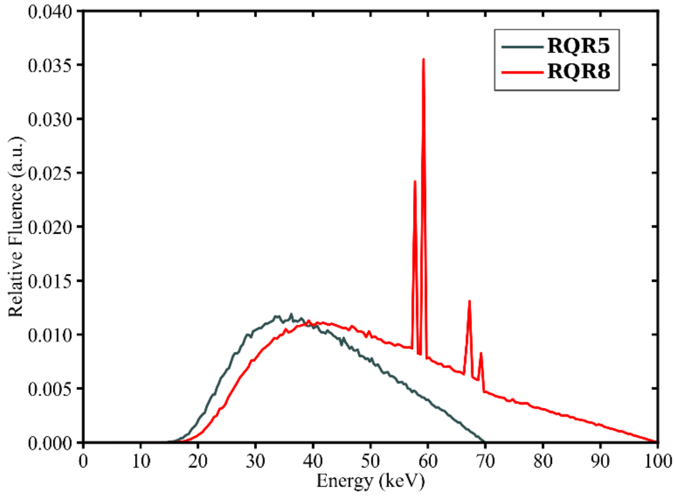

Figure 3: *RQR 5 and RQR 8 spectra simulated in the BEAMnrc.*

In Figure 4 are shown the mammography spectra of RQR M1, M2, M3 and M4. Peaks of characteristic X-rays in 17 keV and 19 keV are visible, originated by the molybdenum anode. The expected shape for each radiation quality simulated in the X-ray tube was also achieved.

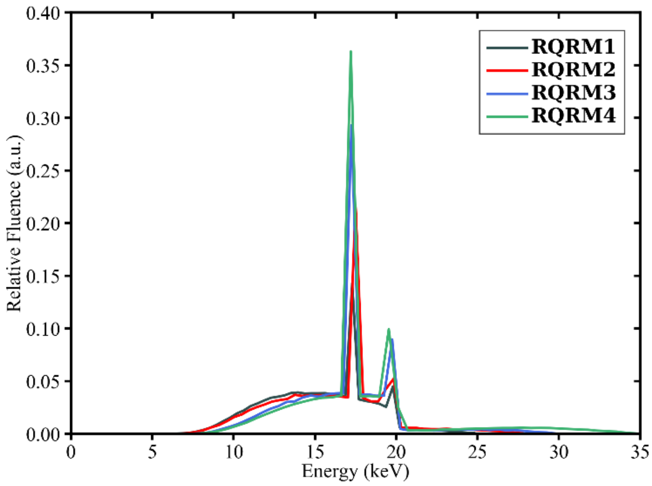

Figure 4: *RQR M1, M2, M3 and M4 spectra simulated in the BEAMnrc.*

3.2. Quality evaluation of the X-ray spectra

The attenuation curves obtained for each simulated spectrum are shown in Figures 5 and 6. The data was fitted with Equation 3, to reproduce the decrease of the air kerma with the increase of the aluminum filter thickness. In Figure 5 are shown the attenuation curves of RQR 5 and RQR 8. In Figure 6 are shown the curves of RQR M1, M2, M3 and M4.

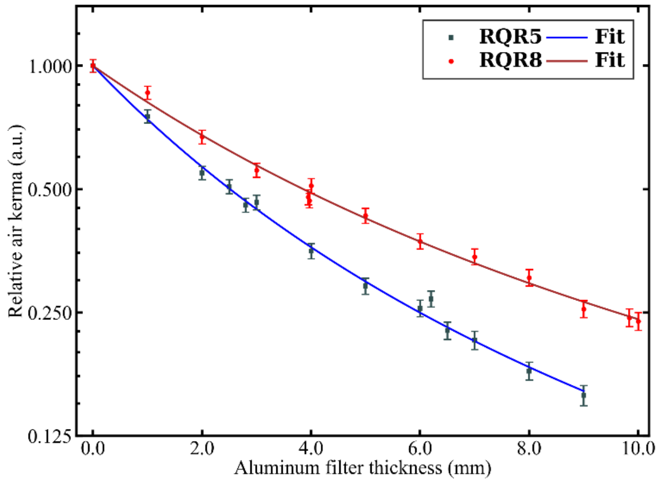

Figure 5: *Attenuation curves for RQR 5 and RQR 8 simulated in egs_kerma.*

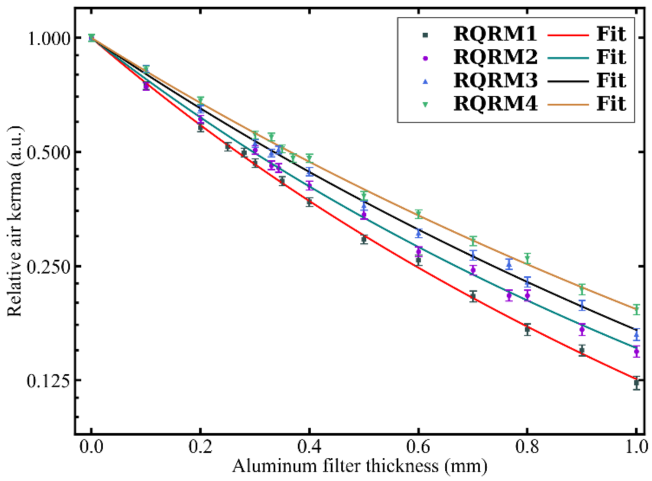

Figure 6: *Attenuation curves for RQR M1, M2, M3 and M4 simulated in egs_kerma.*

Table 1 shows information on the quality of each beam, such as the 1st HVL, the air kerma ratio – that verifies the attenuation of the 1st HVL, and homogeneity coefficients. These parameters agree with the requested recommendation of TRS-457 [1]. The homogeneity coefficients for the RQR M1, M2, M3 and M4 beams were not presented in Table 1 because there are no such reference values in the TRS-457 for those beams.

Table 1: Quality parameters of the radiology and mammography simulated beams. 1st HVL = First Half-Value Layer. Air kerma ratio = Ratio between the obtained air kerma with the 1st HVL thickness and the one without an attenuator.

Radiation quality	Tension	Mean energy	1st HVL (mm Al)		Air kerma ratio (%)		Homogeneity coefficient	
	(kV)	(keV)	MC	TRS-457	MC	TRS-457	MC	TRS-457
RQR M1	25	15.3	(0.268±0.006)	(0.28±0.02)	(51.5±1.8)	(48.5 - 51.5)	-	-
RQR M2	28	16.1	(0.297±0.010)	(0.31±0.02)	(50.7±1.8)	(48.5 - 51.5)	-	-
RQR M3	30	16.8	(0.335±0.012)	(0.33±0.02)	(51.5±1.7)	(48.5 - 51.5)	-	-
RQR M4	35	17.7	(0.365±0.012)	(0.36±0.02)	(51.2±1.7)	(48.5 - 51.5)	-	-
RQR 5	70	40.5	(2.51±0.24)	(2.58±0.08)	(51.2±2.0)	(48.5 - 51.5)	(0.72±0.07)	(0.71±0.02)
RQR 8	100	51.6	(3.9±0.5)	(3.97±0.12)	(50.4±2.0)	(48.5 - 51.5)	(0.67±0.11)	(0.68±0.02)

The uncertainty values of the first half-value layer obtained for the RQR 5 and RQR 8 simulated beams were higher than for their reference values in the TRS-457. This could have happened for mainly two reasons: the number of histories chosen for the simulations was possibly not sufficient to obtain a smaller uncertainty, or the higher uncertainties may come from the chosen non-linear fit.

The Yu method, described in Equation 3, was initially established in high-energy beams, in the range of MeV; however, nowadays it is also used as a method of non-linear fit for beams with keV energies [12,13,14]. As seen in the literature, this method still produces residuals in a non-total uniform distribution [14], which could indicate the necessity of better fit models for attenuation curves in this low-energy range, producing smaller uncertainties to the parameters and for the results of 1st HVL.

4. CONCLUSION

From the results of the simulations of the spectra and their attenuation curves, it could be verified that the beams presented quality parameters comparable with those established in the TRS-457 [1].

Each spectrum presented the expected behavior for the applied high voltage, with characteristic X-ray peaks and the increase of the mean energy of the spectrum with the increase of the high voltage.

From the attenuation curves, it was verified that the first and second half-value layers of the beams agree with those reported by the TRS-457 [1], and their homogeneity coefficients were also compatible with those described in the document.

These results are important because they show the ability to simulate standard X-ray beams with quality parameters comparable to the ones described in the TRS-457 [1], and they also show the functionality of a good geometry to obtain each curve.

With simulated standard X-ray spectra, projects of radiation detectors can be tested in simulations using radiation beams comparable to the ones they are going to be exposed to in laboratories, improving their quality and producing results closer to the ones found in laboratories.

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REFERENCES

[1] IAEA - International Atomic Energy Agency. **Dosimetry in diagnostic radiology: an international code of practice. Technical Reports Series No. 457**. Vienna, 2007.

[2] NAZÁRIO, M.; KHOURY, H. J.; HAZIN, C. Calibração de equipamentos de radioproteção com radiação gama no Laboratório de Metrologia das Radiações Ionizantes - DEN/UFPE. **Metrologia 2003**. Pernambuco, 2003.

[3] PERINI, A. P.; NEVES, L. P.; SANTOS, W. S.; CALDAS, L. V. E. Experimental and Monte Carlo evaluation of an ionization chamber in a ^{60}Co beam. **Journal of Physics: Conference Series 733 012081**, 2016.

[4] HERRNSDORF, L.; ANDERSSON, M. ; GUNNARSSON, M. ; MATTSSON, S. Optimization of energy and directional response of a small 4π silicon dosemeter for quality control of CT/CBCT-units – A 3D CAD, Monte-Carlo, AM approach. **Applied Radiation and Isotopes**, v. 158 – 109050, p. 1 -12, 2020.

[5] SALEHI, Z. ; BALVASI, E. ; AZIZ, M. Z. A. A review of the recent Monte Carlo (MC) simulation for dosimetry in mammographic applications. **Malaysian Journal of Medicine and Health Sciences**, v. 14(SUPP1), p. 76-81, 2018.

[6] IAEA - International Atomic Energy Agency. **Calibration of radiation protection monitoring instruments. Safety Reports Series No. 16**. Vienna, 2000.

[7] KAWRAKOW, I.; ROGERS, D. W. O. The EGSnrc code system: Monte Carlo simulation of electron and photon transport. National Research Council of Canada, NRCC. **Report PIRS-701**, 2003.

[8] ROGERS, D. W. O.; WALTERS, B.; KAWRAKOW, I. BEAMnrc User's Manual. National Research Council of Canada, NRCC. **Report PIRS-0509(A)revL**, 2010.

[9] KAWRAKOW, I.; MAINEGRA-HING, E.; TESSIER, F.; TOWNSON, R.; WALTERS, B. EGSnrc C++ class library. **Report PIRS-898**, 2019.

[10] MA, C.-M. and ROGERS, D. W. O. BEAMDP User's Manual. National Research Council of Canada, NRCC. **Report PIRS-0509(E)revA**, 2020.

[11] YU, M. K.; SLOBODA, R. S.; MURRAY, B. Linear accelerator photon beam quality at off-axis points. **Medical Physics**, v. 24(2), p. 233–239, 1997.

[12] MATHIEU, K. B.; KAPPADATH S. C.; WHITE R. A.; ATKINSON E. N.; CODY D. D. An empirical model of diagnostic x-ray attenuation under narrow-beam geometry. **Medical Physics**, v. 38(8), p. 4546-4555, 2011.

[13] ARNS, A. M. **Towards clinical implementation of ultrafast combined kV-MV cone-beam CT for IGRT of lung tumors within breath-hold: evaluation of dosimetry and registration accuracy based on phantom studies**. Doctorate dissertation – Heidelberg University, Heidelberg, 2016.

[14] BAUR, M.; UHLMANN, N.; PÖSCHEL, T.; SCHRÖTER, M. Correction of beam hardening in X-ray radiograms. **Review of Scientific Instruments**, v. 90, 025108, 2019.