Chernobyl Radiation-induced Thyroid Cancers in Belarus

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Abstract

Assessment of incidence and mortality for thyroid cancers carried out for the Belarusian population is described in the present report. It is found that in the period of 1987-2000 about 4,400 radiation-induced thyroid cancers appeared in Belarus: 692 cancers among children and 3,709 cancers among adolescents and adults. The number of lethal thyroid cancers in this period of time in Belarus was assessed as about 350 cases. The excessive absolute risk, EAR, of thyroid cancer incidence assessed for the period of 1987-2000 on the basis of given data on the morbidity and the assessed collective thyroid dose of irradiation is (2.5 – 5.0) per 10^4 PYGy. The EAR value of thyroid cancer mortality is assessed as (0.20 - 0.40) per 10^4 PYGy. The excessive relative risk, ERR, of thyroid cancer incidence is assessed as (11.2 – 22.4)/Gy. The radiation risks of thyroid cancers found in the present report are higher than the risk coefficients established for atomic bomb survivors that were irradiated with dose rates some thousand times higher than populations of Belarus affected by the Chernobyl accident. The absence of marked latency period is another feature of radiation-induced thyroid cancers caused in Belarus as a result of this accident.

INTRODUCTION

As a result of the Chernobyl accident a large amount of radioactive substances escaped from the destroyed reactor. Especially high release was in case of volatile radionuclides. According to the existing assessments about 50% of the ^{131}I isotope inventory came into the environment [1]. This caused the radioactive contamination of many countries of the Northern Hemisphere [2]. However, the main fraction of radioactive materials released by the accident deposited in Belarus. The total amount of the ^{131}I deposited in Belarus is assessed as approximately $3.3 \cdot 10^{17}$ Bq or about 18.5% of the total amount of ^{131}I that escaped from the Chernobyl reactor [3]. Practically the whole territory of Belarus was contaminated with this and other iodine isotopes. This resulted in very high doses delivered to thyroid gland of a large amount of people in Belarus. It is well known that the highest thyroid doses in Belarus were received by the inhabitants of the south districts of the Gomel region and of the southeast districts of the Brest region [4]. According to the data of Yu.Gavrilin et al.[4], the arithmetic mean thyroid dose in the age group 0-6 years of the children living in settlements of the Khoiniki district settled in the 30-km zone was about 4.7 Gy and maximal doses were about 50 Gy. Very high thyroid doses were received also by the inhabitants of Brest and Mogilev regions. This is the reason for a very high increase in the thyroid cancer incidence in Belarus after the Chernobyl accident, especially among the children of Gomel and Brest regions.

V.Kazakov, E.Demidchik and L.N.Astakhova [5] published the first reliable data on the significant increase in the thyroid cancer morbidity among the children of Belarus after the Chernobyl accident. However, specialists met these data with a big skepticism. There were serious reasons for this skepticism. At first, the data of [5] have shown an unusual short latent period of about 2-3 years. At second, no similar data about the increase in the incidence of thyroid cancer among the children of the affected areas of the Ukraine and Russia were known at the time of publication [5]. This was very strange because all specialists believed that the Ukraine was affected by the Chernobyl accident more significantly than Belarus. It is now clear that such assumption was fully incorrect.

In order to explain an unusually high incidence of thyroid cancer among the children of Belarus some specialists proposed an idea that this increase was caused by the improved screening in Belarus [6].

This situation changed only after the First International Conference on the Radiological Consequences of the Chernobyl Accident held in Mink in 1996 from 18 to 22 March. At the conference new data on the thyroid cancer incidence in Belarus [7] as well as similar data on the increase of the thyroid cancer incidence among the children of the Ukraine [8] and Russia [9] were presented. Data on the thyroid cancer morbidity in these two countries differed only quantitative from the Belarusian data.

Analysis of the data on the thyroid cancer morbidity in three countries has shown that the highest increase in the thyroid cancer incidence was registered in Belarus and the lowest in Russia. Such difference was explained later on the basis of thyroid doses delivered to inhabitants of the affected areas of Belarus, the Ukraine and Russia. It was shown that the highest irradiation doses of thyroid glands were received in Belarus and the lowest in Russia [3].

At the Minsk conference a number of evidences were given that indicated the association between the increase in the incidence in thyroid cancer among the children of Belarus, the Ukraine and Russia and ionizing origin. For example, it was shown that in Belarus thyroid cancer has mainly appeared in the children irradiated as a result of the Chernobyl accident. It was established that out of the total number of 390 thyroid cancers registered among the children of Belarus in 1986-1994 and the first 7 months of 1995 380 cases were diagnosed for the children born before the Chernobyl accident, 6 cases for the children born at the time of the accident and only 4 cases for the children born after full disintegration of radioiodine [7].

Other very important finding relates to the histological types of thyroid cancers in countries affected by the Chernobyl accident. For instance, more than 90% of thyroid cancer in Belarus and the Ukraine were papillary carcinoma as compared to 68% of the England and Wales tumors [10]. Within the papillary carcinoma over 70% of thyroid cancers in the countries affected by the Chernobyl accident were of the solid follicular type compared to only 40% in England and Wales [10].

At present, practically nobody doubts in the manifestation of radiation-induced thyroid cancers among the children of the affected areas of the former USSR [11]. However, up to the present time nobody recognizes the manifestation of radiation-induced thyroid cancers among adolescents and adults despite of the existence of reliable data indicating the presence of radiation-induced thyroid cancers for other age categories than children [12].

The existence of such controversies requires careful studies of incidences of thyroid cancers by different age categories in order to establish evidences on a link between radiation and the increased morbidity of thyroid cancer. The present report describes the results of an analysis of incidences in thyroid cancers among children, adolescents and adults of Belarus. The excessive absolute risk, EAR, and the excessive relative risk, ERR, were also assessed in the report. Only data established for Belarus were considered because the population of Belarus received the highest thyroid dose [3]. Due to this fact a more clear manifestation of irradiation effects may be expected in Belarus. It is also important that the epidemiological data established in Belarus are more comprehensive and accurate than in Russia and the Ukraine. The present report is practically the further development of our previous studies [13,14].

MATERIALS AND METHODS

Data established by specialists of the *Thyroid Surgery Registry* of the Scientific and Practical Centre for Thyroid Tumors of the Institute of Medical Radiology and Endocrinology of the Ministry for Health Care of the Republic of Belarus [5,7,15-19] as well as data of the Belarusian Cancer Registry [20-28] and other official data [29-34] were used in the present report for an assessment of radiation-induced thyroid cancer in Belarus. Results given in the present report were assessed for the mixed populations of children, adolescents and adults of Belarus. In case of adults no separate consideration of persons involved in mitigation work of the Chernobyl accident or so-called liquidators was performed. No separate assessment for males and females was also conducted.

Monitoring of malignant neoplasms in Belarus began in 1950s [20-29]. Therefore, quite accurate data exist at least from 1960s. However, until 1994 only sparse information on the incidence and mortality in separate malignant neoplasms was published in the country. These were data on crude incidence and mortality in malignant neoplasms combined together and given for Belarus in total. Beginning from 1994 the Belarusian Cancer Registry publishes annually their statistical books that contain more detailed information on the incidence and mortality in malignant neoplasms. This information is given for Belarus in total as well as for separate administrative units of the country. Belarus is divided in 7 administrative units: 6 regions (Brest, Vitebsk, Gomel, Grodno, Minsk, Mogilev) and the Minsk city which is the capital of the country [29-34]. The smallest administrative unit is the Mogilev region with 1.2 million of people. The largest unit is the Minsk city with the number of inhabitants about 1.7 million [29-34].

The excessive absolute risk, *EAR*, was estimated with the simplified expression:

$$EAR = (O - E) / N_{PYSv} . \qquad (1)$$

Here O – observed number of thyroid cancer; E – expected number of thyroid cancer; N_{PYSv} – number of person·year·sievert under risk.

The value of N_{PYSv} was assessed on the basis of equation:

$$N_{PYSv} = H_{Th}^{coll} \cdot Y . \qquad (2)$$

Here H_{Th}^{coll} – collective thyroid equivalent dose delivered in 1986; Y – number of years under risk after the accident.

The excessive relative risk, *ERR*, was calculated by using of the expression:

$$ERR = (O / E - 1) / \overline{H}_{ind} . \qquad (3)$$

Here $\overline{H}_{ind}$ – average individual dose of irradiation.

The value of $\overline{H}_{ind}$ can be determined with the formula:

$$\overline{H}_{ind} = H_{Th}^{coll} / N . \qquad (4)$$

Here N is the number of people with irradiated thyroid glands.

RESULTS AND DISCUSSION

Morbidity of thyroid cancers among children of Belarus

Thyroid cancer is a quite rare disease for children. According to the data of the *Thyroid Surgery Registry* [15] in 1966-1985 (or during 20 years) only 21 cases of thyroid cancers were registered in the children of Belarus. This gives 1 case of thyroid cancer per year as a spontaneous morbidity of thyroid cancer for the Belarusian children. The average number of children (less than 15 years old) in Belarus in the pre-accidental period was about 2.37 million [29-34]. As can be calculated from this figures, the spontaneous morbidity of thyroid cancer for the children of Belarus before the Chernobyl accident was approximately 0.4 cases per million. This value is very close to the spontaneous morbidity of thyroid cancer in the children of England and Wales [10] equal to approximately 0.5 cases per million. Data in Table 1 taken from [17] demonstrate that before the Chernobyl accident only 3 possibilities were registered as the number of thyroid cancer incidence among the children. They were 0, 1 and 2 cases per year. This means that the highest number of spontaneous thyroid cancers among the children of Belarus is equal to 2 cases in a year and the spontaneous incidence rate in thyroid cancers for the children of Belarus is 1 ± 1 cases in a year.

The situation changed after the Chernobyl accident. Table 2 contains the numbers of thyroid cancers registered annually in 1986-1997 [16]. Already in 1987, 4 cases of thyroid cancers were registered in the

Belarusian children. This number is by a factor of 2 higher than the maximal possible number of spontaneous cases that can realize annually. The data in Table 2 demonstrate practically an absence of the latency period for radiation-induced thyroid cancers among the children of Belarus. The first radiation-induced thyroid cancers among them, according to Table 2, manifested already in 1987 or 1 year after the Chernobyl accident. This finding was unexpected for the majority of scientists because the believing in the existence of the latency, at least 5 years long, was the common wisdom of radiation biology.

As can be seen from Table 2, the highest increase in the incidence of thyroid cancers among children manifested in Gomel (53.1%) and Brest (23.5) regions and the lowest in Vitebsk region. These findings correlate with the level of contamination of different Belarusian regions with iodine isotopes discharged to the environment by the Chernobyl accident [35].

Our assessment demonstrates that 692 additional thyroid cancers in the children of Belarus were registered in 1987-2000 (see Table 3). The numbers of observed thyroid cancers in children in 1987-1997 were taken from the last row of the previous table.

The numbers of observed thyroid cancers in children in 1998-2000 were established by [19].

Data given in Tables 2 and 3 as well as in Fig. 1 show that the incidence in thyroid cancers among the children of Belarus increased monotonously from 4 cases in 1987 to 91 cases in 1995, and then decreased also monotonously to 31 cases in 2000.

The reason for the decline in thyroid cancers incidence after 1995 is very easy. It is caused simply by the medical statistics used in Belarus [13,14]. All official data on cancer morbidity in Belarus are given for two groups. The first group includes the data for those persons for which cancers as well as thyroid cancer are diagnosed when they are less than 15 years old. The second group includes all persons that are older than 15 years. Thus, when a person reaches 15 years at the time of the thyroid cancer diagnose, this person will be considered as a person belonging to the group of adolescents and adults. This means that there is a permanent transition from the subgroup of children to the subgroup of adolescents and adults. As a result of this transition, the children that received thyroid doses by the Chernobyl accident are being lost

Table 1. Incidence of thyroid cancer among children of Belarus before the Chernobyl accident.

Year	Male	Female	Both	Year	Male	Female	Both
1971	0	0	0	1979	0	0	0
1972	0	0	0	1980	0	0	0
1973	1	1	2	1981	0	1	1
1974	0	2	2	1982	1	0	1
1975	0	1	1	1983	0	0	0
1976	2	0	2	1984	0	0	0
1977	1	1	2	1985	0	2	2
1978	0	1	1	1986	1	1	2

Table 2. Thyroid cancer among children of Belarus after the Chernobyl accident [16].

Region/Year	86	87	88	89	90	91	92	93	94	95	96	97	Total
Brest	0	0	1	1	7	5	17	24	21	21	25	13	135
Vitebsk	0	0	0	0	1	3	2	0	1	0	0	0	7
Gomel	1	2	1	3	14	43	34	36	44	48	42	37	305
Grodno	1	1	1	2	0	2	4	3	5	5	5	3	32
Minsk	0	1	1	1	1	1	4	4	6	1	5	6	31
Mogilev	0	0	0	0	2	3	1	7	4	6	3	4	30
Minsk-city	0	0	1	0	4	2	4	5	1	10	4	3	34
Belarus total	2	4	5	7	29	59	66	79	82	91	84	66	574

Table 3. Incidence of thyroid cancers among children of Belarus after the Chernobyl accident.

Year	Observed	Expected	Observed - Expected	SIR
1987	4	1	3	4
1988	5	1	4	5
1989	7	1	6	7
1990	29	1	28	29
1991	59	1	58	59
1992	66	1	65	66
1993	79	1	78	79
1994	82	1	81	82
1995	91	1	90	91
1996	84	1	83	84
1997	66	1	65	66
1998	54	1	53	54
1999	49	1	48	49
2000	31	1	30	31
1987-2000	706	1	692	50.4

permanently from the children's subgroup. This transition causes the decrease in the incidence in thyroid cancers among the children of Belarus with the time.

Thus, in order to establish real incidence rates of thyroid cancers for the children of Belarus one needs to determine the number of irradiated children in the children's subgroup. Such data are given in the third column of Table 4. It is seen from this table that the number of irradiated children in Belarus decreased from 2.303 million in 1986 down to 0.223 million in 2000.

The last group of the children with thyroid doses caused by iodine isotopes will move to the subgroup of adolescents and adults in the first 3 months of 2001. This group will include only the children that were irradiated *in utero*. It means that beginning from 2002 the incidence of thyroid cancers among the children of Belarus will be the same level as before the Chernobyl accident, or 1 case annually.

For forecasting the number of thyroid cancers for 2001, the simplified procedure described in our previous publication [14] was used. It is based on a linear extrapolation between 2000 and 2002. The data

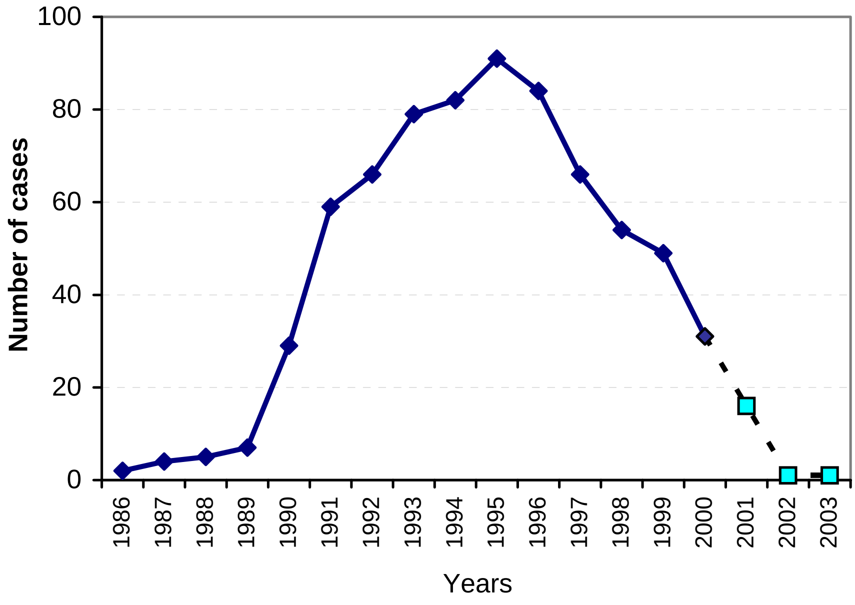

Fig. 1. Number of thyroid cancer incidence among the children of Belarus.

Table 4. Assessment of the incidence rates of thyroid cancers among children of Belarus after the Chernobyl accident.

Year	Total amounts of children (in millions)	Amounts of irradiated children (in millions)	Observed	Observed-Expected	Incidence rate (per 100,000 children)
1986	2.303	2.303	2	1	0.0434
1987	2.315	2.152	4	3	0.1394
1988	2.325	1.999	5	4	0.2001
1989	2.337	1.858	7	6	0.3229
1990	2.337	1.715	29	28	1.6327
1991	2.335	1.581	59	58	3.6686
1992	2.328	1.446	66	65	4.4951
1993	2.327	1.328	79	78	5.8735
1994	2.307	1.198	82	81	6.7669
1995	2.273	1.062	91	90	8.4746
1996	2.217	0.910	84	83	9.1209
1997	2.154	0.758	66	65	8.5752
1998	2.086	0.597	54	53	8.8777
1999	1.961	0.379	49	48	12.6649
2000	1.898	0.223	31	30	13.4529

given in [28] shows that 31 cases of thyroid cancers were registered in 2000. Linear extrapolation between 31cases in 2000 and 1 case in 2002 gives 16 thyroid cancers in 2001 for the children of Belarus. This value is used in constructing Fig. 2.

The total number of thyroid cancers in the Belarusian children that can manifest in the period from 1986 up to 2002 will be then equal to 722 cases. Subtraction from this number of the number of spontaneous thyroid cancers that have to appear in 1987-2001 (15 cases) will give the number of radiation – induced thyroid cancers among the children of Belarus equal to 707 cases.

At the same time, we have to expect some contribution to the additional thyroid cancers that were caused as a result of irradiation of their thyroid glands by other isotopes than isotopes of iodine. This effect can give in reality some higher numbers of thyroid cancers in the children of Belarus after 2001 than

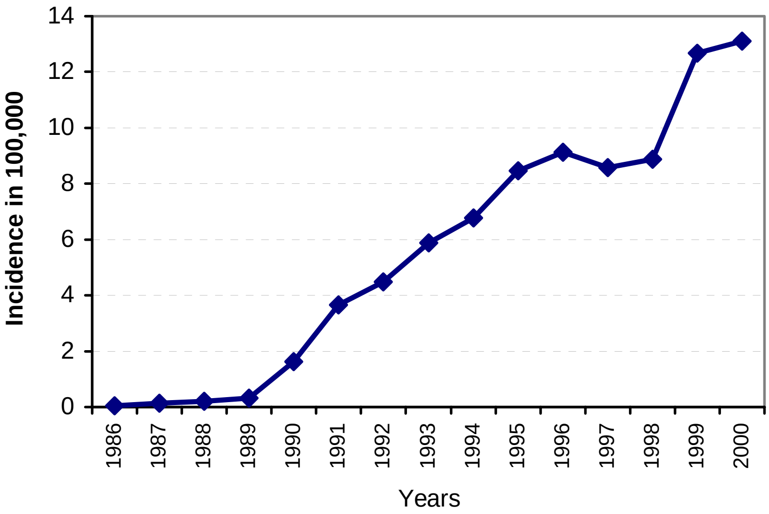

Fig. 2. Incidence rates of thyroid cancer among irradiated children of Belarus.

the spontaneous incidence before the accident. However, this number can not differ very strong from the forecasted number of 707 cases.

As can be seen from Fig. 2, the incidence rate of thyroid cancers in the children of Belarus increases practically linearly after the Chernobyl accident. It increased from 0.0434 cases per 100,000 children in 1987 up to 13.5 cases per 100,000 children in 2000 or by a factor of 310 (see the last column of Table 4). For calculation of incidence rates of thyroid cancers given in the last column of Table 4, the numbers of children in the third column and the numbers of additional thyroid cancers in the fifth column were used.

Assessment of the incidence rate of thyroid cancers in the children of Belarus carried out on the population data presented in the second column of Table 4 gives for 2000 1.58 cases per 100,000 children. This number is 8.5 times less than the real incidence rate of thyroid cancers in 2000 among the children affected by the Chernobyl accident. It is clear that the method of medical statistics used in Belarus gives an apparent decrease of thyroid cancers manifested in children after 1995. This apparent decrease is caused by the transition of persons that reach 15 years to the sub-population of adolescents and adults. We assessed that in 1996-2000 approximately 400 cases of thyroid cancers manifested in persons that were less than 15 years at the time of the Chernobyl accident went to the sub-population of adolescents and adults of Belarus. We assessed this number of thyroid cancers (400 cases) by use of the following expression:

$$Y=13.5\cdot T-26{,}833 \qquad (5)$$

It was developed on the basis of incidences of thyroid cancers in the children of Belarus in 1989-1996 by using of the least square method.

Addition of 400 cases to 706 cases (see the last value in the second column of Table 3) gives the approximate total number of thyroid cancers manifested in Belarus in 1987-2000 in those persons that were children at the time of the Chernobyl accident. It is equal to 1106 cases instead of 706 cases considered by specialists. This simplified analysis demonstrates what incorrect conclusions can be drawn about the development of the morbidity of thyroid cancers in the children of Belarus.

Morbidity in thyroid cancers among adolescents and adults of Belarus

The described above transition of the children with thyroid doses from the children's subgroup into subgroup of adolescents and adults decreases the number of radiation-induced thyroid cancers among the persons that are considered as children according to rules of the medical accounting. At the same time this transition causes an additional increase in the incidence in thyroid cancers by adolescents and adults of Belarus after the accident. However, the transition between different subgroups can not explain a very high increase in the incidence of thyroid cancers among adolescents and adults of Belarus after the Chernobyl accident (see Fig.3). The upper curve in Fig.3 presents the registered number of thyroid cancers in adolescents and adults. Here the data for 1977 –1997 were taken from [7,16]. The observed numbers of thyroid cancers in 1998-2000 were estimated on the basis of the data of the Belarusian Cancer Registry [26-28].

According to [26] the incidence of thyroid cancer among the Belarusian population was 7.5 cases per 100,000 persons in 1998 and the total number of people in Belarus was 10.2 million. By using these data one can calculate the number of thyroid cancers registered in Belarus in 1998 equal to 765 cases. This number is a sum of thyroid cancers in children and in adolescents and adults. Subtraction of the number of children's cancers (54 cases in 1998 [17]) from the total numbers of thyroid cancers gives the number of thyroid cancers in adolescents and adults equal to 711 cases. This value is shown in the second column of Table 6. The similar method was used for assessment of number of thyroid cancers registered by adolescents and adults of Belarus in 1999 and 2000.

Two other curves in Fig.3 give assessed spontaneous or expected cases in the group of adolescents and adults of Belarus.

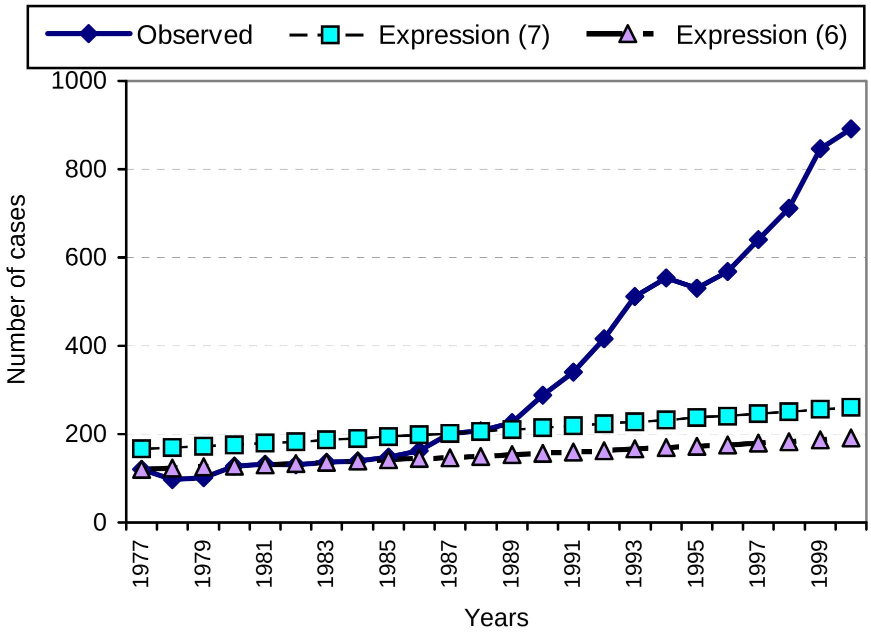

Fig. 3. Incidence of thyroid cancers among adolescents and adults of Belarus in 1977-2000 (absolute numbers).

The expected numbers of thyroid cancers in adolescents and adults of Belarus combined together can be assessed by using of the formula [13]:

$$E_j=E_0\cdot(1+a)^j, \qquad (6)$$

Where E_0 = spontaneous morbidity of adolescents and adults in 1977;

a = is a constant showing the annual increase in the incidence of the thyroid cancer, it is about 0.02 (2% increase annually);

j = is the number of the consequent year beginning with j =0 for 1977 (j = 1 for 1978 and so on);

E_j = spontaneous morbidity of adolescents and adults in the year j.

Data calculated with this expression are presented in Fig.3 (the lower line in figure).

The last expression was established in [13] on the basis of data on thyroid cancer incidences in adolescents and adults of Belarus [7] that were registered before the Chernobyl accident. It was used for calculation of the expected numbers of thyroid cancers among adolescents and adults of Belarus that are also shown in the third column of the Table 5.

Comparison of the data calculated by using of the expression (6) with the observed data presented in the second column of Table 5 demonstrates a very good agreement for 1977-1985 and a quite significant disagreement for 1986 and 1987. We believe that inefficient screening of thyroid cancers among adolescents and adults before the Chernobyl accident causes this disagreement. The following arguments support this idea.

As can be seen from Table 5, the number of registered thyroid cancers in adolescents and adults abruptly increased in 1986 and 1987, and then changed only very insignificant from 1987 to 1988. The probable reason for such change in the incidence in thyroid cancers among adolescents and adults of Belarus can be a more careful investigation of this category of people by specialists or an improved screening.

Table 3 demonstrates that in case of children a clear manifestation of additional thyroid cancers began in 1987 and a marked increase in the incidence occurred only from 1990 or 3 years after the Chernobyl accident. It is difficult to believe that in a case of adolescents and adults a significant manifestation of radiation-induced thyroid cancers began already in 1986. In order to correct the possible effect of inefficient screening in a case of adolescents and adults we modified the expression (6) by inserting of the coefficient *c* that takes into account the screening effect. This modified expression is given below:

$$E_j=E_0 \cdot c \cdot (1+a)^j, \qquad (7)$$

We determined the coefficient *c* by dividing of the observed number in 1987 of thyroid cancers in adolescents and adults by the number calculated with the expression (6). By correcting this way the expected incidences of thyroid cancers in adolescents and adults are shown in the fourth column of Table 5. The middle curve in Fig. 3 presents values calculated with the last expression.

We applied the same method for the possible screening effect to assessment of spontaneous morbidity of thyroid cancers in adolescents and adults of Belarus for the whole period after the Chernobyl accident. The corrected numbers of expected thyroid cancers among this category of the Belarusian population are given in the third column of Table 6.

Data on numbers of thyroid cancers registered by adolescents and adults of Belarus in 1986 – 1997 given in the second column of Table 6 were taken from the report of [16]. The number of thyroid cancers in this column for 1998-2000 were calculated on the basis of the morbidity rate in thyroid cancer of the whole Belarusian population and a number of people in the country that are presented in the reports of the

Table 5. Incidence of thyroid cancers among adolescents and adults of Belarus in 1977-1988.

Year	Observed	Calculated values	
		Expression (6)	Expression (7)
1977	121	121	166
1978	97	123	169
1979	101	126	172
1980	127	128	176
1981	132	131	179
1982	131	134	183
1983	136	136	187
984	139	139	190
1985	148	142	194
1986	162	145	198
1987	202	147	202
1988	207	160	206

Table 6. Incidence of thyroid cancers among adolescents and adults of Belarus after the Chernobyl accident.

Year	Observed	Expected	Observed-Expected	SIR
1987	202	202	0	1
1988	207	206	1	1.005
1989	226	210	16	1.076
1990	289	214	75	1.350
1991	340	219	121	1.552
1992	416	223	193	1.865
1993	512	227	285	2.256
1994	553	232	321	2.384
1995	531	237	294	2.241
1996	568	241	327	2.357
1997	641	246	395	2.606
1998	711	251	460	2.833
1999	847	256	591	3.309
2000	891	261	630	3.414
1987-2000	6934	3225	3709	2.150

Table 7.Additional incidence of thyroid cancers in Belarus in 1987-2000.

Year	Children	Adolescents and adults	All ages
1987	3	0	3
1988	4	1	5
1989	6	16	22
1990	28	75	103
1991	58	121	179
1992	65	193	258
1993	78	285	363
1994	81	321	402
1995	90	294	384
1996	83	327	410
1997	65	395	460
1998	53	460	513
1999	48	591	639
2000	30	630	660
1987-2000	692	3709	4401

Belarusian Cancer Registry [26-28].

As can be seen from Table 6, the first radiation-induced thyroid cancer in the group of adolescents and adults of Belarus, according to our assessment, manifested already in 1988 or 2 years after the Chernobyl accident. This means that the minimal latency period of radiation-induced thyroid cancers by this category is about 2 years and not 10 years later as could be expected on the basis of an experience accumulated previously.

The early manifestation of radiation-induced thyroid cancers in Belarus shows clear an absence of the significant latent period in radiation-induced thyroid cancer in Belarus. This is not surprising. Such possibility was forecasted a long time ago by J.Gofman [36]. He stated in his book “Radiation and Human Health” [36] that the latent period of some cancers can depend on the number of persons in the group under study. In a case of a small group it can be required very long time in order to get provable difference with a control group. On the contrary, in a case of very large group of irradiated persons the provable difference can be reached in a very short time. Such situation had the place in Belarus where about 10,000,000 persons were irradiated.

The total number of additional thyroid cancers among adolescents and adults manifested in Belarus in 1987 - 2000 calculated by using the method described here is equal to 3,709 cases (see Table 6).

Assessment of additional thyroid cancers in Belarus

Table 7 contains the numbers of additional thyroid cancers manifested in Belarus in 1987-2000 estimated in previous sections of the present report. The total number of additional thyroid cancers appeared in the country after the Chernobyl accident is 4,401: 692 cases in children and 3,907 cases in adolescents and adults.

Mortality from radiation-induced thyroid cancers in Belarus

The similar procedure as used by assessment of the thyroid cancer incidence can be used for assessment of the number of people in Belarus that died from thyroid cancer caused by the Chernobyl accident.

Fig. 4 shows the dynamic in the crude mortality rate resulted from the morbidity in thyroid cancers. The data shown in this figure were taken from the reports of the Belarusian Cancer Registry [20-28]. They give the mortality of thyroid cancers for the whole Belarusian population (children, adolescents and

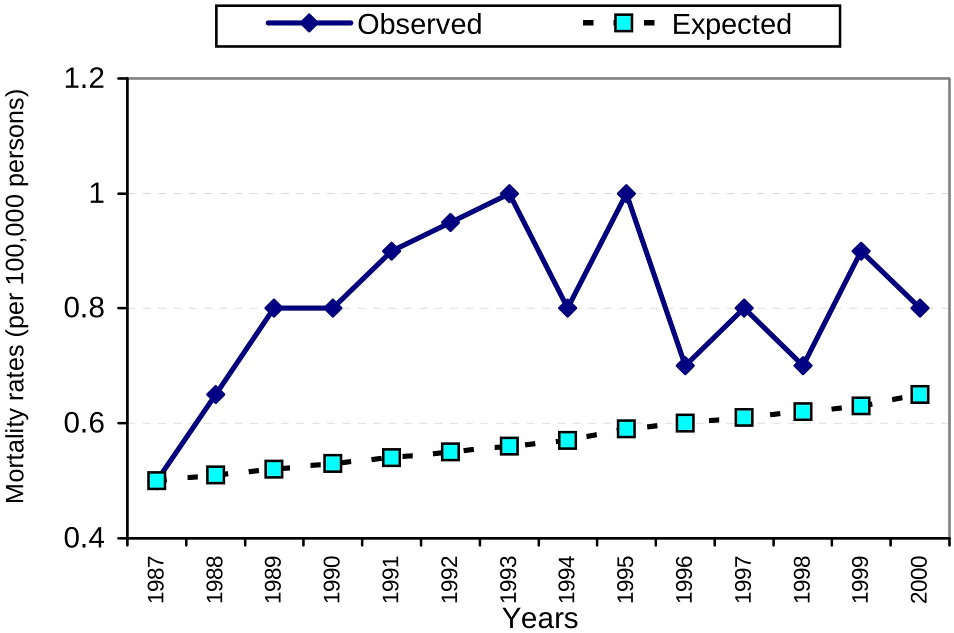

Fig. 4. Mortality rates of thyroid cancers in the Belarusian population.

adults) determined as a number of cases in 100,000 persons. The upper (solid) line gives the observed mortality rates. The lower (dotted) line shows the "spontaneous" mortality rates determined by us. We assessed the "spontaneous" mortality assuming that the mortality rate in 1987 did not differ from the spontaneous mortality and that the annual increase in the spontaneous mortality was in 1987-2000 approximately 2%. Using these data as well as the data on the number of people in Belarus in 1986-2000 [29-34] we assessed the additional number of fatal thyroid cancers in 1987-2000 as approximately 351 cases.

Radiation risks

Excess absolute risk (EAR) for thyroid cancer incidence:

The value of H_{Th}^{coll} equal to $127{\cdot}10^4$ man·Gy was given as the total collective thyroid dose for the Belarusian population in our previous report [3] The assessment of the collective equivalent thyroid dose in the report [3] was carried out assuming the ratio of activities of ^{131}I to ^{137}Cs (recalculated on the 26 April of 1986) in Belarus equal to 20. This is derived from the data on the total discharge of ^{131}I and ^{137}Cs in the environment [3]. In present report we used the corrected value of H_{Th}^{coll} equal to $121{\cdot}10^4$ man·Gy.

However, new experimental data [36] established on the basis of the isotope ^{129}I demonstrates a possibility of incorrectness of the data on release of the isotope ^{131}I accepted in the report [3]. The authors [37] give a value of the ratio of activities of ^{131}I to ^{137}Cs (recalculated on the 26 April of 1986) equal to 10 ±3.1. The collective equivalent thyroid dose assessed using this value is equal to $60.5{\cdot}10^4$ man·Gy. The last value of H_{Th}^{coll} can be considered as the lower limit of the collective equivalent thyroid dose of the Belarusian population caused by the Chernobyl accident. It is by a factor of 2 less than the value of H_{Th}^{coll} equal to $121{\cdot}10^4$ man·Gy, which can be considered as the upper limit of the collective equivalent thyroid doses of the Belarusian population. The real value of H_{Th}^{coll} can be between these two assessments.

Inserting these values and the number of additional thyroid cancers that was assessed in this work (4,401 cases) into the expression (1) gives the value of EAR for the incidence of additional thyroid cancers in Belarus in 1987-2000 to be $(2.5\text{-}5.0)/10^4$ PYGy.

This value of the excessive absolute risk agrees quite well with EARs established in other studies.

For example, according to [37], the value of EAR for inhabitants of the Marshall Islands, which had a strong internal irradiation of thyroid gland, is estimated as 1.1 per 10^4 PYGy [38]. In the study of consequences of the Utah ^{131}I fallout [39] the value of EAR equal to 3.3 per 10^4 PYGy was evaluated. According to [40], the excessive absolute risk of radiation-induced thyroid cancers established for mixed population of atomic bomb survivors is 1.1 per 10^4 PYGy (95% CI=0.55-1.75).

The last value is by factor 2-4 less than the excessive absolute risk of radiation thyroid cancers assessed in this report for the Belarusian population. This discrepancy can not arise from an overestimation of the number of additional thyroid cancers or from an underestimation of the collective dose of thyroid gland irradiation used in the present report. We draw this conclusion because our value of the excessive absolute risk is in a qualitative agreement with the value of EAR established for Russian liquidators [12]. According to Ivanov et al [12], the excessive absolute risk of radiation-induced thyroid cancers estimated for this category of irradiated people for period of 1986-1995 is 1.31 per 10^4 PYGy (95% CI=0.55-1.75). The last value is by factor 1.8-3.6 less than our values of the EAR and close to the value established for atomic bomb survivors. However, Russian liquidators form a special group of people, 93 % of which consist of males that were in average 33.4 years old during their period of duty in the 30-km zone [12]. Therefore, the excessive absolute risk of a mixed population that contains approximately equal fractions of males and females has to be at least 2 times higher than the excessive absolute risk established by Ivanov et al [12] for Russian liquidators.

Thus the high value of the EAR assessed in the present report for the Belarusian population is quite reasonable. This is an unexpected result because it is generally accepted that radiation risks of cancers decline with decrease of dose rates. The hypothesis about existence of such dependence between radiation risks and dose rates was proposed in 1980 by the USA National Council on Radiation Protection and Measurements (NCRP) [41]. In order to take into account this effect the NCRP introduced a special dose-rate-effectiveness factor (DREF). According to the NCRP assessment, values of DREF vary from 2 to 10 for different types of cancers. The United Nations Scientific Commission on Effects of Radiation (UNSCEAR) [42] and the International Commission on Radiological Protection (ICRP) [43] also recognize reduction in a carcinogenic efficiency of ionizing radiation by decrease of a dose rate of irradiation. As an evidence of this effect in case of radiation-induced thyroid cancers, the ICRP considers the findings of Holm [44]. This author showed that a chronic irradiation of thyroid gland with ^{131}I is 4 times less effective than acute irradiation with x-rays.

The irradiation of thyroid gland of atomic bomb survivors occurred in approximately 1 minute. In case of liquidators of the Chernobyl accident as well as populations of the former USSR that were affected by this accident the irradiation of thyroid gland lasted at least 1 month or 43,000 minutes. This means that dose rates of the thyroid gland irradiation of liquidators and affected populations of the Soviet Union were about 40,000 times less than dose rates in case of atomic bomb survivors. It is clear that in case of correctness of the NCRP hypothesis the values of EAR for the Belarusian population and liquidators have to be less than the EAR value for atomic bomb survivors. Our data and the data of [12], however, demonstrate a fully disagreement with this expectation. Such disagreement is not the unique feature of radiation-induced thyroid cancers in Belarus. Ivanov et al [45,46] found that radiation risks of solid cancers other than thyroid cancers for Russian liquidators are also by some factors higher than in case of atomic bomb survivors. The authors [45,46] carried out their study by using the cohort method similar to the method used by specialists of the Radiation Effects Research Foundation (RERF) and are quite reasonable. Similar findings were also found in the report [47].

Excess relative risk (ERR) for thyroid cancer:

By using the data on observed and expected incidences of thyroid cancers in children, adolescents and adults, the averaged value of the excessive relative risk, ERR, was also assessed on the basis of expression (3). The values of *O* and *E* were obtained from the data shown in Tables 3 and 6. The value of $\overline{H}_{ind}$ was calculated by inserting the collective equivalent dose of the thyroid cancer irradiation of the Belarusian population H_{Th}^{coll} equal to (60.5-121)·10^4 man·Gy into expression (4) and the number of population in Belarus equal to 10 millions of people. Thus, the ERR value of (11.2-22.4)/Gy was obtained for the mixed population in Belarus.

The assessed value of ERR is one order in magnitude higher than the value 0.84/Gy established for atomic bomb survivors [40]. However, it agrees very well with the excessive relative risk found for children and adolescents of the affected areas of Belarus, the Ukraine and Russia in the report [48]. According to authors [48], the excess relative risk per unit dose in the study area is equal to 90/Gy. One needs to remember that the ERR value for children and adolescents is by some factors higher than for the mixed population. Therefore, we can state that the excess relative risk assessed in our report for the mixed Belarusian population agree quite well with the data of authors [48]. This allow us to conclude that our value of the ERR for the incidence of radiation-induced thyroid cancers in Belarusian population is quite accurate.

Excess absolute risk (EAR) for thyroid cancer mortality:

The excessive absolute risk of mortality resulting from the radiation-induced thyroid cancers was also assessed. The same method as in case of the incidence in radiation thyroid cancers was used for this purpose. It was found that the excessive absolute risk of mortality in radiation-induced thyroid cancers for the Belarusian population is equal to (0.20-0.40) per 10^4 PYGy.

This value agrees quite well with the excessive absolute risk of the death from radiation-induced thyroid cancer assessed by E.Gilbert [49]. The EAR of this author is about 0.125 - 0.25 per 10^4 PYGy. However, the quality of our assessed data on mortality from radiation-induced thyroid cancers is not so good as in case of data on the incidence in thyroid cancers. Therefore, we consider our assessment on the mortality for radiation thyroid cancers in Belarus as a qualitative assessment.

CONCLUSIONS

1. The morbidity and the mortality from radiation-induced cancers in Belarus as a result of the Chernobyl accident have been assessed for the period of time 1987-2000. According to our assessment, 692 radiation-induced thyroid cancers among the children of Belarus appeared in 1987-2000. The total number of children's thyroid cancers that will manifest in 1987-2001 can be about 707 cases. The number of the radiation-induced thyroid cancers manifested among adolescents and adults of Belarus in 1987-2000 as a result of the Chernobyl accident was assessed as 3,709 cases. The total number of radiation-induced thyroid cancers appeared in this period of time is about 4,401 cases. The number of the people that died in Belarus in 1987-2000 from radiation-induced cancer was assessed as 351 cases.
2. The low latency period of radiation-induced thyroid cancers among the Belarusian population was found: about 1 year in case of children and about 2 years in case of adolescents and adults.
3. The excessive absolute risk, EAR, of the radiation-induced thyroid cancers manifested in Belarus after the Chernobyl accident is assessed as (2.4 – 4.8) per 10^4 PYGy. This value is higher than the excessive absolute risk established for atomic bomb survivors that were irradiated with dose rates many thousands times higher than dose rates of the Belarusian population.
4. The excessive relative risk, ERR, of the incidence in radiation-induced thyroid cancers manifested in Belarus after the Chernobyl accident is assessed as (11.2-22.4)/Gy. These values are one order higher than the excessive relative risk established for atomic bomb survivors.
5. The high value of the radiation risks of the thyroid cancers incidence as well as the absence of significant latency of radiation-induced thyroid cancers by the Belarusian population indicate an

irrelevancy of radiation risks established from atomic bomb survivors for the Belarusian population.

6. The excessive absolute risk of the mortality in Belarus in 1987-2000 from the radiation-induced thyroid cancers was assessed as (0.20 - 0.40) per 10^4 PYGy.

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