Quality control and dosimetry in computed tomography units*

Controle de qualidade e dosimetria em equipamentos de tomografia computadorizada

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Abstract **OBJECTIVE: Evaluation of equipment conditions and dosimetry in computed tomography services utilizing protocols for head, abdomen, and lumbar spine in adult patients (in three different units) and pediatric patients up to 18 months of age (in one of the units evaluated). MATERIALS AND METHODS: Computed tomography dose index and multiple-scan average dose were estimated in studies of adult patients with three different units. Additionally, entrance surface doses as well as absorbed dose were estimated in head studies for both adult and pediatric patients in a single computed tomography unit. RESULTS: Mechanical quality control tests were performed, demonstrating that computed tomography units comply with the equipment-use specifications established by the current standards. Dosimetry results have demonstrated that the multiple-scan average dose values were in excess of up to 109.0% the reference levels, presenting considerable variation amongst the computed tomography units evaluated in the present study. Absorbed doses obtained with pediatric protocols are lower than those with adult patients, presenting a reduction of up to 51.0% in the thyroid gland. CONCLUSION: The present study has analyzed the operational conditions of three computed tomography units, establishing which parameters should be set for the deployment of a quality control program in the institutions where this study was developed.**

Keywords: Computed tomography equipment; Quality control; Dosimetry; Dose reduction.

Resumo **OBJETIVO: Avaliação de condições dos equipamentos e dosimetria em setores de tomografia computadorizada utilizando protocolos de cabeça, abdome e coluna lombar em pacientes adultos (em três equipamentos distintos) e pediátricos com até um ano e meio de vida (em um dos equipamentos avaliados). MATERIAIS E MÉTODOS: Foram estimados o índice de dose em tomografia computadorizada e a dose média em cortes múltiplos, em exames com pacientes adultos, em três distintos equipamentos. Ainda foram estimadas as doses na superfície de entrada e as doses absorvidas em exame de cabeça para pacientes adultos e pediátricos em um dos equipamentos avaliados. RESULTADOS: Foram realizados testes de controle de qualidade, mecânicos, demonstrando que os equipamentos satisfazem as especificações de uso estabelecidas pelas normas vigentes. Os resultados da dosimetria mostraram que valores de dose média em cortes múltiplos excederam em até 109,0% os valores de níveis de referência, apresentando consideráveis variações entre os equipamentos avaliados neste estudo. As doses absorvidas obtidas com protocolos pediátricos são inferiores aos de pacientes adultos, apresentando redução de até 51,0% na tireoide. CONCLUSÃO: Neste estudo foram avaliadas as condições de operação de três equipamentos tomográficos, estabelecendo quais parâmetros devem ser trabalhados para a implantação de um programa de controle de qualidade nas instituições onde esta pesquisa foi desenvolvida.**

Unitermos: Equipamento tomográfico; Controle de qualidade; Dosimetria; Redução de dose.

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INTRODUCTION

Computed tomography (CT) has revolutionized radiological studies by providing sagittal, coronal and axial views of ana-

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tomical structures. This complementary method of imaging diagnosis allows tissue density differentiation in the order of 0.5%, while in conventional radiology this threshold is approximately 5%[1]. However, among the different imaging diagnosis methods based on ionizing radiation, CT is the method that exposes the patient to the highest radiation[2].

In the United Kingdom, studies have shown that although CT studies represent only 7% of the total number of medical procedures involving x-radiation, they represent 47.0% of the total collective dose[3]. In the United States, recent data shows that this examination method corresponds to 10% of all radiologic procedures, contributing with two thirds of the collective doses in the population[1,3]. Thus, the application of this imaging diagnosis method is attracting attention in radiological protection research[4–9]. In any procedure involving an individual exposure to radiation for diagnosis purposes, the applied technique must provide the maximum possible level of visual information (in order to assure the image quality), with exposure of the patient to the minimum dose possible[4–7].

The parameters regarding doses to patients submitted to this type of procedure are related to the frequency range and intensity of x-ray beams, geometrical conditions of the equipment, selection of study protocols and anatomical dimensions of the patient[1,10,11].

Besides being an operational requirement, the quality assurance in CT studies is a provisional requirement on the Ordinance (Portaria) No. 453/98 of the Brazilian Ministry of Health[12]. The objective of a quality control program is assuring that each and every image generated by the CT unit allows a safe medical diagnosis, with as low as reasonably feasible doses[12,13]. However, the adoption of protocols established for adult patients in pediatric studies may compromise this expectation[1,10,11].

The present study was aimed at assessing the equipment conditions in CT services and dosimetry in studies utilizing head, abdomen, and lumbar spine protocols in adult patients (in three different CT units) and pediatric patients up to 18 months of age (in one of the units evaluated).

MATERIALS AND METHODS

Before any study is performed with an equipment, a preliminary procedure is the evaluation of its operational conditions within the specified requirements for its use[12,13]. This evaluation is normally based on quality control tests with the equipment under assessment.

Among the tests defined and specified by current regulations[12,13] the following can be mentioned: i) collimation system; ii) examination table alignment with the gantry; iii) longitudinal movement of the table; iv) gantry inclination; v) noise, accuracy and uniformity of CT number; vi) high- and low-contrast spatial resolution; vii) slice thickness; viii) multiple-scan average dose (MSAD).

Thus, in the present study mechanical quality control tests (i-iv), image quality tests (v-vii) and dose tests (viii)[13] were performed in the CT equipment 1 (Sytec-3000i – General Electric Medical Systems; Milwaukee, USA), CT equipment 2 (helical equipment SCT-7000TS – Shimadzu Co.; Kyoto, Japan) and in CT equipment 3 (Somatom Emotion single slice – Siemens Medical Systems; Erlangen, Germany).

The mechanical (i-iv) and image quality tests (v-vii) were performed as described in literature[12,13]. For the image quality tests (v-vii), a phantom model 76-411Victoreen (Nuclear Associates; Carle Place, USA) was utilized.

The MSAD was performed with high-pressure cylindrical ionization chambers, with a 10 cm sensitive length, called pencil-type ionization chambers. One of the typical characteristics of such chambers is presenting uniform responses to incident radiation at all angles around their axes[1,10]. In the present study, a dully calibrated (IPEN-1423/2005) dosimetric set including an ionization chamber model 10x5-3CT and an electrometer model 9015, both from Radcal (Radcal Corporation; Monrovia, USA), was utilized.

The length of ionization chambers utilized in CT shall be longer than the CT section thickness. The x-ray beam must be perpendicularly directed to center of the sensitive volume of the ionization chamber. Thus the production of electric charges generated inside the chamber will be symmetrically distributed from the center of the chamber, along its length, resulting in a direct reading of the coupled electrometer[1].

The absorbed dose distribution due to a single section exposure may be calculated as function of the slice (T), and of the incident x-radiation intensity. This measurement determines the computed tomography dose index (CTDI)[13]. By knowing the slice thickness and the number of slices (n) in a study, the CTDI can be calculated by means of the equation 1[13].

$$CTDI = \frac{1}{nT}\int_{-\infty}^{+\infty} D(z)dz \qquad \text{Eq. 1}$$

This integral is represented on Figure 1[14] demonstrating the area below the curve of typical dose distribution $D(z)$.

In the CTDI definition, anatomical regions between primary x-ray beams unexposed sections were not considered. By adding up the dispersed doses for each section, the MSAD can be determined by means of equation 2.

MSAD can be calculated by multiplying the slice thickness by CTDI and dividing by the examination table movement increments[13].

$$MSAD = CTDI\left(\frac{T}{e}\right) = \left(\frac{1}{ne}\right)\int_{-\infty}^{+\infty} D(z)dz \qquad \text{Eq. 2}$$

where: e represents the extent of the increments between successive CT slices.

The MSAD is graphically represented on Figure 2[14].

In the present study, the CTDI and MSAD were estimated for the CT units 1, 2 and 3, by inserting an ionization chamber in the center of each dose calibration phantom for head, abdomen and lumbar spine studies, respectively models 76-414 and 76-415 (Cardinal Health; Marlborough, USA). Each phantom was positioned in the CT units gantry, and a CT section was performed in the center of the ionization chamber sensitive volume. This procedure was performed for each CT equipment, following the protocol for adult patients adopted in each service to which the equipment belonged to. For head studies, the MSAD of the supratentorial region are added to that of the posterior cranial fossa, using a 15° angle[13].

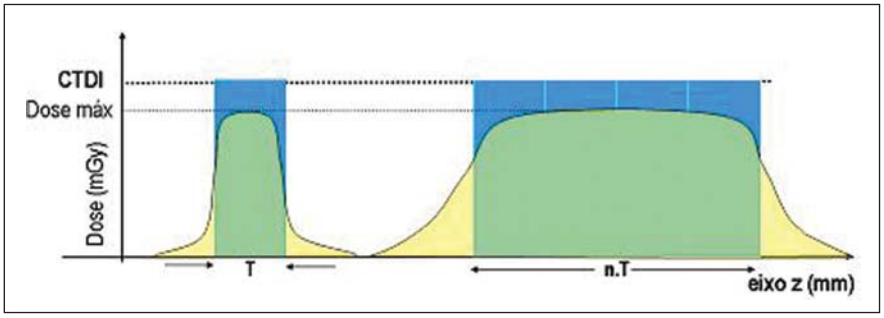

Figure 1. Graphical illustration of CTDI[14] showing the areas below the dose distribution curves involved in its definition.

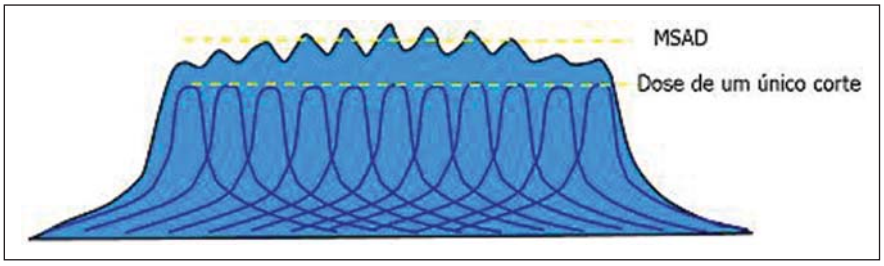

Figure 2. Graphical illustration of MSAD[14] showing the areas below the dose distribution curves involved in its definition.

The protocols adopted in the present study for CT units 1, 2 and 3 are shown on Table 1 as follows: head (supratentorial region and posterior cranial fossa), abdomen and lumbar spine for adult patients. The description of such protocols provides information on the number of channels of the equipment (in this study all of them were single slice), kVp, mA, 360° rotation time, study mode, number of sections, slice characteristics (A = slice thickness, B = table increment) and pitch (length of table advance for each 360° rotation), for studies performed in the helical mode.

Then, the surface entrance doses were monitored in mGy, on 32 points of the skull in the anthropomorphic phantom Rando (radiation analog dosimetry) on the CT equipment 3[15]. In this procedure, an acrylic tube was laterally attached to this anatomic region, as shown on Figure 3 where a picture of the assembly scheme is depicted[16].

In the acrylic tube, 32 thermoluminescent lithium fluoride (TLD-LiF-100)[17] dosimeters (Harshaw Chemical Company; Solon, USA) were inserted, dully calibrated according with the manufacturer's recommendations. The equipment 3 was selected considering the fact that it was the most modern equipment among the ones assessed in the present study.

The entire procedure was based on the protocol for head studies adopted in the clinical routine for adult (standard) and pediatric patients (up to 18 months of age) in the equipment 3, which is described on Table 2. The dose for head examination consists of the sum of the doses utilized in the study of the supratentorial region plus those utilized for the posterior fossa. In this procedure, the distribution of skull surface entrance doses was evaluated, adopting the same phantom (Rando) for both protocols.

Using the same protocols and the same equipment, the absorbed doses were measured in the left and right internal ears, left and right retinas, cerebellar vermis region, right and left cerebellum lobes, and left and right crystalline lens, using the anthropomorphic phantom. This procedure was performed in the same way of the estimation of surface entrance dose. Due to the fact that they are superficial organs, we do not have an electronic equilibrium region required for the calculation of equivalent dose in organs[9]. Thus, the surface entrance dose in superficial organs is pre-

Figure 3. Picture of the acrylic tube assembly containing the TLD-LiF positioned on the lateral region of the phantom.

Table 1 Adult patient protocols for head, abdomen and lumbar spine (for discopathy diagnosis) studies in CT units 1, 2 and 3, with information on the number of channels for each equipment (in this study all of them were single slice), kVp, mA, 360° rotation time, study mode, number of CT sections, slice characteristics (A = slice thickness × B = examination table increments) and pitch (length of table movement during a 360° rotation), for studies performed in helical mode.

Study	Equipment 1	Equipment 2	Equipment 3
Head – supratentorial	120 kVp, 80 mA, 2.7 s, axial, 9 slices, (10 × 10) mm	120 kVp, 80 mA, 1.0 s, axial, 9 slices, (10 × 10) mm	130 kVp, 100 mA, 0.8 s, axial, 9 slices, (10 x 10) mm
Head – posterior fossa	120 kVp, 100 mA, 2.7 s, axial, 6 slices, (2 × 4) mm	120 kVp, 100 mA, 1.0 s, axial, 4 slices, (3 × 5) mm	130 kVp, 100 mA, 0.8 s, axial, 4 slices, (3 x 5) mm
Abdomen	120 kVp, 100 mA, 2.7 s, axial, 20 slices, (10 × 10) mm	120 kVp, 120 mA, 1.0 s, helical, 20 slices, (10 × 10) mm, pitch = 1	130 kVp, 100 mA, 0.8 s, helical, 20 slices, (10 x 10) mm, pitch = 1
Lumbar spine	120 kVp, 130 mA, 2.7 s, axial, 19 slices, (2 × 3) mm	120 kVp, 250 mA, 1.0 s, helical, 13 slices, (3 × 3) mm, pitch = 1	130 kVp, 130 mA, 0.8 s, helical, 19 slices, (2 x 3) mm, pitch = 1

Table 2 Protocols for head studies in adult and pediatric patients, with CT equipment 3, with information on the number of channels of each equipment (in this study all of them were single slice), kVp, mA, 360° rotation time, study mode, number of CT sections, slice characteristics (A = slice thickness × B = examination table increments).

Study	Equipment 3	
	Adult	Pediatric
Head – supratentorial	130 kVp, 120 mA, 0.8 s, axial, 9 slices, (10 x 10) mm	130 kVp, 90 mA, 0.8 s, axial, 9 slices, (10 x 10) mm
Head – posterior fossa	130 kVp, 120 mA, 0.8 s, axial, 6 slices, (2 x 4) mm	130 kVp, 90 mA, 0.8 s, axial, 6 slices, (2 x 4) mm

sented as absorbed dose in mGy units[9]. In this method, the acrylic tube was replaced by sets with three TLD-LiF chips, positioned in the region of each organ in study[10,11].

RESULTS

Table 3 shows the results of the mechanical quality control tests performed to evaluate the CT units 1, 2 and 3[13]. The last column shows the tolerance values for each test[12].

Table 4 shows the results of image quality control tests performed to evaluate the CT units 1, 2 and 3[13]. The last column shows the tolerance values for each test[12]. The term "constancy" refers to the unaltered results, when compared with earlier results of this same test.

Table 5 shows the results of quality control tests regarding MSAD to evaluate the CT units 1, 2 and 3. The last column shows reference values for each study [12].

Figure 4 shows the CTDI values for the CT units 1, 2 and 3 obtained for head (red), abdomen (blue) and lumbar spine (green) studies utilizing protocols for adult patients.

Figures 5, 6 and 7 show MSAD values for CT units 1, 2 and 3, for head, abdomen and lumbar spine studies, respectively, utilizing protocols for adult patients of the imaging diagnosis services which the CT units belong to. The dashed lines represent the reference values[12] for each study analyzed.

Figure 8A shows the doses according to the TLDs-LiF positions (distribution within the acrylic tube), utilizing the protocol for adult (yellow curve) and pediatric (red curve) patients. Figure 8B shows the detail of the distributions on the Cartesian axis.

Table 6 shows absorbed doses for the cranial organs evaluated in the head studies utilizing the protocols for adult and pediatric patients. The last column shows the rate of dose reduction in pediatric studies as compared with the same studies utilizing protocols for adult patients.

Table 3 Mechanical tests (collimation, table alignment in relation to the gantry, longitudinal examination table movement, and inclination in relation to the gantry) for assessment of CT units 1, 2 and 3. The last column shows the tolerance values for each test[12].

Test	Equipment			Tolerance
	1	2	3	
Collimation system	3.0 mm	1.0 mm	0.0 mm	± 2.0 mm
Examination table – gantry alignment	1.0 mm	0.0 mm	0.0 mm	± 5.0 mm
Longitudinal examination table movement	0.0 mm	1.0 mm	0.0 mm	± 2.0 mm
Gantry inclination	1.0°	0°	1.0°	± 3.0°

Table 4 Image quality tests (noise, accuracy, uniformity, slice thickness, high contrast spatial resolution, low contrast spatial resolution, linearity and sensitivity) for assessment of CT units 1, 2, and 3. The last column indicates tolerance values for each test[12], by means of nominal slice thickness.

Test	Equipment			Tolerance
	1	2	3	
Noise	1.1%	2.2%	1.2%	10.0%
Accuracy	–0.5 UH	–1,7 UH	1.5 UH	± 5.0 UH
Uniformity	3.6 UH	2,. UH	1.45 UH	± 5.0 UH
Slice thickness	0.2 mm 1.0 mm	0.4 mm 1.0 mm	0.1 mm 0.0 mm	± 50.0% NST > 2.0 mm ± 1.0 mm NST > 2.0 mm
Contrast-HCSR	Satisfactory	Satisfactory	Satisfactory	Constancy
Contrast-LCSR	Satisfactory	Satisfactory	Satisfactory	Constancy
Linearity	Satisfactory	Satisfactory	Satisfactory	Constancy
Sensitivity	Satisfactory	Satisfactory	Satisfactory	Constancy

HCSR, high contrast spatial resolution; LCSR, low contrast spatial resolution; NST, nominal slice thickness.

Table 5 MSAD tests (mGy) in head, lumbar spine and abdomen regions, for evaluation of CT units 1, 2 and 3. The last column shows the reference levels for each study[12].

Test	Equipment			Reference level (mGy)
	1	2	3	
Head	104.5	34.4	26.7	50.0
Lumbar spine	17.2	7.6	6.4	35.0
Abdomen	20.6	9.6	3.4	25.0

DISCUSSION

The quality control tests results have demonstrated that the CT units 2 and 3 are compliant with the requirements described

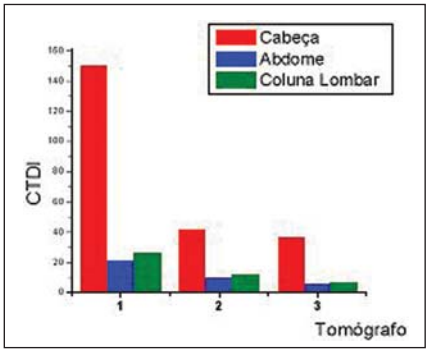

Figure 4. CTDI for CT units 1, 2 and 3 in head, abdomen and lumbar spine studies

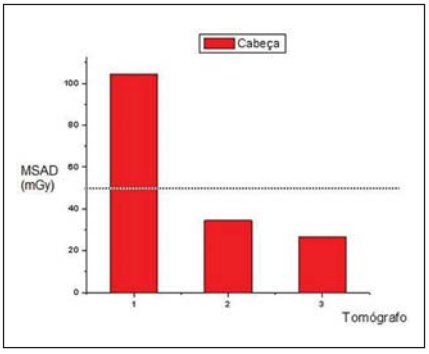

Figure 5. MSAD for units 1, 2 and 3, in head examinations. The dashed line indicates the reference levels (50 mGy) for this study.

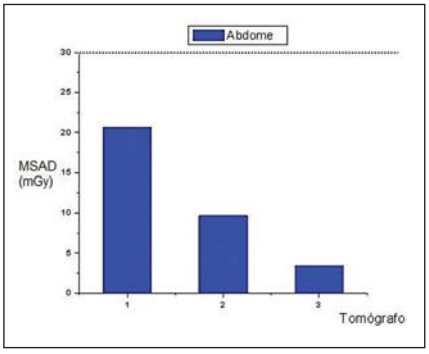

Figure 6. MSAD for units 1, 2 and 3, in abdominal examinations. The dashed line indicates the reference levels (30 mGy) for this study.

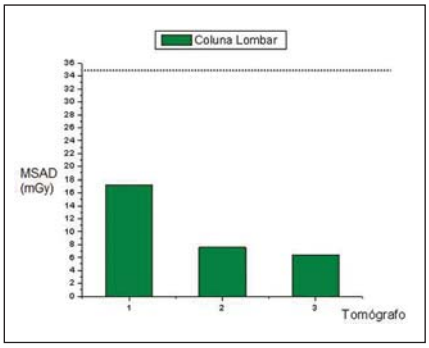

Figure 7. MSAD for units 1, 2 and 3, in lumbar spine examinations. The dashed line indicates the reference levels (35 mGy) for this study.

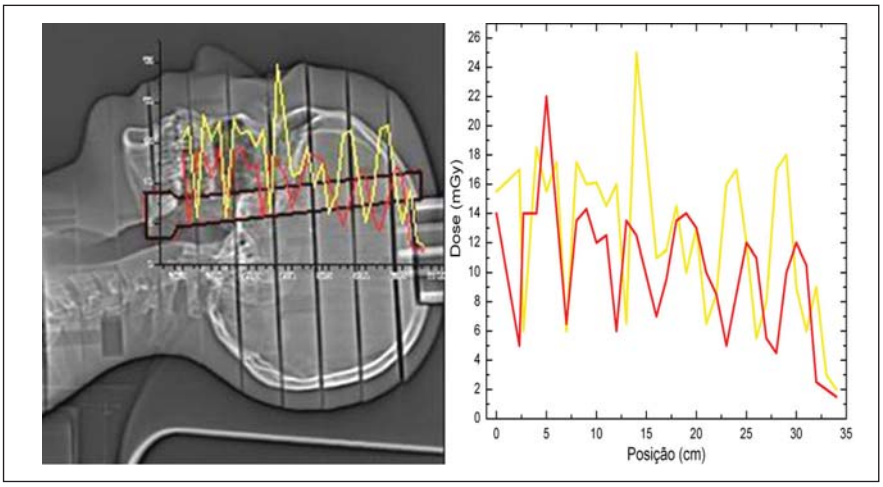

Figure 8. A: Dose distribution as a function of the TLDs-LiF position (positioned within the acrylic tube in the anthropomorphic phantom), obtained with protocols for adult (yellow curve) and pediatric (red curve) patients. **B:** Detail of dose distribution as a function of the position demonstrated on A.

Table 6 Absorbed doses for certain cranial organs, in head studies performed with protocols for adult and pediatric patients. The last column presents the rates of reduction in absorbed dose (%) for pediatric studies compared with adult studies.

Region	Dose in the protocol for adult patients (mGy)	Dose in the protocol for pediatric patients (mGy)	Reduction (%)
Left internal ear	12.2	8.2	33.3
Right internal ear	11.5	9.4	18.3
Left retina	12.8	7.4	41.9
Right retina	11.7	7.6	35.3
Left cerebellum lobe	11.5	8.1	29.3
Cerebellar vermis	11.8	8.4	28.6
Right cerebellum lobe	11.4	8.6	24.8
Left cristalline lens	15.6	9.4	39.9
Right cristalline lens	16.4	8.4	48.6
Thyroid gland	0.5	0.2	51.4

in the in the current standards[13]. This was not the case with equipment 1, which failed one of the mechanical tests (collimation system). It is important to mention that such failure was informed to the engineering department of the institution to which the equipment belongs, and the problem was immediately solved.

The comparison of CTDI and MSAD among the CT units involved in the present study showed that the equipment 1 presented higher CTDI and MSAD values than the equipment 2 and 3. The CT unit 1 presented a CTDI increase of 311.0% for head studies, 306.0% for abdomen studies and 302.0% for lumbar spine studies as compared with the equipment 3. This is due to the fact that the equipment 1 has a longer 360° rotation time than the equipment 3, besides the fact that the equipment 1 performs sequential CT sections, while the equipment 3 performs continuous and/or contiguous CT sections (helical). The number of slices adopted in each protocol also contributed to the increase in the dose. For these reasons MSAD values for the CT unit 1 are higher when compared with the other equipment evaluated in the study (Table 1). However, for all the studies (head, abdomen and lumbar spine), the MSAD values are below the reference levels, except for

the head study performed on the equipment 1 1, which presented a MSAD 109.0% higher than the reference level[12,13]. These doses can be optimized by monitoring image noise (controlling mAs), and not allowing the image noise levels to exceed the recommended levels in current standards. Such problems, as well as solution alternatives were informed to the institutions to which the equipment 1 belongs. It is important to mention that the appropriate department is taking the necessary actions, with the support of professionals of medical physics to deploy a process to optimize the doses without affecting the image quality in head studies.

Regarding radiological protection, the ICRU 60 suggests that doses should be measured in mSv[9]. Considering that, for x-rays, in the energy range of radiodiagnosis the radiation weighting factor (Wr) corresponds to 1.0, the values presented in Table 5 are numerically equal to the unit in mSv. The present study compares the doses obtained with the reference levels established by the Brazilian standards[12,13], and such standards refer to doses represented in mGy units. For this reason dose units in Table 5 are shown in mGy.

The absorbed dose results estimated in cranial organs were measured as surface entrance dose, considering that the organs evaluated corresponded to surfaces such as: the left and right internal ears, left and right retinas, cerebellar vermis region, left and right cerebellum lobes, left and right crystalline lens. In these organs there is no region of electronic equilibrium, which is required for the calculation of dose equivalent. Thus the entrance surface dose in superficial organs is presented as absorbed dose.

The adoption of the same protocol for CT studies in adult and pediatric patients is still very common[16]. The present study demonstrates that the pediatric protocol adopted in the service to which the equipment 3 belongs resulted in a significant reduction in the entrance surface dose, as shown on Figure 8. However, the red curve on Figure 8 shows that the major contribution of the entrance surface dose occurs in the crystalline lens, one of the most radiosensitive regions of the human body.

Studies have demonstrated that absorbed dose between 200 and 700 cGy (which for this organ, is equal to the entrance surface dose) may induce opacity of this organ in adult patients, and doses < 2.5 cGy may lead to cataract in the pediatric patients. Therefore, it is important to stress that although the literature does not report reference levels for pediatric studies, the current standards establish that the doses shall be lower than the one for adult patients, and as low as reasonably feasible without affecting the image quality[1,11,14]. Absorbed dose results presented on Table 6 show a reduction of up to 51% in the thyroid gland.

CONCLUSION

The entrance surface doses were estimated for head studies (supratentorial and posterior fossa regions) utilizing an anthropomorphic phantom and protocols for adult and pediatric patients (up to 18 months of age). The difference between adult and pediatric skulls were not taken into consideration because, in the present study, no radiation absorption factor in cranial structures was considered, but only backscattering on entrance surface due to the techniques of the studied protocols.

Recent studies show that CT units with different technologies and/or different manufacturers present doses with discrepancies that reach up to a factor of 3. Additionally, it has been observed that studies performed in different services with CT equipment of a same model and manufacturer and with similar performances, provided dose variations factor of 11[1,2,14]. Thus it is important to point out that CTDI and MSAD responses are intimately connected with the characteristics of the different CT units, their performances in the quality control tests and the protocols adopted by each tomography service.

The Brazilian Agency for Sanitary Vigilance (Secretaria de Vigilância Sanitária) suggests that all institutions using ionizing radiations deploy a quality assurance program including three main objectives: improvement of radiographic image quality, reduction of doses for patients, and reduction of costs for the institution. These parameters cannot be considered isolatedly and the quality assurance program must be suited to each CT service, in such a way to simultaneously address equipment characteristics, performance and adopted protocols.

The present study contributes to the evaluation of operational conditions in computed tomography services, and establishes which parameters must be dealt with for the deployment of a quality control program in the institutions where this study was developed.

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