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ANALYSIS OF DOSE DISTRIBUTION AROUND A COMPUTED TOMOGRAPHY SCANNER IN TERMS OF EXPOSURE TO SCATTERED IONIZING RADIATION OF CAREGIVERS OF PEDIATRIC PATIENTS

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Abstract
Objectives: During computed tomography (CT), a large amount of ionizing radiation is emitted to ensure high quality of the obtained radiological image. This study measured the dose distribution around the CT scanner and the exposure of people staying near the CT scanner during the examination. **Material and Methods:** The measurements used an anthropomorphic phantom to assess human exposure to ionizing radiation. The probability of inducing leukemia and other cancers as a result of absorbing doses recorded around the CT device was also calculated. **Results:** The highest exposure to scattered radiation in the proximity of the CT scanner is recorded at the gantry of the tomograph, i.e., 55.7 μGy, and the lowest, below lower detection limit of 6 μGy at the end of the diagnostic table. The whole-body detector placed on the anthropomorphic phantom located at the diagnostic table right next to the CT gantry recorded 59.5 μSv and at the end of the table 1.5 μSv. The average doses to the lenses in these locations were: 32.1 μSv and 2.9 μSv, respectively. **Conclusions:** The probability of induction of leukemia or other types of cancer is low, but the need for people to stay in the examination room during a CT examination should be limited to the necessary minimum. Int J Occup Med Environ Health. 2024;37(3):326–34

Key words:
effective dose, radiological protection, leukemia, CT scanner, probability of induction of leukemia, pediatric radiology

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INTRODUCTION

Computed tomography (CT) is one of the most frequently performed highly specialized imaging technique in which a high level of ionizing radiation is emitted to obtain a large amount of diagnostic information. In Organization for Economic Cooperation and Development (OECD) countries, on average 160 CT examinations are performed for every thousand people in the population [1]. This is a significant number of procedures that significantly influence the level of population exposure to the adverse effects of ionizing radiation. In medicine, CT is used in many types of diagnostic and therapeutic procedures. It is the main diagnostic technique for detecting many dangerous diseases and is an indispensable tool in the implementation of several therapeutic procedures. However, it should be remembered that the high-quality diagnostic image obtained in CT is obtained because of the emission of a large dose of radiation compared to other medical imaging techniques [2–5]. In some CT procedures, exposure to a high dose of ionizing radiation affects not only the patient being examined, but also parents or legal guardians in the case of pediatric patients who are in the examination room during the procedure.

The purpose of the following study is to measure the dose distribution around a medical CT scanner, determine the exposure to ionizing radiation of people staying close to the CT scanner during the study, and estimate the probability of induction of leukemia and other cancers as a result of doses of receive. It should be added that there are many studies on the exposure of medical personnel during interventional radiology procedures or on the doses received by patients during tomography [6–11], but few researchers deal with the exposure of caregivers of pediatric patients who must stay directly next to the operating CT scanner. This is since in most cases, medical personnel operating the CT scanner or caregivers of pediatric patients are in the device's control room, which is well protected against radiation. However, there are several medical procedures in which caregivers of pediatric patients must be in eye contact with the child during the examination to ensure the proper course of the examination. This applies especially to pediatric patients who cannot be sedated.

MATERIAL AND METHODS

A Canon Aquilion Prime CT scanner from Canon (Tokyo, Japan) was used for the measurements. This is a 256-slice CT scanner manufactured in 2020. Exposure measurements were performed while scanning a phantom simulating the chest using the "chest" study protocol. To increase reading accuracy, each measurement of dose and exposure distribution was performed using 5 series of helical scans. In each series of measurements, the dose length product (DLP) value was 115 mGy × cm. All obtained results were converted into 1 series of scans, i.e., 1 examination.

Highly sensitive thermoluminescent detectors (TLDs type MCP-N manufactured by Radcard, Kraków, Poland) were used in the measurements [12–15]. Calibration of the whole-body and eye lens dosimeters was performed in accordance with the accredited procedure used at Nofer Institute of Medicine (NIOM), Łódź, Poland, for routine individual dose measurements, i.e., on slab and head phantoms, respectively, in units of $H_p(10)$, $H_p(3)$ for the reference energy spectrum ISO N-80 [16]. Calibration of loose TLDs for measurements using an anthropomorphic phantom was performed in a cesium-137 gamma radiation field (662 keV). An overall 20% measurement uncertainty was estimated, and it is mainly due to the energy dependence of TL detectors. The estimated lower detection limit (LDL) for measurement with TLDs was 6 mSv.

The dose distribution around the CT scanner was measured using cardboard walls (wall material selected in such a way as not to disturb the radiation dose distribution) on which TL dosimeters were placed at the following heights: 1 cm, 50 cm, 100 cm, 150 cm and 170 cm relative to the floor. The walls were placed at 20 cm and 70 cm from the CT scanner (Figure 1).

An anthropomorphic phantom from CIRS (Sun Nuclear Corporation, Melbourne, USA) was used to assess human exposure to ionizing radiation [17]. This phantom simulates the build of an adult man, 173 cm tall and weighing 73 kg. The phantom is divided into 2.5 cm layers with marked organs, in which there are holes for placing TLDs. The anthropomorphic phantom was positioned in 2 places: at the gantry of the CT scanner (point C1) and at the end of the table, i.e., 290 cm from the gantry of the CT scanner (point C8). Thermoluminescent dosimeters were placed inside the phantom to assess exposure to ionizing radiation: brain, lenses, thyroid, lungs, heart, kidneys, stomach, liver, bladder, prostate and testicles. The phantom was also equipped with 3 individual dosimeters enabling the assessment of the whole body dose and the eye lens doses (EYE-D). Eye lens individual dosimeters were placed on the right and left temples. Additionally, 2 dosimeters were placed on the right and left eyebrows to assess the dose to the eye lens. The phantom was not equipped with any individual shields, which allows measuring the maximum radiation doses to which a person is exposed at points C1 and C8. Any individual shields used reduces exposure.

Based on the Biologic Effects of Ionizing Radiation (BEIR) VII report [18], an analysis was made of the risk of leukemia and other cancers, which during the examination would be located right next to the gantry of the CT scanner and at the end of the table on which the patient undergoing the examination lies. These probabilities were calculated for caregivers of pediatric patients who are often in the CT room when examining children. Probabilities were calculated for caregivers aged 25 years, 30 years, 35 years, and 40 years, assuming that the caregiver participates in such examination once in the child's lifetime. These estimates are obtained as combined estimates based on relative and absolute risk transport and

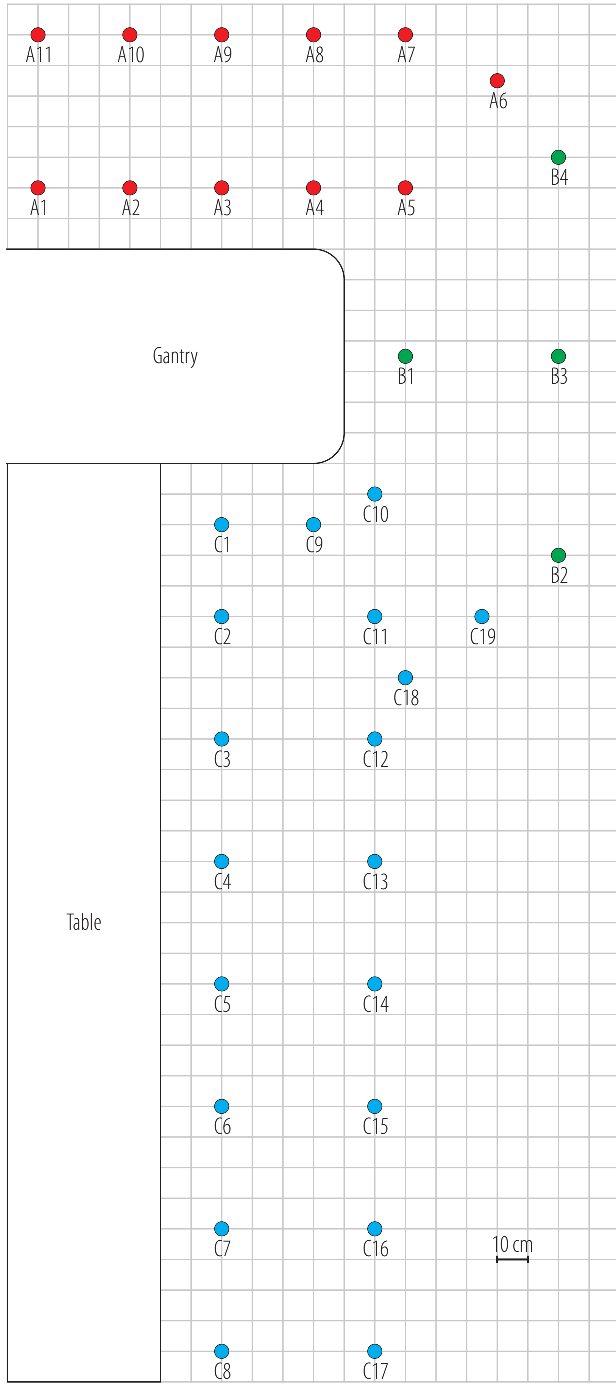

Figure 1. Arrangement of measurement points of ionizing radiation dose values around the computed tomography scanner used in the study

have been adjusted by a dose-rate effectiveness factor of 1.5, except for leukemia, which is based on a linear-quadratic model.

The statistical analysis of the results obtained in this work was performed using Statistica 13.1 software. The statistical tool used to compare 2 groups of results is the Student's t-test. The significance level adopted was $\alpha = 0.05$, therefore $p < 0.05$ confirms the statistical difference between the tested samples. The uncertainty of measuring dose levels determined using TL detectors is the standard uncertainty.

RESULTS

The arrangement of measurement points around the CT scanner is shown in Figure 1. At each measurement point, the measurement was made at 5 heights relative to the ground, as shown in Table 1. The measurement results are included in the table along with the standard error.

The doses measured in the anthropomorphic phantom, simulating the caregiver, positioned in 2 different places in relation to the gantry of the CT scanner and thus in relation to the radiation source are presented in Table 2. The measurement results are included in the table along with the standard error.

Doses obtained from individual dosimeters installed on the phantom are presented in Table 3.

Considering the dose to the whole body and using the BEIR VII report [18], the probability of induction of leukemia or other cancers was calculated for people located at the gantry of the CT scanner and standing at the end of the therapeutic table, i.e., 290 cm from the gantry (Table 4). If caregivers participate in research multiple times a year, the probabilities add up.

DISCUSSION

When analyzing the dose distribution around the CT scanner, it should be remembered that scattered radiation is being measured. In the case of a CT scanner, the radiation beam is narrow and very well collimated. Only the patient being examined is exposed to the primary beam.

The measurement points around the CT scanner were divided into 3 groups: A, B, C. These groups represent areas where the dose differs. Considering measurements at all heights, characteristic averages were determined for each area A, B and C – they are 10.70 μGy, below LDL, 5.65 μGy, respectively. These values indicate that the safest area to be in during the examination is area B – the lowest scattered radiation was in this area. Comparing area C to area A, the average registered dose is lower by a factor of 2 ($p = 0.0019$) is observed.

Analyzing the results presented in Table 1, the closer to the gantry opening and the diagnostic table, the greater the exposure. The highest radiation doses were recorded by dosimeters in the position marked C1 at all altitudes of a given point. Also, dosimeters located directly behind the gantry (A1, A2 and A3) recorded high doses, especially at the heights of 50 cm, 100 cm, 150 cm and 170 cm. The dosimeters positioned in A1, A2, A3 and C1 obtained the highest dose values among all those measured, which is due to their smallest distance from the primary radiation beam.

Analyzing the dose distribution along the treatment table, it can be observed that dosimeters close to the table (C4–C8) received lower doses than the corresponding dosimeters located in the same line (C13–C17), but distant from the table and theoretically also more distant from the radiation source. The situation is repeated for these dosimeters placed at the heights of 0 cm, 50 cm and 100 cm. These measurements show that the diagnostic table (located at a height of 100 cm during the measurements) absorbs part of the scattered radiation.

Results of measurements performed with individual dosimeters on the anthropomorphic phantom show that the most exposed person is the one who is the closest to both the gantry and the table during the examination (C1). The doses in all organs in the phantom placed in this location were several times higher than in the case of the phantom placed at the end of the diagnostic table,

Table 1. Dose values of ionizing radiation during computed tomography (CT) at each measurement point and at various heights relative to the floor taken on the Aquilion Prime CT scanner from Canon (Tokyo, Japan)

Point No.	Dose [μGy] (M±SD)				
	1 cm	50 cm	100 cm	150 cm	170 cm
A					
A1	1.8±0.4	37.1±7.4	52.0±10.4	30.6±6.1	22.9±4.6
A2	3.0±0.6	29.6±5.9	37.1±7.4	25.8±5.2	19.9±4.0
A3	1.3±0.2	20.1±4.0	33.0±6.6	21.0±4.2	4.4±0.9
A4	n.a.	1.7±0.3	6.3±1.3	2.1±0.4	n.a.
A5	n.a.	n.a.	1.2±0.2	n.a.	n.a.
A6	n.a.	n.a.	1.3±0.3	n.a.	n.a.
A7	1.9±0.4	4.6±0.9	6.6±1.3	4.8±1.0	3.3±0.7
A8	4.2±0.9	9.4±1.9	8.9±1.8	9.0±1.8	7.8±1.6
A9	9.0±1.8	11.2±2.2	10.4±2.1	9.7±2.0	10.0±2.0
A10	10.7±2.1	12.0±2.4	11.7±2.3	10.4±2.1	10.2±2.0
A11	13.5±2.7	15.0±3.0	14.0±2.8	12.8±2.6	11.3±2.3
B					
B1	n.a.	n.a.	n.a.	n.a.	n.a.
B2	n.a.	n.a.	n.a.	n.a.	n.a.
B3	n.a.	n.a.	n.a.	n.a.	n.a.
B4	n.a.	n.a.	n.a.	n.a.	n.a.
C					
C1	10.1±2.0	39.8±8.0	55.7±11.1	32.1±6.4	13.8±2.8
C2	13.4±2.7	14.3±2.9	18.5±3.7	19.1±3.8	14.3±2.9
C3	7.9±1.6	3.3±0.7	8.9±1.8	10.5±2.1	9.7±1.9
C4	3.8±0.8	1.9±0.4	4.9±1.0	6.1±1.2	6.2±1.2
C5	1.9±0.4	1.3±0.3	2.7±0.5	4.0±0.8	4.1±0.8
C6	n.a.	n.a.	1.9±0.4	2.8±0.6	3.0±0.6
C7	n.a.	n.a.	1.3±0.2	1.9±0.4	2.0±0.4
C8	n.a.	n.a.	1.3±0.3	2.0±0.4	2.0±0.4
C9	4.5±0.9	10.4±2.1	12.6±2.5	2.4±0.5	1.3±0.2
C10	2.8±0.6	6.2±1.3	1.4±0.3	0.9±0.2	n.a.
C11	6.1±1.2	9.1±1.8	10.1±2.0	8.9±1.8	7.3±1.5
C12	5.5±1.1	5.6±1.1	6.5±1.3	6.5±1.3	6.5±1.3
C13	4.3±0.9	2.5±0.5	4.0±0.8	4.5±0.9	4.5±0.9
C14	2.1±0.4	1.7±0.3	2.5±0.5	3.0±0.6	3.1±0.6
C15	n.a.	n.a.	2.0±0.4	2.4±0.5	2.3±0.5
C16	n.a.	n.a.	1.4±0.3	1.4±0.3	1.8±0.4
C17	n.a.	n.a.	1.5±0.3	1.3±0.3	1.6±0.3

Table 1. Dose values of ionizing radiation during computed tomography (CT) at each measurement point and at various heights relative to the floor taken on the Aquilion Prime CT scanner from Canon (Tokyo, Japan) – cont.

Point No.	Dose [μGy] (M±SD)				
	1 cm	50 cm	100 cm	150 cm	170 cm
C – cont.					
C18	5.9±1.2	6.8±1.4	7.9±1.6	8.1±1.6	7.5±1.5
C19	2.0±0.4	2.8±0.6	1.8±0.4	1.3±0.2	1.6±0.3

n.a. – dose value below lower detection limit (LDL).
A set of measurement points located according to Figure 1: A – behind the tomograph gantry, B – next to the tomograph gantry, C – placed next to the computed tomography table.

Table 2. Dose values of ionizing radiation during computed tomography (CT) in organs measured in an anthropomorphic phantom placed at various distances from the computed tomography gantry taken on the Aquilion Prime CT scanner from Canon (Tokyo, Japan)

Organ	Dose [μGy] (M±SD)	
	at the CT gantry	at the end of the CT table[a]
Brain	7.2±3.6	n.a.
Eye lens		
left	32.2±4.7	2.7±0.3
right	38.7±4.8	4.6±1.7
Thyroid	29.8±4.1	2.2±0.3
Lungs	19.7±6.6	1.2±0.2
Heart	25.7±5.1	1.2± 1.1
Kidney		
right	12.5±3.5	n.a.
left	9.2±0.1	n.a.
Stomach	33.7±7.3	1.2±0.3
Liver	48.8±3.0	1.3±0.2
Bladder	15.1±3.6	n.a.
Prostate	12.0±1.2	n.a.
Testicles	46.5±3.0	n.a.
Eyebrow arch		
left	38.6±8.0	2.6±0.6
right	42.4±9.0	2.6±0.5

n.a. – dose value below lower detection limit (LDL).
[a] 2.9 m from the gantry.

Table 3. Doses values of ionizing radiation during computed tomography (CT) obtained from the whole body dosimeter and the eye lens doses (EYE-D) dosimeter taken on the Aquilion Prime CT scanner from Canon (Tokyo, Japan)

Dosimeter	Dose [μSv] (M±SD)	
	at the CT gantry	at the end of the CT table[a]
Whole body	59.5±7.7	1.5±1.2
EYE-D		
left	28.9±6.1	2.9±0.7
right	35.3±7.6	3.0±0.6

[a] 2.9 m from the gantry.

290 cm from the gantry (C8). In the phantom placed in the C1 location, the liver and testicles received the highest dose while the brain received the smallest dose.

The average whole-body dose determined with the use of individual dosimeter was 39-fold higher in the case of the phantom placed in the C1 position relative to the C8 position. In turn a much smaller difference was observed between average eye lens doses estimated with EYE-D dosimeters in both phantom locations. The reading from position C1 relative to C8 was 11 times higher. Convergence of the results obtained from the EYE-D dosimeters with the readings obtained in the anthropomorphic

Table 4. Number of cases due to leukemia or other cancer per 100 000 people for individual age groups of people standing at the computed tomography (CT) gantry and at the end of the diagnostic table based on BEIR VII report [18]

Variable	Cases in age groups [n/100 000 people]									
	at the CT gantry					at the end of the CT table				
	20 years	25 years	30 years	35 years	40 years	20 years	25 years	30 years	35 years	40 years
Leukemia										
males	57.1	53.5	50.0	50.0	50.0	1.5	1.4	1.3	1.3	1.3
females	42.2	39.9	37.5	37.2	36.9	1.1	1.0	1.0	1.0	0.9
All cancers										
males	581.2	494.7	408.1	396.8	385.5	14.9	12.7	10.5	10.2	9.9
females	979.2	806.4	633.6	580.3	527.1	25.2	20.7	16.3	14.9	13.6

phantom was also observed. This means that EYE-D dosimeters placed on the temples correctly determine the dose in the lenses.

During the examination of pediatric patients, the guardian of the examined child is very often present in the CT examination room. To ensure the correctness of the examination and the child's peace of mind, the caregiver must maintain eye contact with the patient being examined. The measurements clearly show that the caregiver should stand during the examination at the end of the diagnostic table, at the greatest possible distance from the device's gantry. The area next to the CT gantry (area B) is also a relatively safe place. However, the presence of the guardian of the examined child in this place does not provide him with eye contact, which is necessary in some cases.

The presence of parents or legal guardians in the laboratory during the examination is in each case associated with receiving a dose of radiation that may cause adverse health effects in the future. Tables 4 and 5 show the probability of inducing leukemia or another type of cancer after receiving a dose of ionizing radiation. The analysis of these results shows that the highest probability of the occurrence of other types of cancer is higher for women than for men for all analyzed age groups. It decreases significantly as the radiation dose decreases. For people at the end of the diagnostic table, the probability of inducing leukemia or any other cancer is at the level of tenths of a permille. It increases for location C1, but it is still low. The probability decreases as the age of the exposed person increases. The caregiver who is staying next to examined child is equipped with personal protective equipment (protective apron, cap, thyroid shield), which additionally reduces the level of exposure to ionizing radiation. It should be added that all presented exposure values from the anthropomorphic phantom were obtained without additional individual shields. Incidental stay in the examination room during the examination does not carry too much health risk for the caregiver. However, increasing the frequency of visits to the laboratory proportionally increases this risk. Therefore, it is so important for medical staff to avoid being in the examination room while acquiring the images, because the addition of even small doses of radiation may lead to a high probability of leukemia or other types of cancer.

CONCLUSIONS

Computed tomography examination poses a real threat to radiological safety. Staying in the laboratory during the examination should be strictly avoided unless the clinical situation requires the participation of a guardian to ensure the safety of the diagnostic procedure. It is essential to move away from the radiation source to minimize the doses received from scattered radiation. Individual radiation shielding should be used to reduce exposure to ionizing radiation. If you must stay near the gantry and the examination table, there is a risk of inducing cancer in caregivers of pediatric patients, especially young caregivers or parents around the age of 20 years. However, despite receiving the highest doses of radiation in this place, its probability is low.

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