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THYROID MASS IN CHILDREN AND ADOLESCENTS LIVING IN THE MOST EXPOSED AREAS TO CHERNOBYL FALLOUT IN BELARUS

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This paper aims to determine the thyroid volumes in children and teenagers living in Gomel and Mogilev Oblasts, which are the areas of Belarus that were most affected by the Chernobyl accident. Results of thyroid volume measurements performed in 1991–1996 by the Sasakawa Memorial Health Foundation were used to evaluate the variation by age of the thyroid volumes for girls and boys aged from 5 to 16 y. Thyroid volumes for age groups without measurements were also estimated. For a given age and gender, the differences between children from Gomel and Mogilev Oblasts do not exceed 12 %, which is relatively small when the variability of individual values is considered. For children of a given age, the individual values show a variability characterised by geometric standard deviation (GSD) of 1.25–1.4. Values of thyroid mass that were derived from the measured thyroid volumes are being used within the framework of the on-going Belarusian-American cohort study of thyroid cancer and other thyroid diseases after the Chernobyl accident to estimate with more accuracy the thyroid doses that were received by the cohort members.

INTRODUCTION

One of the most important parameters in the calculation of the thyroid dose is the thyroid mass that can be estimated from measured thyroid volume. The thyroid mass is a parameter that accounts for around 50 % of the thyroid dose uncertainty(1). The evaluation of the consequences of the thyroid exposure to radioactive iodine as a result of the Chernobyl accident should be based on reliable information on thyroid volumes in the considered population at the time of the accident. This is especially important for the children who showed multiple manifestations of thyroid pathology including malignant tumours. As the thyroid volume generally reflects the conditions of dietary intake of stable iodine, the thyroid volume may vary from one region to another(2). Information on thyroid volume among populations in the most affected regions of Belarus, which are Gomel and Mogilev Oblasts, is necessary if thyroid doses to children who resided in these areas at the time of, or shortly after, the Chernobyl accident have to be calculated.

The best estimates of thyroid dose from ^{131}I intakes have been derived from direct measurements of ^{131}I activity in the thyroid(3); unfortunately, measurements of thyroid volume were not made at the same time as the direct thyroid measurements. Estimates of thyroid volume could be made for these children or for other children of the same regions, but they had to be made within a few years after the accident to make sure that the conditions of iodine supply with diet had not substantially changed. Such measurements were carried out by the Sasakawa Memorial Health Foundation(4) within the framework of the international Project 'Chernobyl, Sasakawa' in 1991–1996. The measurements were made in the most contaminated areas of Russia, Ukraine and Belarus. In Belarus, mass screening covered about 57 500 children living in Gomel and Mogilev Oblasts.

The US National Cancer Institute and the Ministry of Health of Belarus are collaborating to conduct a cohort study of thyroid cancer and other thyroid diseases in Belarus after the Chernobyl accident(5). Dose estimates for about 11 800 study subjects exposed in childhood and adolescence to Chernobyl fallout are based upon the measurements of ^{131}I content in thyroids that were conducted during the first few weeks after the accident(6). Because thyroid mass is one of the most important parameters of thyroid dosimetry model for ^{131}I intakes, this parameter should be estimated with as high accuracy as possible(1). Therefore, it was very

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important to perform a careful analysis of the thyroid-volume measurements that were kindly transferred by Sasakawa Memorial Health Foundation to the Ministry of Health of Belarus for use in the determination of thyroid doses within the framework of the on-going Belarusian-American cohort study.

The databases that were obtained from Sasakawa Memorial Health Foundation were used to estimate age-gender-specific thyroid volumes for children living in Gomel and Mogilev Oblasts. The following activities were performed within the framework of this study.

(1) Analysis and cleaning of databases to make them more suitable to the needs of the Belarusian-American study. It was found that Sasakawa database with the results of thyroid-volume measurements in children who resided at the time of the measurements in Gomel Oblast contains errors. Approach was suggested in this study to identify and correct the errors.
(2) Estimation of the thyroid volumes for age–gender groups that were not measured in the framework of the Sasakawa project.
(3) Comparison of the obtained average age–gender specific thyroid-mass values for Belarus with the values recommended by the ICRP[7].

MATERIALS AND METHODS

Ultrasound measurements

Ultrasound measurements of thyroid volume for children and adolescents in Gomel and Mogilev Oblasts of Belarus were performed by the Sasakawa Memorial Health Foundation during a mass screening campaign within the framework of the Project 'Chernobyl, Sasakawa' in 1991–1996[4]. For this purpose, Japanese scientists used an automatic arch-scanning ultrasonographic device (Aloka-SSD 520, Aloca Co., Tokyo, Japan) with a 7.5-MHz annular array transducer 25 mm in diameter[8]. The thyroid volume was calculated by computerised digitiser using images of 11 cross sections at 5 mm intervals recorded on a optic disk[9].

The measurements of thyroid volume were made under the supervision of Japanese experts by the employees of the specialised dispensary in Gomel city and of the diagnostic centre of Mogilev city. In the cities of Gomel and Mogilev, the measurements of children and teenagers (boys and girls) residing in cities and countryside were carried out in medical buildings; in other areas, the measurements were made by mobile teams, mainly in schools and preschool kindergartens.

The Sasakawa databases of thyroid volumes for children screened in the Gomel and Mogilev Oblasts contain information on 57 490 measurements. In addition, iodine and creatinine content in the urine as well as serum-free thyroxine and thyroid-stimulating hormone levels were measured for some of the examined children. This paper considers the measurements of thyroid volume only.

It should be noted that oblast is the largest administrative unit in Belarus. Typical size of an oblast is 30 000–40 000 km^2 with a population of 1.1–1.5 million persons. There are six oblasts in Belarus; their borders are shown as thin lines on Figure 1. The figure also shows the geographical pattern of deposition density of ^{137}Cs in Belarus resulting from the Chernobyl accident (according to the Committee for Hydrometeorology of Belarus). Cities of Gomel, Mogilev, Mozyr, Zhlobin, Rechitsa and Svetlogorsk, mentioned in the paper, are also shown in the figure.

Processing of Sasakawa databases

There are two Sasakawa databases. One contains results of 29 644 thyroid-volume measurements in children aged from 3 to 18 y who resided at the time of the measurements in Mogilev Oblast. The other contains results of 27 846 measurements in Gomel Oblasts. Besides information on results of the thyroid-volume measurements, the Sasakawa databases have information on age and gender of measured children and on the date of measurement. Databases for Mogilev and Gomel Oblasts were analysed separately.

Analysis of the Mogilev database

The analysis was based on yearly age–gender data. The use of the Kolmogorov–Smirnov test showed that all Mogilev yearly age–gender arrays are log-normally distributed. A comparison of the average thyroid volumes measured in successive years indicated that, for unknown reasons, the thyroid volumes measured in 1992 were systematically smaller than those measured in other years for all age–gender groups (Figure 2). Therefore, it was decided not to include the results of the thyroid measurements made in 1992 in the estimation of average thyroid volumes of children from Mogilev Oblast. Unfortunately, it was not possible to identify the reason why values of thyroid volumes measured in 1992 are smaller than those measured in other years. However, Prof. Shunichi Yamashita, one of the Japanese scientists who organised and performed the measurements in Belarus agreed with this proposed exclusion from further analysis of smaller volumes measured in 1992 (Shunichi Yamashita, personal communication, 2010).

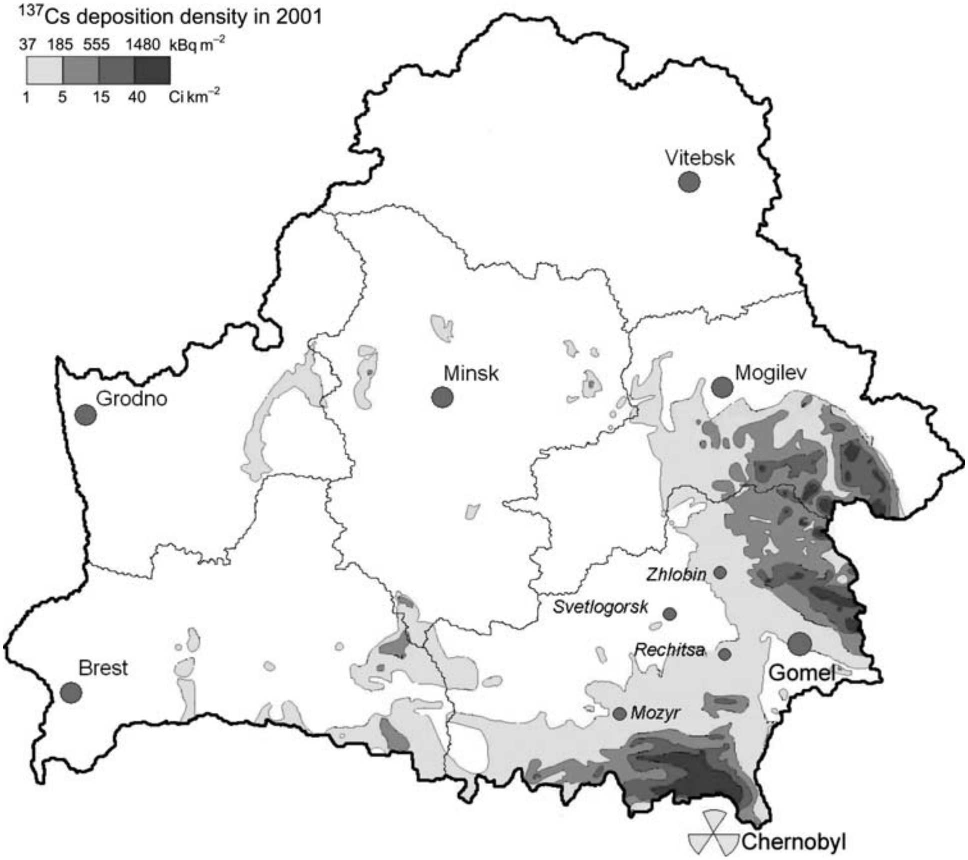

Figure 1. Deposition density of ^{137}Cs in Belarus resulting from the Chernobyl accident according to the Committee for Hydrometeorology of Belarus.

Analysis of the Gomel database

Analysis of yearly age–gender distributions of thyroid volumes showed that yearly age–gender arrays for 1994, 1995 and 1996 were log-normally distributed, but that yearly age–gender arrays for 1991, 1992 and 1993 did not satisfy the Kolmogorov–Smirnov test for log-normal distribution. Frequency analysis (estimation of number [frequency] of times that every value in the considered array is occurred) showed that all yearly age–gender arrays for years of 1991, 1992 and 1993 had at least one so-called 'anomalous' frequency. The anomalous frequencies were more than one order of magnitude higher than neighboring frequencies. Figure 3 shows example of 'anomalous' frequency observed in the distribution of thyroid volumes measured in Gomel Oblast in 1993 among boys aged 10 y.

To identify the reason for such 'anomalous' results, several specialists were contacted who participated in the measurement campaign in 1991–1993. It was found out in 1993 that one employee of the Gomel dispensary who performed the measurements did not make the elaborate and time-consuming thyroid-volume calculations based on the results of the measurements with the Aloka-SSD 520. Instead, this person assigned to some children the age- and gender-specific tabulated value of thyroid volume measured in Gomel Oblast in 1991–1993. This employee was fired in 1993. These values assigned to children were not the reference values of thyroid volume used either in Belarus either in Russia in early 1990s; their origin is unknown (Dr. V. Drozd and Prof. V. Parshin, personal communications).

The determination of the yearly age–gender arrays containing 'anomalous' frequencies was made using χ^2 statistics:

$$\chi^2 = \sum_i \frac{(n_{e,i} - n_{t,i})^2}{n_{t,i}}, \quad (1)$$

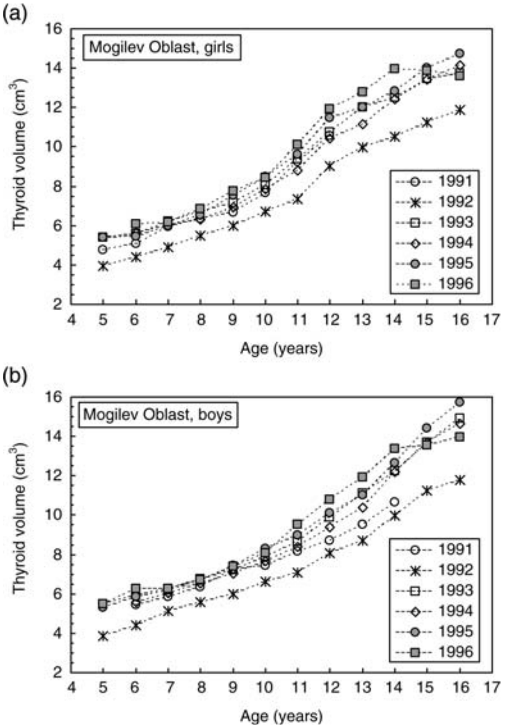

Figure 2. Mean thyroid volumes measured in Mogilev Oblast in different years in (**a**) girls and (**b**) boys.

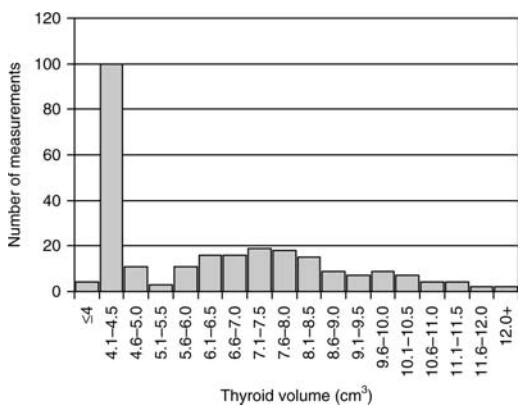

Figure 3. Distribution of thyroid volumes measured in Gomel Oblast in 1993 among boys aged 10 y, which shows an example of 'anomalous' frequency observed.

where $n_{e,i}$ is the observed frequency of value i; $n_{t,i}$ is the theoretical frequency of value i.

Maximal value of χ^2 for log-normally distributed yearly age–gender arrays of thyroid-volumes values in Mogilev and Gomel Oblasts was 47.6 while values of χ^2 for yearly age–gender arrays of thyroid volumes with 'anomalous' frequency were found to be 76–3529. On this basis, a value of χ^2=48 was used as an indication of the presence of anomalous frequencies. An algorithm was developed of accurate slashing of anomalous frequencies until value of χ^2 for them will become less than 48 with parallel checking of the whole yearly age–gender array with Kolmogorov–Smirnov test. Yearly age–gender log-normally distributed arrays of thyroid volumes measured in 1991, 1992 and 1993 were obtained as a result of the frequency correction procedure.

It was found that the values of thyroid volumes measured in 1992 are somewhat smaller than those measured in 1991 and 1993–1996. By analogy with what was done for the Mogilev database, it was decided not to use the results of measurements made in 1992 in the estimation of the average thyroid volumes for the children of Gomel Oblast.

Table 1. Number of children included in the revised databases according to age and gender.

Age (years)	Age group (years)	Gomel Oblast		Mogilev Oblast	
		Girls	Boys	Girls	Boys
3.0–3.99	3	20	31	5	8
4.0–4.99	4	119	140	81	62
5.0–5.99	5	415	365	310	305
6.0–6.99	6	568	579	871	881
7.0–7.99	7	936	856	1200	1182
8.0–8.99	8	1280	1160	1166	1172
9.0–9.99	9	1302	1307	1288	1299
10.0–10.99	10	1295	1198	1243	1240
11.0–11.99	11	1259	1097	1314	1193
12.0–12.99	12	1183	1112	1176	1122
13.0–13.99	13	1162	1050	1142	1056
14.0–14.99	14	1026	863	1054	1080
15.0–15.99	15	473	371	835	746
16.0–16.99	16	160	112	610	479
17.0–17.99	17	106	77	156	122
18.0–18.99	18	8	4	6	4
Total		11 312	10 322	12 457	11 951

RESULTS AND DISCUSSION

Revised Sasakawa databases for Gomel and Mogilev Oblasts

As a result of the databases processing, 11 448 of the original 57 490 measurements (20 %) were excluded from the Sasakawa databases, so that the number of measurements included in the study is 46 042 (21 634 for Gomel and 24 408 for Mogilev Oblasts). The number of children included in the revised databases, according to oblast, age and gender is shown in Table 1.

Comparison of the values of thyroid volume in rural and urban populations

The subjects of the Belarusian-American cohort study resided at the time of the accident in settlements that could be rural or urban. For individuals who resided in rural areas, the diet consisted mainly of locally produced foodstuffs that provided most of the daily iodine intake. The food supply in large cities was mainly dependent on foodstuffs imported from iodine-sufficient regions outside Belarus. As the thyroid volume generally reflects the conditions of dietary intake of stable iodine[(2)], thyroid volumes in rural and urban population may be different. The thyroid volume values obtained for rural population and cities in Gomel Oblast were compared by age and gender (Table 2). It should be noted that this comparison does not include thyroid-volume values measured in inhabitants of towns who consumed, in similar proportions, both locally produced foodstuffs from their private farms and foodstuffs from the trade network. The comparison of thyroid volumes between rural and urban populations was not done for Mogilev Oblast as majority of measurements in this oblast were done among rural population.

As can be seen from Table 2, there are statistically significant differences between the thyroid volumes measured in rural and urban populations, except for boys aged 5.0–7.99 y and 14.0–15.99 y. Although the differences were found to be statistically significant, they are small in absolute terms; for the purposes of this study, it was decided not to separate rural and urban populations. Therefore, the revised databases were used in the analyses without consideration of the results obtained separately for rural and urban populations.

Distribution of the thyroid volume by gender and age

Tables 3 and 4 show the parameters of the distributions of the thyroid volume by age and gender for children from Gomel and Mogilev Oblasts. Results are not given for age groups 3, 4, 17 and 18 y as relatively small numbers of children were measured in these age groups (Table 1). The trends in the increase of the thyroid volume with age are practically the same in the two Belarusian oblasts. As a rule, the thyroid volumes in Mogilev Oblast are somewhat higher (up to 12 %) than in Gomel Oblast. In each oblast, there is a difference between the thyroid volumes of girls and boys of ages 10–14 y; that difference is more noticeable in Gomel Oblast (up to 14 %) than in Mogilev Oblast (up to 10 %). For girls and boys less than 10 y old within the same oblast, there is no significant difference between the thyroid volumes of children of the same age. For that reason, the results of the thyroid volume measurements for boys and girls aged less

Table 2. Comparison of thyroid-volume (TV) values for rural population and urban population in Gomel Oblast by age and gender.

Oblast, population	Age groups (years)							
	5–7.99		8–10.99		11–13.99		14–15.99	
	n	TV (cm^3)	*n*	TV (cm^3)	*n*	TV (cm^3)	*n*	TV (cm^3)
Girls								
Gomel Oblast, rural	1170	5.2 ± 1.6[a]	2615	7.0 ± 2.3	2447	10.0 ± 3.4	1046	12.2 ± 3.7
Gomel Oblast, urban[b]	857	5.4 ± 1.6	1261	7.3 ± 2.7	1123	11.1 ± 4.9	406	13.5 ± 5.1
Difference[c]	P=0.001		P=0.004		$P < 0.001$		$P < 0.001$	
Boys								
Gomel Oblast, rural	1101	5.3 ± 1.7	2547	6.7 ± 1.9	2305	8.9 ± 2.8	920	11.8 ± 3.8
Gomel Oblast, urban[b]	815	5.3 ± 1.7	1096	6.9 ± 2.0	883	9.4 ± 3.1	276	12.2 ± 3.9
Difference[c]	P=0.68		P=0.03		P=0.004		P=0.30	

[a]Values are arithmetic mean ± standard deviation.
[b]Population resided in the following cities: Gomel, Mozyr, Zhlobin, Rechitsa and Svetlogorsk.
[c]To evaluate the difference, *t*-test was applied for distribution of log-transformed values of TV.

Table 3. Parameters of distribution of the thyroid-volume values by age and gender for children from Gomel Oblast.

Age (years)	Age group (years)	Girls				Boys			
		Mean (cm^3)	SD (cm^3)	Median (cm^3)	GSD	Mean (cm^3)	SD (cm^3)	Median (cm^3)	GSD
5.0–5.99	5	4.5	1.6	4.3	1.40	4.6	1.3	4.4	1.34
6.0–6.99	6	5.1	1.4	4.9	1.31	5.1	1.6	4.9	1.35
7.0–7.99	7	5.8	1.6	5.5	1.32	5.9	1.6	5.7	1.31
8.0–8.99	8	6.4	2.4	6.1	1.35	6.2	1.7	6.0	1.31
9.0–9.99	9	7.0	2.2	6.7	1.34	6.8	1.7	6.6	1.30
10.0–10.99	10	8.0	2.8	7.6	1.38	7.5	2.1	7.2	1.30
11.0–11.99	11	9.1	3.3	8.6	1.39	8.1	2.2	7.8	1.31
12.0–12.99	12	10.5	3.8	9.9	1.40	9.1	2.7	8.7	1.34
13.0–13.99	13	12.0	4.4	11.3	1.40	10.3	3.2	9.9	1.25
14.0–14.99	14	12.3	4.2	11.6	1.40	11.6	3.5	11.1	1.38
15.0–15.99	15	12.6	4.2	12.0	1.37	12.8	4.4	12.2	1.36
16.0–16.99	16	13.3	4.3	12.7	1.34	14.5	4.2	14.0	1.29

Table 4. Parameters of distribution of the thyroid-volume values by age and gender for children from Mogilev Oblast.

Age (years)	Age group (years)	Girls				Boys			
		Mean (cm^3)	SD (cm^3)	Median (cm^3)	GSD	Mean (cm^3)	SD (cm^3)	Median (cm^3)	GSD
5.0–5.99	5	5.1	1.5	4.9	1.33	5.1	1.3	5.0	1.29
6.0–6.99	6	5.5	1.4	5.4	1.29	5.9	1.5	5.7	1.30
7.0–7.99	7	6.0	1.7	5.7	1.33	6.0	1.6	5.8	1.30
8.0–8.99	8	6.5	1.8	6.3	1.32	6.6	1.8	6.4	1.30
9.0–9.99	9	7.2	2.1	6.9	1.34	7.2	1.9	7.0	1.31
10.0–10.99	10	8.1	2.3	7.8	1.33	7.9	2.2	7.6	1.31
11.0–11.99	11	9.4	2.7	9.0	1.32	8.8	2.4	8.5	1.32
12.0–12.99	12	11.1	3.3	10.6	1.34	10.0	2.7	9.6	1.30
13.0–13.99	13	11.9	3.5	11.4	1.34	11.0	3.1	10.6	1.32
14.0–14.99	14	12.8	3.8	12.3	1.33	12.5	3.7	12.0	1.33
15.0–15.99	15	13.6	3.9	13.1	1.32	13.9	4.0	13.3	1.33
16.0–16.99	16	14.0	4.2	13.4	1.33	14.6	4.1	14.1	1.31

than 10 y were merged in the estimation of the average thyroid volumes for children.

Average values of thyroid volumes for Belarusian children of all ages

The revised databases were used to estimate the age–oblast-dependent thyroid-volume values for children aged less than 5 y and age–gender–oblast dependent for teenagers over 16 y, for whom there are not enough thyroid measurements or measurements were not done at all. The average age–oblast-dependent thyroid-volume values for children aged less than 5 y were extrapolated by a linear function that linked the measured values for children aged 5–9 y with a value for newborns (age group of 0 y) of 1.24 cm^3, that is obtained as the ratio of a thyroid mass for newborns of 1.3 g, according to ICRP Publication 89[(7)] and the results of measurements made in Ukraine (Prof. I.A. Likhtarev, personal communication, Radiation Protection Institute, Kiev, Ukraine), and of a specific gravity of the thyroid gland of 1.05 g cm^{-3}, according to ICRP Publication 23[(10)].

The interpolation was done in such a way that the average age–oblast-dependent thyroid-volume values for children aged 1, 2, 3 and 4 y were located on the best fit straight line going through thyroid-volume values from newborn to 9 y children. Extrapolation of average thyroid volumes for teenagers of 17 and 18 y based on the average thyroid-volume values for children aged from 10 to 16 y. The variability in thyroid-volume values that was observed for the children with measurements is characterised by the GSDs vary from 1.25 to 1.4 (Tables 3 and 4). On that basis, the variability of thyroid volume was subjectively assigned to be characterised with GSD=1.4 in sub-groups of children for whom thyroid volumes were estimated using the extrapolation procedure.

Table 5. Average thyroid-mass values for children from Gomel and Mogilev Oblasts by age and gender and comparison with ICRP data.

Age (years)	Age group (years)	Gomel Oblast				Mogilev Oblast				ICRP Publication 89(7)	
		Thyroid mass[a] (g)		GSD		Thyroid mass (g)		GSD		Thyroid mass (g)	
		Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys	Girls	Boys
0–0.99	Newborns	1.3		1.4[b]		1.3		1.4[b]		1.3	
1.0–1.99	1	2.0		1.4[b]		2.3		1.4[b]		1.8	
2.0–2.99	2	2.7		1.4[b]		3.1		1.4[b]			
3.0–3.99	3	3.4		1.4[b]		3.9		1.4[b]			
4.0–4.99	4	4.1		1.4[b]		4.7		1.4[b]			
5.0–5.99	5	4.7		1.39		5.4		1.28		3.4	
6.0–6.99	6	5.4		1.31		6.0		1.27			
7.0–7.99	7	6.1		1.29		6.3		1.29			
8.0–8.99	8	6.6		1.36		6.9		1.29			
9.0–9.99	9	7.2		1.31		7.6		1.30			
10.0–10.99	10	8.4	7.8	1.38	1.30	8.5	8.3	1.33	1.31	7.9	
11.0–11.99	11	9.5	8.5	1.39	1.31	9.8	9.2	1.32	1.32		
12.0–12.99	12	11.0	9.5	1.40	1.34	11.6	10.4	1.34	1.30		
13.0–13.99	13	12.6	10.8	1.40	1.25	12.5	11.6	1.34	1.32		
14.0–14.99	14	12.9	12.2	1.40	1.38	13.4	13.2	1.33	1.33		
15.0–15.99	15	13.2	13.5	1.37	1.36	14.3	14.6	1.32	1.33	12	
16.0–16.99	16	14.2	14.7	1.34	1.29	14.7	15.3	1.33	1.31		
17.0–17.99	17	14.9	16.0	1.4[b]		15.5	16.6	1.4[b]			
18.0–18.99	Adults	15.6	17.3	1.4[b]		16.2	17.8	1.4[b]		17	20

[a]Arithmetic mean.
[b]Subjectively assigned to children and adolescents for whom values of thyroid mass were extrapolated.

Thyroid mass for Belarusian children of all ages

The average thyroid-volume values that are estimated in this study were converted to thyroid mass using a specific gravity of 1.05 g cm^{-3} for the thyroid gland(10). The values obtained for the thyroid masses and their variabilities are presented in Table 5. They are also used in thyroid dose reconstruction for the members of a cohort of Belarusian children within the framework of the on-going Belarusian-American cohort study of thyroid cancer and other thyroid diseases.

The thyroid masses derived from the databases were compared with the reference values of thyroid mass recommended by the ICRP in its Publication 89(7) (Table 5). As can be seen from the table, the thyroid-mass values obtained in this study are in good agreement (within 8 %) with the ICRP reference values for children aged 10 y, but they are higher than the ICRP reference values by up to 30 % for children aged 1 y, by up to 60 % for children aged 5 y and by up to 22 % for adolescents aged 15 y. For persons aged 18 y, the average thyroid masses for Belarus are lower than the ICRP reference by up to 8 % for girls and by up to 14 % for boys.

CONCLUSIONS

The average thyroid-volume values obtained in this study are considered to be reliable estimates of the thyroid volumes for the children and adolescents who resided at the time of, or shortly after, the Chernobyl accident in Gomel and Mogilev Oblasts of Belarus. The differences between oblasts do not exceed 12 %, which is relatively small when the variability of individual values is considered. In a given age group, the individual values show a variability characterised by GSD of 1.25–1.4.

The average thyroid-volume values estimated in this study were recalculated to thyroid-mass values that are being used in dose reconstruction within framework of the on-going Belarusian-American cohort study of thyroid cancer and other thyroid disease after the Chernobyl accident. The thyroid-mass values obtained in this study for Gomel and Mogilev Oblasts in Belarus are in good agreement with the ICRP reference values for children aged 10 y. However, the thyroid-mass values obtained in this study are significantly higher than the ICRP reference values for children aged 1, 5 and 15 y. Using the ICRP reference values of thyroid mass for reconstruction of thyroid doses from ^{131}I intakes may lead to overestimation of thyroid doses for children of these ages, and, therefore, underestimation of radiation risk.

It is necessary to specify that this study aimed at obtaining realistic estimates of thyroid mass in the study area to be used in thyroid dose reconstruction, and was not meant to lead to the establishment of regional or national reference values of thyroid volume. It should be also noted that the thyroid-volume and thyroid-mass values obtained in this study for only two of the six oblasts in Belarus cannot be considered to be representative for the entire country.

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