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Radiation Doses and Risk Assessment during Computed Tomography of the Chest in COVID-19 Patients

Elena Ivanovna Matkevich and Ivan Vasilievich Ivanov

Abstract

Accounting for the effective dose (ED, mSv) and calculating the radiation risk during CT is necessary to predict the long-term consequences of radiation exposure on the population. We analyzed the results of 1003 CT examinations of the chest in patients with suspected COVID-19 in the city diagnostic center. The average ED and confidence intervals ($p \leq 0.05$) for patients with a single CT scan were: children (12–14 years) 2.59 ± 0.19 mSv, adolescents (15–19 years) 3.23 ± 0.17 mSv, adults (20–64 years), 3.43 ± 0.08 mSv, older persons (65 years and older) 3.28 ± 0.19 mSv. The maximum radiation risk values were $31.2 \cdot 10^{-5}$ in women children and $29.3 \cdot 10^{-5}$ in women adolescents, which exceeds the risk values for men in these age groups by 2.3 and 1.9 times, respectively. For the group of adult patients the risk was $11.2 \cdot 10^{-5}$ in men and $17.4 \cdot 10^{-5}$ in women, which is 1.6 times higher than in men. All these risk values are in the range of $10 \cdot 10^{-5}$ – $100 \cdot 10^{-5}$, which corresponds to the level LOW. For the group of older age patients, the radiation risk was $2.6 \cdot 10^{-5}$, which corresponds to the level of $1 \cdot 10^{-5}$ – $10 \cdot 10^{-5}$, VERY LOW. Our materials shows in detail the technique to evaluate effective radiation doses for chest CT and calculate the radiation risk of the carcinogenic effects of this exposure.

Keywords: computed tomography, chest CT diagnostics, effective dose, radiation risks levels, the dependence of the radiation risk levels of sex and age

1. Introduction

In the coming years, due to the introduction of methods of medical diagnostics and treatment using ionizing radiation, the growth of medical exposure of the Russian population expected to continue, especially due to computed tomography (CT). Therefore, it is important to evaluate radiation dose levels and population radiation risks in the form of a possible oncological pathology among the population in the long term after exposure [1–8].

Estimating the stochastic effects on the basis of a linear non-threshold model, P. Galle [9] concluded that, compared to 700,000 spontaneous cancers per year, when recalculated to the French population, 7,000 deadly cancers are caused by radiation causes. Of these, 3,000 are associated with high concentrations in radon homes, 1,000- with radiation medical procedures, 10 - with radiation from the work of the

nuclear industry and 1 - from increased natural radiation background. Therefore, from medical exposure, 14.3% of all radiation-related oncological pathologies arise.

Due to the widespread use of CT of the chest organs for the diagnosis of COVID-19, including during repeated examinations, this issue is of particular relevance.

The aim of the study was to assess effective radiation doses for chest CT for the diagnosis of Covid-19 and calculate the radiation risk of the effects of this exposure.

2. Material and methods

2.1 General characteristics of patients

We analyzed the results of 1003 CT examinations of the chest performed in patients with suspected COVID-19 during one week in October 2020 in the city diagnostic center. Among these patients were 6.2% children in the ages of 12–14 years old, 15.3% adolescents in the ages of 15–19 years old, 60.1% adults in the ages of 20–64 years old, and 18.4% older persons of ages 65 years and older. The average ages and confidence intervals ($p \leq 0,05$) were 13.8 ± 0.20 years old in group 1 (children), 17.1 ± 0.41 years old in group 2 (adolescents); 45.8 ± 1.47 years old in group 3 (adults) (of which 41.8% are of ages 20–45 years old and 58.2% are of ages 46–64 years old); 69.4 ± 1.79 years old in group 4 (older persons). The percentage number of male (female) persons in the groups are 51.6% (48.4%) in group 1, 52.3% (47.7%) in group 2, 46.3% (53.7%) in group 3, 47% (53%) in group 4. The proportion of patients with CT signs of pneumonia and without pathological signs amounted to a total of 54,6% and 45,4%, respectively, for each of the four age groups. The distribution of the patients into groups during CT examination is given in Table 1.

Groups	Age (ears)	Subgroups by patient sex	Number of patients	Proportion of patients with CT signs pneumonia, %	Proportion of patients without CT signs of pathology, %
1	Children (12–14)	1.1. Men	32	15.6	84.4
		1.2. Women	30	13.3	86.7
		1. Total	62	14.5	85.5
2	Adolescents (15–19)	2.1. Men	80	26.3	73.7
		2.2. Women	73	21.9	78.1
		2. Total	153	24.2	75.8
3	Adults (20–64)	3.1. Men	279	55.6	44.4
		3.2. Women	324	71.0	29.0
		3. Total	603	63.8	36.2
4	Older people (65 and older)	4.1. Men	87	77.0	23.0
		4.2. Women	98	51.0	49.0
		4. Total	85	63.2	36.8
Total Sample			1003	54.6	45.4

Table 1.
The distribution of patients in groups during CT examination on COVID-19.

2.2 Description of computed tomography technique, calculation of effective dose and radiation risk

CT studies of the chest were performed on a Siemens Somatom Emotion 16 scanner (16-slice) using a standard algorithm. The voltage on the tube was 130 kV with automatic modulation of the amperage; the slice thickness was 0.8 mm (pitch 1.4) or 1.5 mm (pitch 1.2). Of each patient, the values of the parameters determining the radiation load were entered into the database CTDI_{vol} (mGy), DLP (mGy*cm) and ED, mSv.

The calculation of the effective dose (ED, mSv) for a single phase CT scan was performed according to the following equation.

The CTDI_{vol} values were entered into the database from the CT scanner console. Then, the DLP was calculated by the formula:

$$DLP \text{ (mGy} \cdot \text{cm)} = CTDI_{vol} \text{ (mGy)} \times \text{irradiated length (cm)} \quad (1)$$

The procedure for registering the indicator “irradiated length (cm)” was as follows. Previously, the X-ray technician performed an X-ray (tomogram) of the chest. Then the region of interest (ROI) was installed on the CT scanner console in accordance with the Recommendations of EUR16262, 1999 [10]: Volume of investigation (routine chest) - from lung apex to the base of the lungs. The length of this area (irradiated length) was measured individually in each patient. In this area, a CT scan was subsequently performed and, accordingly, the patient was irradiated. DLP was calculated for this zone.

In our study, for the chest the “irradiated length” (Median, 25th and 75th percentile) was (cm): 31.3 (30.1–33.4) - in children, 34.7 (32.6–36.6) - in adolescents, 36.6 (34.9–38.7) - in adults, 33.3 (31.6–36.8) – for persons 65 years and older.

Then, using the DLP, the effective doses was estimated according to the formula [11]:

$$ED, \text{ mSv} = K_{ED \text{ DLP}} \cdot DLP. \quad (2)$$

To calculate the effective dose (ED, mSv) the chest $K_{ED \text{ DLP}}$ conversion factor (mSv*mGy⁻¹*cm⁻¹) used was $K_{ED \text{ DLP}} = 0.012$ for both the children group (12–14 years old) and the adolescent group (15–19 years old) and $K_{ED \text{ DLP}} = 0.016$ for the subjects older than 19 years [12, 13].

The method of calculating the risk of radiation consequences is based on the analysis of the frequency of leukemia and other oncological diseases, hereditary disorders in subsequent generations in the population after irradiation of people during the atomic explosions in Hiroshima and Nagasaki, the Marshall Islands, after gamma irradiation of patients with cancer and after incidents and accidents at nuclear reactors. Several hundred publications with this information were summarized in ICRP Publication 103, 2007 [11], and the risks of these consequences in persons of different genders and ages were calculated depending on the radiation dose received. In our study, calculations of radiation risk are carried out according to the National Methodological Recommendations [14] as follows:

$$R = ED \cdot r, \quad (3)$$

where

R is the radiation risk per 100,000 population at an exposure dose of ED, mSv;

ED - effective dose, mSv;

r - risk indicator for exposure of 1 mSv (mSv⁻¹).

Age, years	Man	Woman	Age, years	Man	Woman
0–4	$5,6 \cdot 10^{-5}$	$2,2 \cdot 10^{-4}$	45–49	$2,9 \cdot 10^{-5}$	$4,9 \cdot 10^{-5}$
5–9	$5,0 \cdot 10^{-5}$	$1,8 \cdot 10^{-4}$	50–54	$2,6 \cdot 10^{-5}$	$4,1 \cdot 10^{-5}$
10–14	$4,6 \cdot 10^{-5}$	$1,4 \cdot 10^{-4}$	55–59	$2,1 \cdot 10^{-5}$	$3,4 \cdot 10^{-5}$
15–19	$4,4 \cdot 10^{-5}$	$1,0 \cdot 10^{-4}$	60–64	$1,7 \cdot 10^{-5}$	$2,7 \cdot 10^{-5}$
20–24	$4,0 \cdot 10^{-5}$	$8,1 \cdot 10^{-5}$	65–69	$1,3 \cdot 10^{-5}$	$2,0 \cdot 10^{-5}$
25–29	$3,8 \cdot 10^{-5}$	$7,1 \cdot 10^{-5}$	70–74	$9,5 \cdot 10^{-6}$	$1,3 \cdot 10^{-5}$
30–34	$3,6 \cdot 10^{-5}$	$6,3 \cdot 10^{-5}$	75–79	$6,4 \cdot 10^{-6}$	$7,9 \cdot 10^{-6}$
35–39	$3,4 \cdot 10^{-5}$	$5,6 \cdot 10^{-5}$	80–84	$4,3 \cdot 10^{-6}$	$4,6 \cdot 10^{-6}$
40–44	$3,3 \cdot 10^{-5}$	$5,7 \cdot 10^{-5}$	85+	$2,1 \cdot 10^{-6}$	$1,3 \cdot 10^{-6}$

Table 2.
Lifetime risk of death ratios, taking into account harm from reduced quality of life, calculated [14] per 1 mSv effective dose for medical diagnostic chest irradiation.

Radiation risk levels	Radiation risk	
	Values	Values per 100,000 people
NEGLIGIBLE	$<10^{-6}$ (less than 1 case per 1,000,000 people)	< 0.1
MINIMUM	10^{-6} – 10^{-5} (1 to 10 cases per 1,000,000 people)	0.1–1
VERY LOW	10^{-5} – 10^{-4} (1 to 10 cases per 100,000 people)	1–10
LOW	10^{-4} – 10^{-3} (1 to 10 cases per 10,000 people)	10–100
MODERATE	10^{-3} – $3 \cdot 10^{-3}$ (1 to 3 cases per 1,000 people)	100–300

Table 3.
The radiation risk levels (individual lifetime risk) to a patient’s health associated with medical exposure during diagnostic studies or treatment procedures [14].

A risk indicator for exposure of 1 mSv used, lifetime cancer risk of radiation is $5.5 \cdot 10^{-5} \text{ mSv}^{-1}$ for the entire population regardless of age and sex. However, in this study r (risk indicator) were used, taking into account the age and sex of patients (**Table 2**) in accordance with the National Methodological Recommendations [14]. These values were calculated for the Russian population (mortality and morbidity data for 2008) using risk models and ICRP calculation methods [11, 15]. When calculating Radiation risk level, the scales listed in **Table 3** were used.

The mean and median values of effective doses in the formed groups were close, the assessment of the data according to Kolmogorov–Smirnov test for normality and Shapiro–Wilk’s W test showed that the nature of their distribution is close to normal. The measured data were expressed as the average \pm confidence interval ($X \pm CI$) at $p \leq 0.05$, as well as median (Me, 25th and 75th percentile). The significance of differences between the groups according to Student t -criterion, P value < 0.05 was considered for statistical significance. STATISTICA statistical software (version 10.0; Stat Soft. Inc., United States) was used for analysis.

3. Results and discussion

The average effective doses to patients with a single CT scan in the formed groups as illustrated in **Table 4** and **Figure 1A** were $2.59 \pm 0.19 \text{ mSv}$ in group 1 (children 12–14 years old), $3.23 \pm 0.17 \text{ mSv}$ in group 2 (adolescents 15–19 years

Groups	Age (years)	Subgroups by sex	ED, Me (25th; 75th percentile), mSv [*]	ED, X ± CI, mSv [*]	Radiation risk			
					Cases, per 100,000 people			Level
					Calculating	Values	Criteria interval	
1	Children (12–14)	Men	2.65 (2.45; 2.96)	2.92 ± 0.30	ED*4.6	13.4	10–100	LOW
		Women	2.17 (1.88; 2.46)	2.23 ± 0.16	ED*14.0*	31.2	10–100	LOW
		Total	2.46 (2.13; 2.70)	2.59 ± 0.19	ED*9.3*	24.1	10–100	LOW
2	Adolescents (15–19)	Men	3.38 (3.01; 3.88)	3.50 ± 0.23	ED*4.4	15.4	10–100	LOW
		Women	2.51 (2.37; 3.15)	2.93 ± 0.23	ED*10.0	29.3	10–100	LOW
		Total	3.13 (2.37; 3.60)	3.23 ± 0.17	ED*7.2	23.3	10–100	LOW
3	Adults (20–64)	Men	3.69 (3.05; 4.10)	3.61 ± 0.08	ED*3.1	11.2	10–100	LOW
		Women	3.27 (2.42; 3.77)	3.28 ± 0.13	ED*5.3	17.4	10–100	LOW
		Total	3.39 (2.72; 3.93)	3.43 ± 0.08 ^{1,2}	ED*4.2	14.4	10–100	LOW
4	Older people (65 and older)	Men	3.15 (2.57; 3.90)	3.30 ± 0.23	ED*0.7	2.3	1–10	VERY LOW
		Women	3.26 (2.05; 4.20)	3.26 ± 0.30	ED*0.9	2.9	1–10	VERY LOW
		Total	3.21 (2.51; 3.90)	3.28 ± 0.19 ^{3,4}	ED*0.8	2.6	1–10	VERY LOW

^{*}Significance of differences mean values ED (X) between groups ($p \leq 0,05$) ¹1 and 3, ²2 and 3, ³1 and 4, ⁴2 and 4.

Table 4.
Effective doses and their compliance with radiation risk levels in patient groups with a single CT scan of the chest on COVID-19.

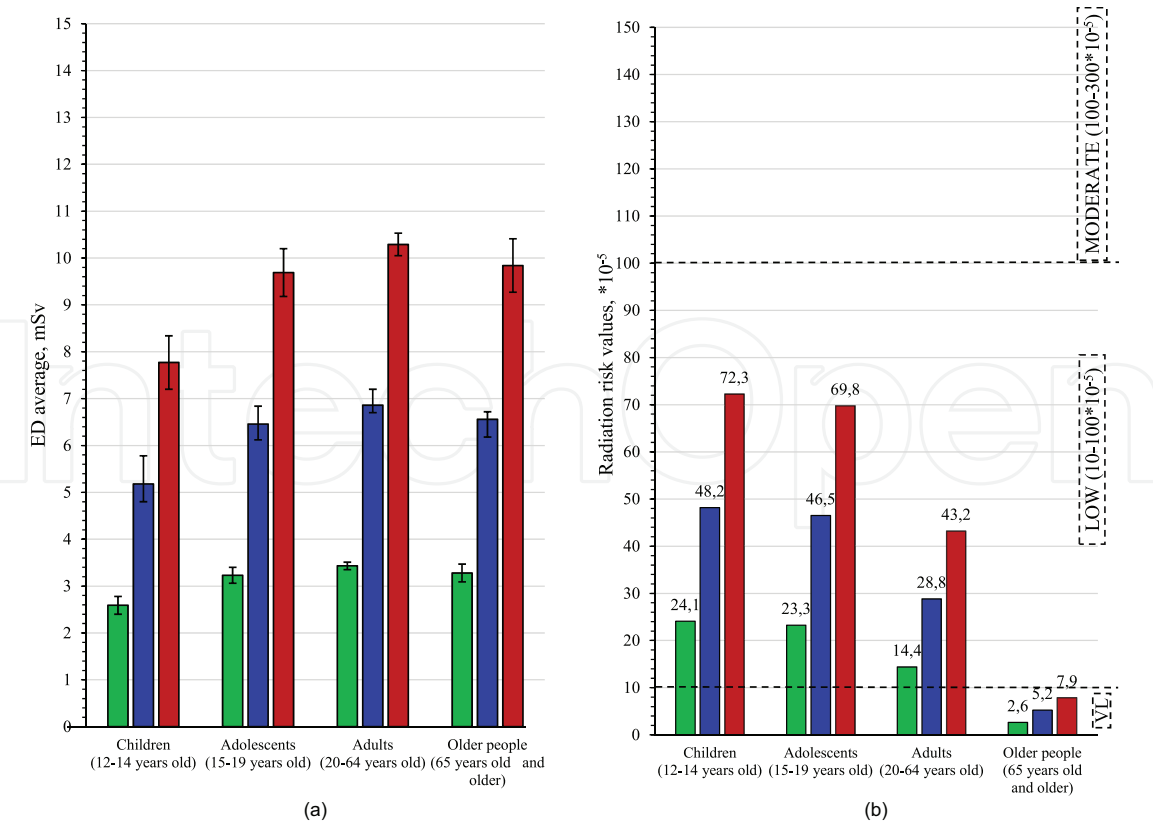


Figure 1. Average doses, mSv (A), and radiation risk values by age groups of patients (B) with a single, double and triple computed tomography of the chest. On the ordinate axis: (A) – average effective dose and confidence intervals ($p \leq 0.05$), mSv; (B) – values of radiation risk per 100,000 people; on the abscissa: age groups. Legend: number of CT scans of the patient, ■ – single, ■ – double, ■ – triple. The dashed lines show the boundaries between the levels of radiation risk (*).

old), 3.43 ± 0.08 mSv in group 3 (adults 19–64 years old) and 3.28 ± 0.19 mSv in group 4 (older persons – 65 years and older).

These doses are comparable with the ED values shown in the report [16] on the evaluation of DRLs for adult CT in European countries and in studies of other authors [17–19]. The DRLs for CT of adult chest organs in European countries were: 4.7–6.31 mSv in Netherlands [11, 14], 5.1–5.95 mSv in Germany [16, 18], 6.8 mSv in Austria [16], 5.95–10.4 mSv in Great Britain [16, 19], 7.31 mSv in Finland [16], 8.5–10.5 in Denmark [16], as well as 7.65 mSv in Australia [20].

In our earlier study [21], with standard protocols on different CT scanners, the values of the ED were in the ranges of 2.4–6.04 mSv and 8.4–15.33 mSv, for a single-phase and multiphase with contrast CTs, respectively. The use of low-dose protocols (tube voltage from 80 to 100 kV with automatic modulation of current) made it possible to reduce the ED to 1.6 mSv, when applying the iterative reconstruction algorithm MBIR for single-phase CTs and to 4.41 mSv when applying the iterative reconstruction algorithm ASIR for multiphase CTs [22].

Based on the risk indicator value for exposure of 1 mSv with age and sex (Table 3) were calculations radiation risk values and radiation risk levels after chest CT radiation per 100,000 exposed persons (Table 4). The maximum radiation risk values for a single CT were observed (Figure 1B) in groups of children ($24.1 \cdot 10^{-5}$) and adolescents ($23.3 \cdot 10^{-5}$). As can be seen in Figure 2B, the radiation risk values for a single CT were $31.2 \cdot 10^{-5}$ in women children (12–14 years old) and $29.3 \cdot 10^{-5}$ in women adolescents (15–19 years old), which exceeds the risk values for men in these groups by 2.3 and 1.9 times, respectively. For the group of adult patients the

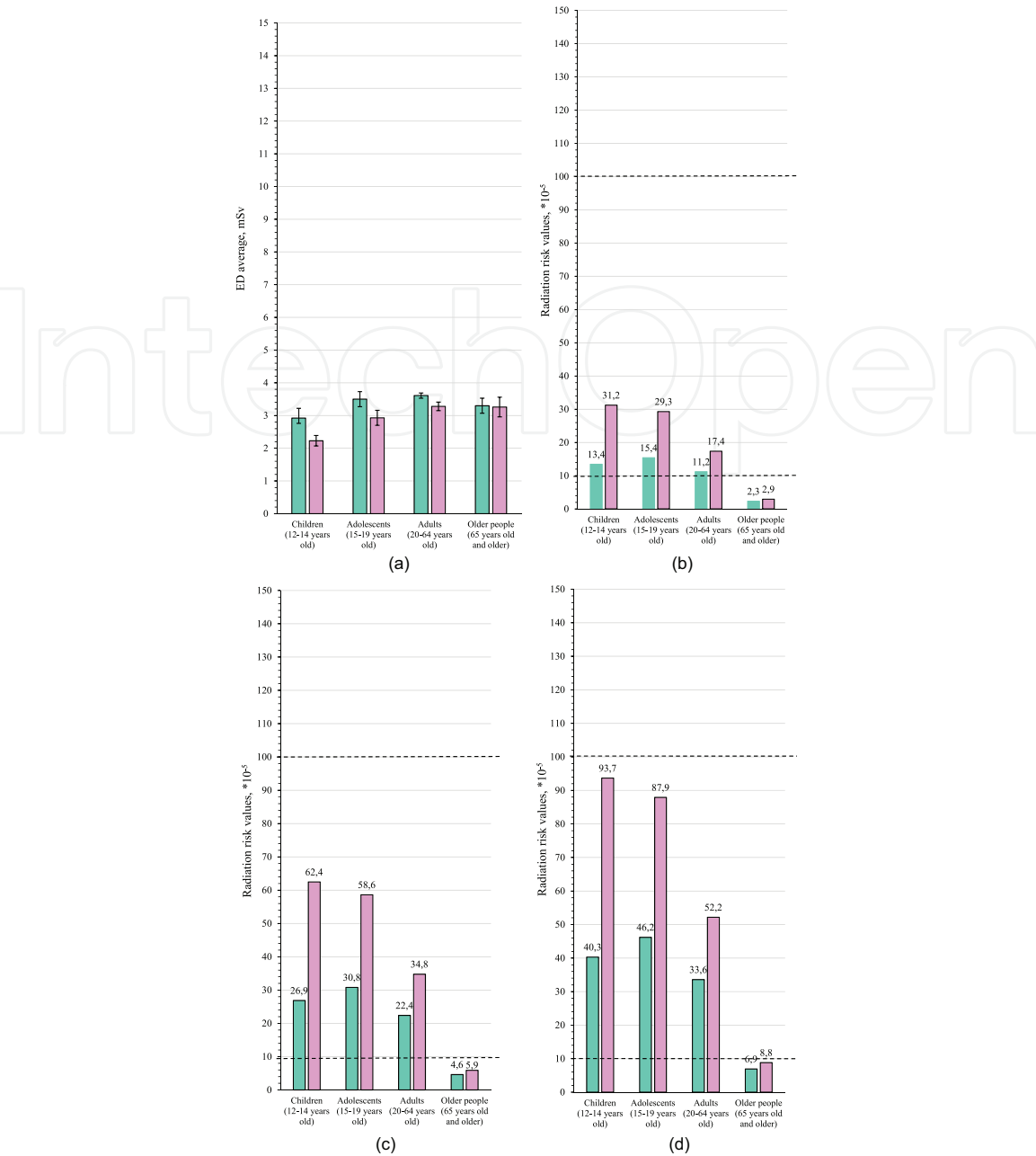


Figure 2. Average doses for a single CT scan (A), radiation risk values for a single (B), twice repeated (C) and triple (D) CT, distribution by levels of radiation risk by age groups and depending on the sex of patients. On the ordinate axis: (A) – average effective dose and confidence intervals ($p \leq 0.05$), mSv; (B–D) – values of radiation risk per 100,000 people; on the abscissa axis: age groups. Legend: ■ – men, ■ – women. The dashed lines show the boundaries between the levels of radiation risk (*).

average risk was $14.4 \cdot 10^{-5}$, ($11.2 \cdot 10^{-5}$) in men and $17.4 \cdot 10^{-5}$ in women, which is 1.6 times higher than in men. Nevertheless, all these risk values are in the range of $10 \cdot 10^{-5}$ – $100 \cdot 10^{-5}$, which corresponds to the level LOW. For the group of older age patients, the radiation risk was $2.6 \cdot 10^{-5}$, which corresponds to the level range of $1 \cdot 10^{-5}$ – $10 \cdot 10^{-5}$, VERY LOW.

We have compared the calculations with estimates of radiation risks in other studies.

For example, when planning the limits of exposure of astronauts [23], the risk of oncological diseases and genetic effects are rather low: $0.2 \cdot 10^{-6}$ for leukemia, $0.2 \cdot 10^{-6}$ for other types of malignant neoplasms, and $0.05 \cdot 10^{-6}$ for genetic effects, per year per dose of additional irradiation of 1 mSv. Spontaneous incidence are

$50 \cdot 10^{-6}$ for leukemia, $1000\text{--}2000 \cdot 10^{-6}$ for other types of malignant neoplasms and $8000 \cdot 10^{-6}$ for genetic effects per year.

In publication 103 of the ICRP [11], new views of the ICRP on the principles and approaches to ensuring radiation safety, are formulated in comparison with the previous document - Publication 60 of the ICRP [15]. Epidemiological data obtained since the publication of Publication 60 of the ICRP served as a reason for revising the values of the nominal risk factors per unit dose for radiogenic cancers and hereditary effects (**Table 5**).

As we can see, the new risk values in Publication 103 are slightly lower as those specified in Publication 60. But, at the same time, for children compared with adults, they were increased in terms of Malignant neoplasms from 1.5 to 1.68, for hereditary defects from 2.25 to 3.0, and in the total number of negative effects from 1.61 to 2.0. Our results are comparable to these guidelines.

I.A. Tsalaftoutas, G.V. Koukourakis [24] emphasize that stochastic negative effects can be caused even by small doses of radiation, and give the following example of calculating the risk associated with radiation during CT. The assumption of a 5% probability of risk per 1 Sv (1,000 mSv) for the occurrence of cancer or hereditary effects means that the examination, which leads to patient exposure in $ED = 10$ mSv (typical for CT of the abdomen and pelvis), implies 0.05% chance of such risks. That is, for every 10,000 patients, who underwent CT with a dose of 10 mSv, five people can be expected, to develop cancer or hereditary effects as the result of radiation.

There was calculation individual of effective dose and risk of malignancy based on Monte Carlo simulations after whole body CT [25]. The Excess Relative Risk (ERR_{MC}), as a measurement of the exceeding risk of an exposed person compared to a non-exposed person, calculated using the solid cancer mortality in the United States as baseline (female: 17,500/100,000; male: 22,100/100,000).

There was calculation individual of Effective Dose and estimation of organ-specific additional Lifetime Attributable Risk (LAR) of cancer mortality after Whole Body Computed Tomography based on Monte Carlo simulations and report VII about Biologic Effects of Ionizing Radiation (BEIR VII). Considering the effective doses of 1.48 ± 0.15 mSv for the lungs, the LAR for mortality from lung cancer [$n / 100,000$] was 13.25 ± 4.24 .

In our study, it was shown that with a single chest CT scan in patients with suspected COVID-19, additional (to a spontaneous level) cases of oncological pathology per 100,000 people may occur: 24.1 cases in children, 23.3 cases in adolescents, 14.4 cases in adults, 2.6 cases in older persons.

The average effective dose will increase in proportion to the increase in the number of CTs performed on the patient from 2.6–3.4 mSv with a single CT scan to the calculated values of 7.8–10.3 mSv with three times CTs. This will lead to a threefold increase in radiation risks to levels per 100,000 people may occur

Irradiated population	Malignant neoplasms		Hereditary effects		Total	
	Publ. 103	Publ. 60	Publ. 103	Publ. 60	Publ. 103	Publ. 60
Whole population	5.5	6.0	0.2	1.3	6.0	7.3
Adults	4.1	4.8	0.1	0.8	4.0	5.6
Children	6.9	7.2	0.3	1.8	8.0	9.0
$K_{Adults/Children}$	1.68	1.5	3.0	2.25	2.0	1.61

Table 5.
Comparison of the risk of negative effects of exposure from a dose of 1 mSv, number of cases per 10^5 people (ICRP Publication 103, 2007 [11]; ICRP Publication 60, 1991 [15]).

(**Figure 1B**): 72.3 cases in children, 69.8 cases in adolescents, 43.2 cases in adults, 7.9 cases in older persons. Due to the increased post-radiation risks in children; currently, both the European and the American Society of Pediatric Radiology do not recommend the use of CT to diagnose COVID-19 pneumonia in children. CT is indicated only for severe, where concurrent pathology need to be excluded.

In men, the average radiation doses in the four age groups were slightly higher than in women (**Figure 2A**). However, with an increase in the number of CT scans from one (**Figure 2B**) to two (**Figure 2C**) and up to three (**Figure 2D**) in females, the increase in the calculated radiation risk compared to men is more significant, especially in women children (in 2.3 times) and among women adolescent (in 1.9 times). The radiation risk in men and women in all subgroups by age up to 65 years remains at the LOW level (10×10^{-5} – 100×10^{-5}), and in the older subgroup at the VERY LOW level (1×10^{-5} – 10×10^{-5}). However, with a three-fold CT scan in groups of children and adolescents, the radiation risk in women approaches the border of the MODERATE level (100×10^{-5} – 300×10^{-5}), and in the old group to the border of the LOW level (10×10^{-5} – 100×10^{-5}).

By evaluating the lung irradiation with the doses used in the ongoing clinical trials to treat COVID -19 patients, our data shows that a radiation dose 0.5 Gy provides an acceptable Risk Identification Checklist (RIC) estimate (LAR 1%), irrespective of sex and age at exposure [26]. However, a promising direction is the use of modern CT scanners, which allow the use of low-dose algorithms for CT diagnostics [27], while significantly reducing the radiation exposure to patients.

4. Conclusions

Because the study established effective radiation doses for chest CTs of patients with the diagnosis of COVID-19, the radiation risks for a single, double and triple chest CTs in different age and sex of patients were calculated. It has been found, that the radiation risk due to a single, double and triple chest CTs for patients under 65 years old is LOW, and for 65 years old and older patents is VERY LOW. Taking into account the radiation risk during CT is necessary to reduce the long-term consequences of radiation exposure on the population.

Financing

The study was performed without external funding.

Conflict of interest

The authors declare no conflict of interest.

Conformity with the principles of ethics

The study was approved by the local ethics committee.

Abbreviations

ASIR	Adaptive Statistical Iterative Reconstruction
CT	Computed tomography

CTDI _{vol}	Computed tomography dose index
DLP	Dose length product
DRLs	Diagnostic reference levels
ED	Effective doses
ICRP	International Commission on Radiological Protection
LAR	Lifetime Attributable Risk
MBIR	Model-Based Iterative Reconstruction

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