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Original article

COMPARISON OF THE RISK OF MORTALITY FROM SOLID CANCERS AFTER RADIATION INCIDENTS AND OCCUPATIONAL EXPOSURES

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Abstract. .The purpose of the study was to compare the excess relative risk of mortality (ERR per 1 Sv) from solid cancers during acute — catastrophic or accidental and occupational, fractionated or chronic — exposure.

Study materials and methods. Materials of the study: maintained database (source database) on nuclear industry workers from about 40 countries, based on which a pooled analysis of data was conducted to determine the integral value of ERR per 1 Gy for mortality from solid cancers; indicators of cohorts exposed to catastrophic and accidental radiation: the cohort LSS victims of the atomic bombings in Japan; residents of the Techa River — radioactive contamination resulting from releases from "Mayak" production association; Russian liquidators of the Chernobyl nuclear accident.

Study results and analysis. Comparison of the ERR of 1 Sv deaths from solid cancers for workers in the global nuclear industry (pooling analysis of data from 37 studies) with those of the LSS cohort; Techa River residents and Chernobyl accident liquidators showed no logical and principled differences, with the risks for the latter two cohorts being the highest.

Although the findings partly support the approach of the UN Scientific Committee on the Effects of Atomic Radiation that the carcinogenic effects of acute (catastrophic or accidental) and occupational (fractionated or chronic) radiation exposure are independent of the dose rate factor (DDREF), this issue cannot be considered unequivocally resolved, given the biological mechanisms and radiobiological experimental data.

Based on the ERR per 1 Sv, the average external dose, and the annual background cancer mortality rates in Russia and the United States, the expected cancer mortality increase for 100,000 workers in the nuclear industry would be an average of 32-69 people over 10 years — 0.032-0.069% of the group. Such risks, due to multiple carcinogenic non-radiation factors of life and work, as well as fluctuating background values, cannot be taken into account in the practice of disaster medicine and public health.

Key words: *atomic bomb victims, catastrophic exposure, Chernobyl accident liquidators, chronic exposure, emergency exposure, fractionated exposure, mortality risk, nuclear industry workers, solid cancers, Techa River residents*

Conflict of interest. The authors declare no conflict of interest

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Оригинальная статья

СРАВНЕНИЕ РИСКА СМЕРТНОСТИ ОТ СÓЛИДНЫХ РАКОВ ПОСЛЕ РАДИАЦИОННЫХ ИНЦИДЕНТОВ И ПРОФЕССИОНАЛЬНОГО ОБЛУЧЕНИЯ

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Резюме. *Цель исследования* – сравнение избыточного относительного риска смертности (ERR на 1 Зв) от сóлидных раков при остром – катастрофическом или аварийном и профессиональном – фракционированном или хроническом – облучении.

Материалы и методы исследования. Материалы исследования: поддерживаемая база данных (база источников) по работникам ядерной индустрии из примерно 40 стран, на основе которой проведен объединяющий анализ данных для определения интегральной величины ERR на 1 Гр по смертности от сóлидных раков; показатели когорт, подвергавшихся катастрофическому и аварийному облучению: когорта LSS пострадавших от атомных бомбардировок в Японии; резиденты реки Теча – радиоактивное загрязнение в результате выбросов ПО «Маяк»; российские ликвидаторы аварии на Чернобыльской АЭС.

Результаты исследования и их анализ. Сравнение величины ERR смертности от сóлидных раков на 1 Зв для работников мировой ядерной индустрии (объединяющий анализ данных 37 исследований) с показателями когорты LSS; резидентов на реке Теча и ликвидаторов аварии на Чернобыльской АЭС – продемонстрировало отсутствие поддающихся логике и принципиальных отличий, причем риски для двух последних когорт были наиболее высокими.

Хотя полученные данные отчасти подтверждают подход Научного комитета по действию атомной радиации ООН, согласно которому канцерогенные эффекты острого (катастрофического или аварийного) и профессионального (фракционированного или хронического) лучевых воздействий не зависят от фактора мощности дозы (DDREF), тем не менее, с учетом биологических механизмов и данных радиобиологических экспериментов, этот вопрос не может считаться однозначно решенным.

Исходя из ERR на 1 Зв, из средней дозы внешнего облучения, а также из величины ежегодной фоновой смертности от рака в России и США ожидаемая прибавка смертности от раков для 100 тыс. работников ядерной индустрии составит в среднем 32–69 чел. за 10 лет – 0,032–0,069% от группы. Подобные риски, в связи со множеством канцерогенных нелучевых факторов жизни и работы, равно как и с колебаниями фонового значения, невозможно учитывать в практике медицины катастроф и здравоохранения.

Ключевые слова: *аварийное облучение, катастрофическое облучение, ликвидаторы аварии на Чернобыльской АЭС, пострадавшие от атомных бомбардировок, работники ядерной индустрии, резиденты реки Теча, риск смертности, со́лидные раки, фракционированное облучение, хроническое облучение*

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Introduction. The problem of comparing medico-biological effects of acute exposure, including accidental irradiation and irradiation after nuclear accidents, with the effects of fractionated and chronic exposure has arisen since the first stages of the formation and development of radiation disciplines [1, 2]. It has been repeatedly found in experiments that the yield of various effects of radiation exposure decreases depending on the level (rate) of dose, since cells "have time" to recover from sublethal damage [3].

The fact that dose and dose-rate-effectiveness factor (DDREF) influences on the biological effects of irradiation is not questioned. However, discussions on the extent to which DDREF accounting can be reflected in epidemiological risk assessments have been going on for a long time [4-7]. Previously, international organizations (the UN Scientific Committee on the Effects of Radiation — UNSCEAR; the International Commission on Radiation Protection — ICRP) used a DDREF of two to study chronic exposure to radiation with low linear energy transfer (LET). That is, the effectiveness of acute exposure had to be divided by 2 [3, 7, 8].Thus, only the dose rate factor, i.e., DREF, was taken into account. At the same time, BEIR-VII, a periodic document of the US Academy of Sciences Committee on Radiation Effects, states that DDREF also depends on dose. It varies from 1.5 to 3 for different solid cancers in the Japanese Life Span Study (LSS) cohort of atomic bombing victims and different experimental models [4, 9, 10].

The question of the role of DDREF has been complicated by studies of the incidence of carcinogenic effects in a combined cohort of nuclear industry workers from 15 countries — E. Cardis et al. (2005-2008) — [11-13]. Based on these data, UNSCEAR concluded that the previous DDREF value of two was "very high" for nuclear industry workers. Therefore, the risk at low doses can be estimated by linear extrapolation from the risk for the LSS cohort without applying the DDREF factor, i.e., DDREF = 1 [14, 15].

Thus, a comparison of the incidence of cancer and leukemia in the pooled cohort of nuclear industry workers with the considered reference value for the LSS cohort has in part already been done. But its results have never led international organizations to a definitive conclusion as to which value should be used for chronic or prolonged occupational exposures. So there are still discussions on this issue [4, 5, 8-16]. In addition, the already mentioned studies by E. Cardis et al. in 2005-2008 were criticized for the non-homogeneity of the cohort, in which the main contribution to the increase of carcinogenesis frequency was made by Canadian workers [4, 11-13, 17, 18].

Our maintained database (source database) on biomedical and epidemiological effects in workers in about 40 countries has about 1,000 papers and documents. Therefore, we have been able to combine a considerable amount of data on Excess relative risks (ERR) of cancer per unit dose (1 Sv) for workers in major nuclear-industry countries. As a result, we obtained a certain integral value characterizing the risk for the category "world nuclear industry workers per se". This can be important in comparing the effects in different categories of workers dealing with radiation exposure. The sample included both individual studies and all pooled analyses performed to date — see below.

Purpose of the study was to summarize the data on ERR per 1 Sv for the world cohort of nuclear industry workers (fractionated and chronic exposure) followed by comparison of the obtained value with the table value of this parameter: for the LSS cohort, whose radiation exposure was acute and catastrophic; for residents of the Techa River — radioactive contamination from "Mayak" Industrial Association and for liquidators of the Chernobyl NPP accident. On the basis of the results obtained, the excess absolute risk of cancer for workers in the nuclear industry was also assessed.

Materials and methods of research. Sources in the available database with publications and documents related to biomedical effects in employees of the nuclear industry in different countries of the world. ERR per 1 Sv was analyzed for the incidence of mortality from solid cancers — ERR = RR -1, where RR is the relative risk [9]. A number of studies used ERR values per 0.1 Sv — such data were excluded. In addition, studies in uranium mine workers were not included in the analysis.

Typically, sample processing in synthetic studies (review, meta-analysis, and pooled analysis, including simple pooling) involves assessing their heterogeneity and eliminating outlier values [19, 20]. In the presented study, the sample was evaluated for normality of distribution, central tendencies, and outliers using Statistica, ver. 10. The forest-plot was also plotted using this program. Outlier values were determined using Chauvenet's criterion (table up to 50-1000 variants) [21].

Results of the study and their analysis. Currently, not all of the publications in our database of sources have been analyzed, but we managed to collect 37 studies from 6 countries, as well as international papers that provided data for the final ERR per 1 Sv for mortality from solid cancers (Table 1, Figure). A visual illustration summarizing all samples and data is the corresponding forest-plot (with ERR = 0 – no risk).

Table 1 and the figure show that the risk for workers from different industries and different countries varies greatly — the highest values were found for the Canadian cohort and

Таблица 1 /Table No.1

ERR на 1 Зв смертности от сóлидных раков для работников мировой ядерной индустрии

Excessive relative risk of death from cancer (ERR per 1 Sv) for world nuclear workers

Когорта / Cohort	ERR на 1 Зв -90%-й CI* ERR per 1 Sv –90% CI*	Источник Source
Великобритания / United Kingdom		
АЭС UKAWE / UKAWE NPP	7,6 (0,4; 15,3)	Beral V., et al., 1988 [22]
АЭС UKAEA / UKAEA NPP	0,8 (–1,0; 3,1)	Fraser P.L., et al., 1993 [23]
Обогащение урана Capenhurst Capenhurst uranium enrichment	1,3 (0; 2,4)	McGeoghegan D., et al., 2000 [24]
АЭС Sellafield / Sellafield NPP	0,11 (–0,4; 0,8)	Douglas A.J., et al., 1994 [25]
Производство ядерного топлива Springfields Springfields nuclear fuel production	0,64 (–0,95; 2,7)	McGeoghegan D. Et al., 2000 [24]
UK National Registry for Radiation Workers 1976–1988	0,47 (–0,12; 1,2)	Kendall, et al. 1992 [26], Russ A. Et al., 2006 [27]
Производство ядерного топлива British Nuclear Fuels (BNFL) British Nuclear Fuels (BNFL) nuclear fuel production	0,29 (0,02; 0,59)	Gillies M, Haylock R., 2014 [28]
National Registry for Radiation Workers	0,28 (0,06; 0,53)	Haylock R.G.E., et al., 2018 [29]
То же / Ibid	1,42 (0,51; 2,38); исключены данные для доз свыше 0,1 Гр / 1.42 (0.51; 2.38); data for doses above 0.1 Gy are excluded.	Haylock R.G.E., et al., 2018 [29]
Канада / Canada		
АЭС AECL / AECL NPP	0,049 (–0,68; 2,17)	Gribbin M.A., et al., 1993 [30]
То же / Ibid	2,37 (–0,37, 6,60)	Zablotska L.B., et al., 2014 [31]
То же / Ibid	1,20 (–0,73, 4,33); коррекция на дозы, социоэкономический статус и др. 1.20 (-0.73, 4.33); correction for doses, socioeconomic status, etc.	Zablotska L.B., et al., 2014 [31]
The National Dose Registry (NDR) of Canada	3,0 (1,1; 4,9); только мужчины (женщины – нет эффекта) 3.0 (1.1; 4.9); men only (women – no effect)	Ashmore J.P. et al., 1991; 1997 [33, 36], Zielinski J.M. et al., 2008 [34]
То же / Ibid	2,6 (1,3; 4,3); только мужчины (для женщин выборка мала) 2.6 (1.3; 4.3); men only (too small sample for women)	Sont W.N. et al., 2001 [35], Zielinski J.M., et al., 2008 [34]
Канадские работники АЭС (AECL) в объединенном исследовании трёх стран (по данным [37]) Canadian nuclear power plant workers (AECL) in a combined 3-country study (based on [37])	0,13 (<0; 2,1)	Cardis E., et al., 1995 [36], Ashmore J.P., et al., 2007 [37]
Канадские работники АЭС (AECL) workers в объединенном исследовании 15 стран (по данным [37]) Canadian nuclear power plant (AECL) workers in a pooled study of 15 countries (based on [37])	6,65 (2,56; 13,00)	Cardis E., et al., 2007 [12], Ashmore J.P., et al., 2007 [37]
То же** / Ibid**	3,60 (1,03; 7,27)	Cardis, 2007 [12], Vrijheid, et al., 2008 [13]
США / USA		
X-10 workers	1,45 (0,15; 3,48)	Wing S., 1991 [38]
Hanford Nuclear Reservation	3,24 (0,80; 6,17)	Wing S., Richardson D.B., 2005 [39]
Производство ядерного оружия Rocky Flats / Rocky Flats nuclear weapons production	–0,04 (–1,7; 1,25)	Gilbert E.S., et al., 1993*b* [40]
Oak Ridge National Laboratory (ORNL)	1,5 (0,2; 3,5)	Frome E.L., et al. 1997 [41], Russ A., et al., 2006 [27]
То же / Ibid	4,28 (95% CI: –0,40, 11,6)	Ashmore J.P., et al., 2007; 2010 [37, 42]
Франция / France		
Объединенная когорта работников ядерной индустрии Франции United cohort of French nuclear industry workers	0,34 (–0,56; 1,38)	Metz-Flamant C., et al., 2013 [43]
Работники ядерной индустрии Франции (CEA, AREVA NC и EDF) Employees of the French nuclear industry (CEA, AREVA NC and EDF)	0,34 (–0,44; 1,24)	Fournier L., et al., 2018 [44]
То же / Ibid	0,37 (–0,44; 1,30)	Leuraud K., et al., 2017 [45]
Россия / Russia		
Работники Institute of Physics и Power Engineering (IPPE) Workers of the Institute of Physics и Power Engineering (IPPE)	0,22 (95% CI: –4,22; 7,96)	Ivanov V.K., et al., 2004; 2006 [46]
Работники ПО «Маяк» Workers of "Mayak" production association	0,3 (0,2; 0,4); для lag-периода 20 лет 0.3 (0.2; 0.4); for a lag period of 20 years	Shilnikova N.S., et al., 2003 [47]

Когорта / Cohort	ERR на 1 Зв -90%-й CI* ERR per 1 Sv –90% CI*	Источник Source
Япония / Japan		
Регистр работников ядерной индустрии Nuclear industry workers Registry	1,26 (95% CI: –0,27, 3,00)	Akiba S., Mizuno S., 2012 [48]
То же / Ibid	0,38 (–0,84; 1,81); с поправкой на курение, lag-период 15 лет 0.38 (-0.84; 1.81); adjusted for smoking, lag period of 15 years	Kudo S.. et al., 2018 [49]
Объединенные когорты / Combined cohorts		
Объединенный анализ работников ядерной индустрии Канады Combined analysis of Canada nuclear industry workers	2,80 (–0,038; 7,13)	Zablotska L.B., et al., 2004 [50]
Объединенный анализ работников ядерной индустрии Великобритании Combined analysis of United Kingdom nuclear industry workers	–0,02 (–0,5; 0,6)	Carpenter L., et al., 1994; 1998 [51, 52]
Объединенный анализ работников ядерной индустрии Великобритании (NRRW) Combined analysis of United Kingdom nuclear industry workers (NRRW)	0,086 (–0,28; 0,52)	Muirhead C.R., et al., 1999 [53]
	0,275 (0,02; 0,56)	Muirhead C.R., et al., 2009 [54]
Объединенный анализ работников ядерных предприятий США по обогащению топлива Combined analysis of U.S. nuclear enrichment workers	0,506 (–2,01; 4,64)	Zablotska L.B., et al., 2004 [50]
Объединенное исследование работников ядерной индустрии Великобритании, Канады и США Combined study of nuclear industry workers of UK, Canada, USA	–0,07 (–0,39; 0,30)	Cardis E., et al., 1995 [36]
Объединенное исследование работников ядерной индустрии 15 стран (Европа – Америка – Восточная Азия) Combined study of nuclear industry workers of 15 countries (Europe – America – East Asia)	0,87 (0,03; 1,88)	Thierry-Chef M., et al., 2007; Cardis E., et al., 2005; 2007; Vrijheid M., et al., 2007, 2008; [11–13, 55, 56]
Объединенное исследование работников ядерной индустрии 14 стран (Европа – Америка – Восточная Азия). То же, что в предыдущем случае, но без Канады Combined survey of nuclear industry workers of 14 countries (Europe – America – East Asia). Same as the previous case, but without Canada	0,58 (–0,1; 1,39)	Wakeford R., 2014 [17]
Объединенное исследование работников ядерной индустрии Франции, Англии и США (INWORK) Joint INWORK study of nuclear industry workers of France, England, and the United States	0,42; (0,13; 0,73)	Daniels R.D., et al., 2017 [57]
То же / Ibid	0,47; (0,18; 0,79)	Richardson D.B., et al., 2015 [58], Laurier D., et al., 2017 [59]

* Если не указаны иные CI (CI – доверительные интервалы) / Unless otherwise specified CI (CI – confidence intervals)

** Две различные когорты, вторая – дополненная / Two different cohorts, second augmented

slightly less for the United States. It should be noted that in the works of Ashmore J.P. et al. (2007, 2010) with high values for the United States, the authors presented a value only for the Oak Ridge Nuclear Center [37, 42].

The results of the pooled analysis of the ERR per Sv data for nuclear industry workers compared to the cohorts of victims of nuclear incidents are presented in Table 2.

Table 2 shows that the original sample of 36 studies for all countries — the data from one study were outliers — is heterogeneous. This was shown both by analysis of distribution normality and by comparison of central tendencies: the mean and median are very different. In a pooled analysis of data for 15 countries, Cardis E. et al. (2005-2008), a significant contribution to the distortion of the results was made, as mentioned above, by the data-dropout cohort of Canadian workers [11-13]. Therefore, the above analysis was later corrected in the study of Wakeford R. (2014) by eliminating data for Canada from the sample, resulting in a one and a half fold decrease in the pooled ERR per 1 Sv for workers from 14 countries [17] — see Table 1, Pooled Cohorts. The anomalous nature of the Canadian cohort in terms of cancer mortality risk has been discussed many times, including the fundamental benefits and BEIR-VII [4, 9, 18, 62, 63]. For this cohort, the risk of lung cancer from — probably — non-radiational factors prevailed, including no adjustment for smoking [62, 63]. In addition, the main contributor to the effect was a subgroup from one of the plants with relatively early employment — before 1965. [63].

For this reason, in our pooling analysis, too, data for Canadian workers were excluded from the sample, which became much more homogeneous (cf. mean and median in Table 2), although a completely normal distribution was not achieved.

For comparison with the effect of occupational, i.e., fractionated or chronic, exposure, data on ERR per 1 Sv were taken for cohorts of those affected by radiation incidents. As already noted, the "tabulated" one for radiation risks to date is the Japanese LSS cohort, whose last study (follow-up — 1950-2003) revealed an ERR per 1 Sv equal to 0.42 [4, 5, 8-13, 18, 61-63]. One can see from Table 2 that this value is less than for the residents on the Techa river who suffered from uncontrolled releases from the "Mayak" Industrial

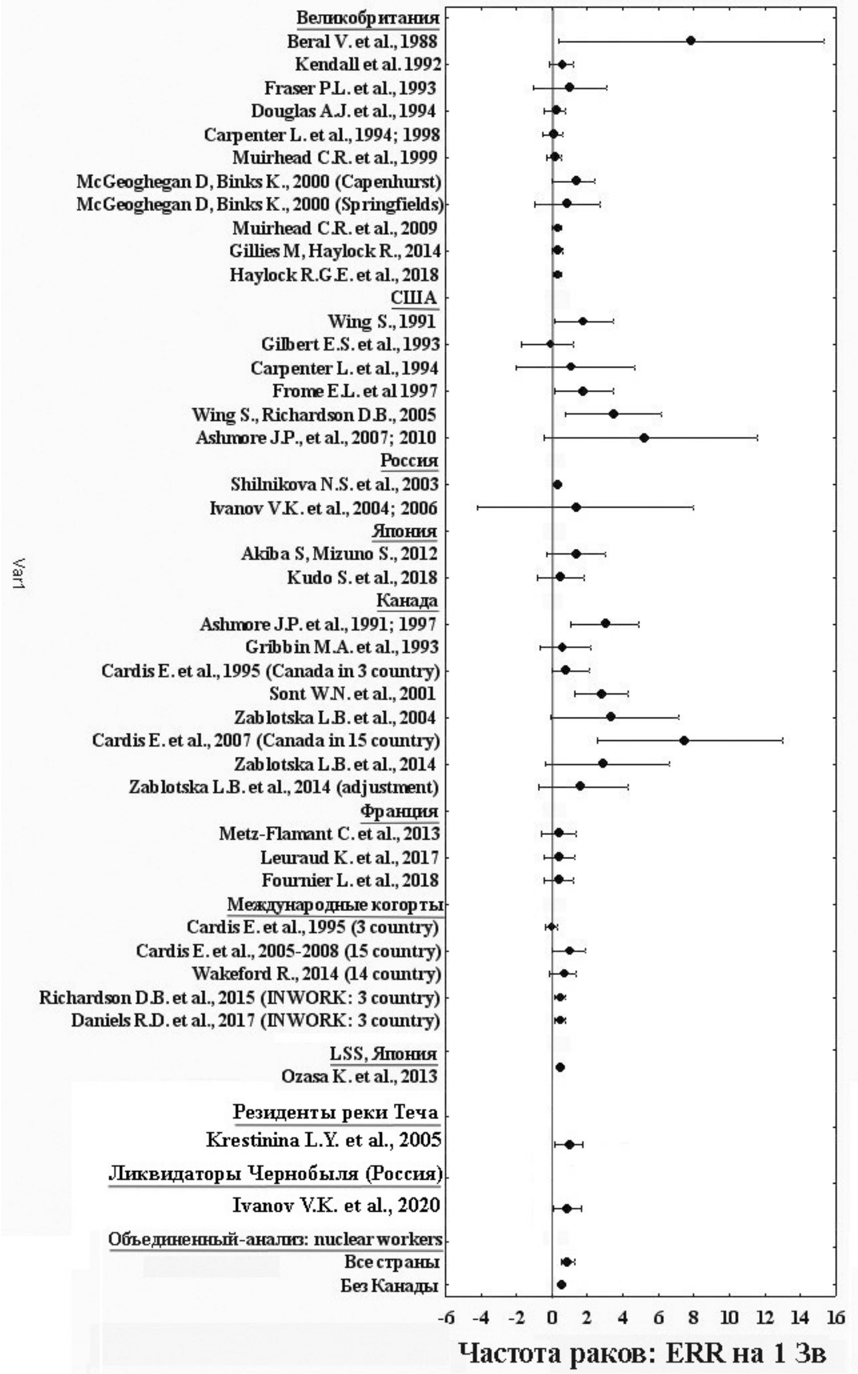

Рисунок. Forest-plot подборки источников по ERR на 1 Зв для сóлидных раков (с 90%-ным или 95%-ным CI; см. в табл. 1) для работников ядерной индустрии различных стран вместе с международными исследованиями объединенных когорт. Представлены также данные для когорты LSS пострадавших от атомных бомбардировок в Японии, для резидентов реки Теча, российских ликвидаторов аварии на Чернобыльской АЭС и результаты настоящего объединяющего анализа (нижние строки)

Figure. Forest-plot of a set of ERR sources per 1 Sv for solid crayfish (with 90% or 95% CI; see Table 1) for nuclear industry workers from different countries, coupled with international studies of pooled cohorts. Data are also presented for the LSS cohort of atomic bomb victims in Japan, residents of the Techa River, Russian liquidators of the Chernobyl accident, and the results of this merging analysis (bottom lines)

Association in the 1950s and for the Russian liquidators of the Chernobyl accident, the last data of 2020. [60, 61]. The corresponding values were 0.92 and 0.82. It should be said, however, that these 2 cohorts may have been influenced by a mass of uncontrolled intervening factors, resulting in difficulties in detecting true radiation dependencies [64]. For example, the effects of chemical agents, including lead and detergents, as well as the effects of stress and radiophobia in the 1990s, are known for liquidators, often leading to heavy smoking and alcohol abuse [65]. On the other hand, the data for the Japanese LSS cohort as well, with its triply revised dosimetry and with uncertainties in the contribution of neutron exposure, can also be called "report card" only conventionally, since there is nothing more appropriate [62].

Of course, in all the above cases, the control group was chosen within the cohort as the lowest dose group in the ERR calculations. Comparison with the general population is incorrect due to both the healthy worker effect and the clearly

Таблица 2 /Table No. 2

ERR на 1 Зв смертности от со́лидных раков для пострадавших от радиационных инцидентов и работников мировой ядерной индустрии

ERR per 1 Sv for solid cancer mortality for victims of radiation accidents and for world nuclear workers

Когорта Cohort	Mean –95% CI	Median –25% и 75% quartile Median –25% and 75% quartile
LSS [10]*	0,42 (0,32; 0,53)	–
Резиденты реки Теча [60] Techa river residents [60]	0,92 (0,2; 1,7)	–
Российские ликвидаторы аварии на Чернобыльской АЭС [61] Russian liquidators of the Chernobyl accident [61]	0,82 (0,1; 1,65)	–
Работники ядерной индустрии; настоящее исследование (вся выборка; 36 вариантов**) Nuclear industry workers; present study (entire sample; 36 options**)	1,1 (0,61; 1,58)	0,47 (0,28; 1,43)
Работники ядерной индустрии; настоящее исследование (без Канады; 26 вариантов**) Nuclear industry workers; present study (without Canada; 26 options**)	0,51 (0,33; 0,69)	0,38 (0,28; 0,64)

* Риск к возрасту 70 лет при облучении в возрасте от 30 лет / Risk by the age of 70 with the exposure from the age of 30

** После анализа на выпадающие значения / After analysis for outlier variants

better medical care in the exposed groups. But here one should take into account the possibility of different mentality of those who are in different dose groups [62]. For example, for Japanese workers of the nuclear industry, an association has been shown between the level of absorbed radiation dose, on the one hand, and smoking, as well as alcoholism, on the other. In addition, it turned out that for higher dose groups the frequency of routine diagnostics was lower [66]. There is an association between the radiation dose and the frequency of mortality from nonradiated pathologies (liver cirrhosis, oral and pharyngeal cancer, psychosis, external causes) among French nuclear industry workers — imitation of the "dose — effect" relation by alcohol [67]. All these factors are capable of distorting not only the "dose — effect" association for radiation exposure, but even of changing its character in a qualitative sense, if the radiation doses are not too high.

Nevertheless, it follows from Table 2 that the combined ERR per Sv for solid cancer mortality we obtained for workers in the global nuclear industry after excluding data for Canada is generally comparable to military and accidental radiation incidents. But even here we should take into account that a significant contribution to the frequency of cancers was made by those employed in the nuclear industries of the early 1940's to 1950's [68]. [68].

At the same time, the data we obtained do not provide a strong argument for the rejection by UNSCEAR in recent years of the DDREF coefficient in epidemiological studies of radiation carcinogenesis [14, 15]. Biological mechanisms of radiation effects as well as experimental radiobiological data do not allow one to agree with seemingly implausible conclusions from observational studies of populations with multiple intervening nonradiation factors (confounders) and biases [3, 9, 64]. Of course, the canons of establishing causality in epidemiology and evidence-based medicine are, first, the reliance on data for humans and, second, if clinical experimentation is not possible, on epidemiological and observational, rather than laboratory studies [69-73]. At the same time, some authors point to the fundamental importance of confirming the statistical regularities identified for humans by biological mechanisms, sometimes placing the latter at the forefront of the evidence [74]. Such views, of course, are somewhat marginal from the standpoint of epidemiology basics, but should probably be taken into account in the case of strange epidemiological data [75]. As one of the pioneers of evidence-based methodologies in epidemiology and evidence-based medicine, A.B.Hill, said: one should never "throw common sense out the window" [75-77].

It was of interest both epidemiologically and socially to estimate the absolute increase in the number of solid cancer cases based on the estimated ERR values for workers in the global nuclear industry. In other words, an answer to the question of what is the occupational hazard of this disease.

According to GLOBOSCAN, the average annual incidence of male cancer mortality is 126 deaths per 100,000 people (2012) [78]. In the United States and Russia (Rosstat) this figure is 200 deaths per year (2020) per 100,000 population, which we will take as our baseline. In our pooling study (without Canada), the ERR per Sv is 0.51. Thus, for 100,000 workers in the nuclear industry, if they had received a dose of 1 Sv each over, say, 10 years (~2,000 background cancer deaths), given the resulting risk value, we would expect 1020 additional deaths. However, in fact, there were fewer of them, because the "background" cancer rate for workers of harmful industries is lower than that for the corresponding sex-age group of the general population, because of the "healthy worker effect" [62].

In addition, workers in the nuclear industry did not receive average doses in the order of 1 Sv by the hundreds of thousands. Based on a sample of 63 items in our database of nuclear industry workers, the average individual accumulated external dose ranged from 3.8 mSv (Company NPP, CEA-COGEMA, France; 1946-1994) to 128 mSv (Sellafield NPP, UK; 1947-1988) [11, 25]. According to our calculations, the mean value for all countries and enterprises was 31.1 mSv (95% CI: 24.6 and 37.5) and the median was 24.0 mSv.

In other words, the expected increase in mortality from solid cancers for 100 thousand employees of the nuclear industry with the obtained risk value will be on average 32 persons for 10 years, i.e. 0.032% of the group. Such risks, due to many carcinogenic non-radiation factors of everyday life and work and fluctuations of the background value, cannot be taken into account in the practice of disaster medicine and public health [80]. Even if we assume an ERR value of 1 Sv for the entire original sample, including data for Canada, the conclusion would not change too much: the expected increase in cancer mortality would be 0.069% of the group.

Conclusions

1. Comparison of excess relative risk of mortality from solid cancers per unit external dose (per 1 Sv) for nuclear industry workers from different countries (pooling analysis of 37 studies) with corresponding values for atomic bombing vic-

tims in Japan (LSS cohort); for residents on the Techa — radioactive contamination in the 1950s; for liquidators of the Chernobyl accident in Russia — showed no logical and fundamental differences, with the risks for the latter two cohorts being the highest.

2. Although the findings partially support the UNSCEAR approach of recent years, according to which the carcinogenic effects of acute, accident and fractionated or chronic radiation exposure are independent of the dose rate factor (DDREF), nevertheless, taking into account biological mechanisms and data from radiobiological experiments, this question cannot be considered unequivocally resolved.

3. Based on the excess relative risk per Sv obtained in the pooling analysis, on the average accumulated external radiation dose, as well as on the value of the annual background cancer mortality rate in Russia and the USA — the expected increase in mortality from solid cancers for 100 thousand employees of the nuclear industry will be on average 32-69 persons over 10 years — 0.032-0.069% of the group. Such risks — due to the many carcinogenic non-radiation factors of everyday life and work and fluctuating background values — cannot be taken into account in the practice of disaster medicine and public health.

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