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STRONTIUM FALLOUT FROM CHERNOBYL AND PERINATAL MORTALITY IN UKRAINE AND BELARUS

© 2003 г. A. Korblein*

Münich Environmental Institute, Münich, Germany

Perinatal mortality rates in the regions of Ukraine and Belarus surrounding the Chernobyl site increased in 1987, the year following the Chernobyl accident. The same year, increases of perinatal mortality were also observed in Germany and Poland, and the effect can be associated with the caesium burden in pregnant women. After 1989, there is an unexpected second rise of perinatal mortality in Belarus and Ukraine. This increase is shown to correlate with the strontium content in pregnant women. The findings parallel an increase of perinatal mortality in Germany following the atmospheric bomb tests in the 1950's and 1960's. While the effect from caesium is essentially limited to 1987, the effect from strontium persists until the end of the study period in 1998. The cumulative effect from strontium around Chernobyl outweighs the effect from caesium by at least a factor of 10. This is contrary to the assertion that the caesium content in the Chernobyl fallout was more than 10-times greater than the strontium content. Thus, the dose factor presently used seems to severely underestimate the effect of strontium on perinatal mortality.

Chernobyl, perinatal mortality, strontium, Belarus.

INTRODUCTION

Pregnancy outcome is a very sensitive indicator of exposure to low-level ionising radiation. While congenital malformation data are not available in many countries, perinatal mortality data, i.e. stillbirth and early neonatal mortality data, usually can be obtained. Therefore studies about possible adverse pregnancy outcomes following Chernobyl are easier to conduct using stillbirth or perinatal mortality data. Research on congenital anomalies did not show consistent evidence of a detrimental effect of the Chernobyl accident [1]. Kulakov et al., however, reported significant increases of perinatal mortality and other endpoints in highly contaminated areas of Belarus and the Ukraine [2].

In Germany, a temporary increase of perinatal mortality relative to the long-term trend was found following Chernobyl. The increase was associated with the caesium burden in pregnant women as a result of consuming contaminated milk [3]. The effect was confirmed by data from Poland [4].

A literature search did not reveal a single investigation of a possible effect of the strontium emissions from Chernobyl on perinatal mortality. This is remarkable since there was considerable strontium contamination in the regions surrounding the Chernobyl site which extended well beyond the 30 km zone (see Fig. 1).

A recent regression analysis of perinatal mortality in West Germany before and after the atmospheric bomb tests in the 1950's and 1960's showed that the pattern of the observed data are well described by a continuously falling trend and an additive term which depends on the average strontium concentration in pregnant women (see Fig. 2). Between 1955 and 1985, approximately 110.000 excess perinatal deaths can be attributed to strontium in the fallout [5]. In the present paper, a similar approach is used to analyse perinatal mortality data from Belarus and Ukraine.

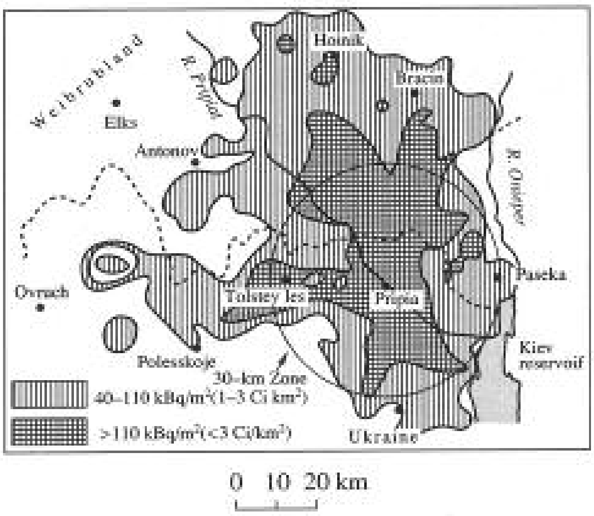

Fig. 1. Strontium deposit near the Chernobyl reactor. The circle is the 30 km zone. The hatched areas correspond to a strontium soil contamination of 1–3 Ci and more than 3 Ci per square km. From German journal "Atomwirtschaft", March 1991.

* Adress for correspondence: Münich Evironmental Institute, Schwere-Reiter Str. 35/1B, 80797, Münich, Germany; e-mail: ak@umweltinstitut.org.

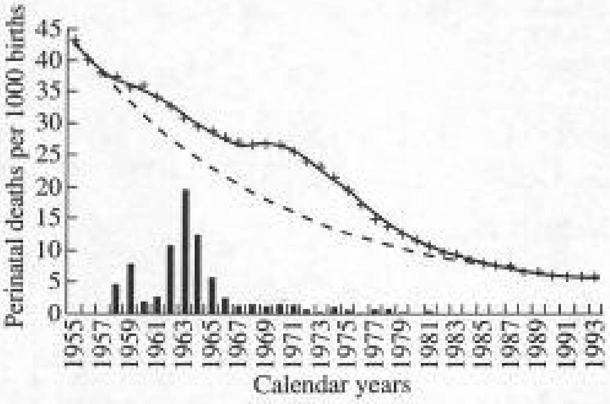

Fig. 2. Perinatal mortality in West Germany 1955 to 1993. The course of the data can well be approximated by the superposition of a monotonously falling long-term trend and an extra term which is calculated using the average strontium concentration in pregnant women. The black columns denote the strontium concentration in the fallout (data before 1958 are not available).

DATA AND METHODS

Perinatal mortality is defined as the number of stillbirths and early neonatal deaths (first 7 days), divided by the number of live births plus stillbirths. After 1993, the definition of stillbirth was changed in Belarus and Ukraine from a birth weight of 1000 g to 500 g.

Data for three Ukrainian oblasts neighbouring the Chernobyl reactor (Zhitomir, Kiev-City and Kiev-region), 1985–1991, were obtained from the centre for medical statistics of the Ukrainian Ministry of Health [6] (Tables 1 and 2).

Table 1. Perinatal mortality data from Kiev (Kiev oblast plus Kiev City)

Year	Live births	Stillbirths	Early neonatal deaths (0–7 days)
1985	67376	693	651
1986	65680	602	491
1987	58156	578	442
1988	67388	654	468
1989	61457	553	378
1990	55569	483	373
1991	51602	428	378

Table 2. Perinatal mortality data from Zhitomir oblast

Year	Live births	Stillbirths	Early neonatal deaths (0–7 days)
1985	23909	214	107
1986	24489	190	93
1987	21763	184	129
1988	21992	170	93
1989	21115	155	96
1990	19634	185	116
1991	19477	165	144

The statistical department of the Ministry of Health provided annual data of perinatal mortality in Belarus by oblast (region), 1985–1998 [7] (Tables 3 and 4).

For Belarus, the range of available perinatal mortality data extends to 1998. The data for the oblasts Gomel and Minsk City, together with the data for Belarus minus Gomel and Minsk City, are shown in Fig. 3. In all three data sets, there is a significant increase in 1994 which is caused by the change of definition of stillbirth in that year. In Gomel, the oblast of Belarus with the highest fallout, perinatal mortality rises after 1989 compared to Belarus minus Gomel and Minsk City. Minsk City is omitted from the comparison since it shows an unusual drop after 1996 which is unlikely to have biological reasons.

In [5], the trend of West German perinatal mortality data was approximated by the sum of a downward trend and an extra term which depends on the average strontium concentration in pregnant women. The same approach is applied here to perinatal mortality data from Ukraine and Belarus.

Strontium replaces calcium in the human body. The maximum uptake of strontium occurs during menarche, i.e. at about age 14 [8]. In a first approach it is assumed that the average strontium concentration in mothers depends, first, on the proportion of mothers born in 1972, i.e. mothers who were 14 years old at the time of the Chernobyl accident, and second on the biological half-life of strontium in the female body.

To determine, in each year following Chernobyl, the proportion of pregnant women who were born in 1972, annual data of the maternal age distribution are needed. Since such data were not made available for Belarus and Ukraine, data from a St. Petersburg maternity hospital, averaged over 1990–1999, which were provided by a Russian colleague, were used (see Fig. 4). Since the living conditions were similar within the European part of the former Soviet Union, this approximation is considered to be a valid first approach.

Tables of the strontium elimination rates in the human body as a function of age are provided in ICRP 67. The strontium concentration as a function of time after exposure can be approximated by the sum of two exponential functions with half lives 2.42 and 13.65 years. Thus, the average strontium concentration in year t after 1986 is the proportion P of mothers age $(t + 14)$, multiplied by a term which allows for the strontium elimination:

$$\mathrm{Sr}(t) = P(t+14)(0.135\exp(-\ln(2)t/2.42) + \\ + 0.099\exp(-\ln(2)t/13.65)). \quad (1)$$

The regression model used to analyse the Ukrainian data is a simple exponentially decreasing trend, with additional terms for a possible effect from caesium in

Table 3. Perinatal mortality data from Gomel oblast

Year	Live births	Stillbirths	Early neonatal deaths (0–7 days)
1985	29025	219	156
1986	29057	208	168
1987	25000	187	152
1988	27750	200	138
1989	26039	171	136
1990	22462	161	151
1991	20584	151	138
1992	20432	138	108
1993	19363	119	106
1994	18061	121	138
1995	16269	123	109
1996	15217	81	101
1997	14501	103	70
1998	14943	83	86

Table 4. Perinatal mortality data from Belarus minus Gomel and Minsk City

Year	Live births	Stillbirths	Early neonatal deaths (0–7 days)
1985	109606	823	570
1986	115377	810	657
1987	111615	811	584
1988	109026	694	619
1989	102541	612	519
1990	96890	590	505
1991	91289	544	442
1992	88672	477	459
1993	81192	374	361
1994	76740	444	411
1995	70270	385	379
1996	66453	338	314
1997	62309	344	299
1998	64432	312	245

1987, the year following Chernobyl, and from strontium in later years. The model has the following form:

$$p = c_1\exp(-c_2t) + c_3d87 + c_4Sr(t\text{-}1986), \qquad (2)$$

where p is perinatal mortality, $d87$ is a dummy variable which marks the year 1987, and c_1 through c_4 are parameters. Parameters c_1 and c_2 estimate the intercept and the slope of the trend curve, parameter c_3 the increase in 1987 (caesium term) and parameter c_4 the prefactor in the strontium term. The null-hypothesis to be tested is H0: $c_2 \le 0$ and $c_3 \le 0$ versus H1: $c_2 > 0$, $c_3 > 0$ (one sided t-test).

Perinatal mortality data are population-weighted with binomial variances σ^2 defined by

$$\sigma^2 = p(1-p)/N, \qquad (3)$$

where N is the number of live births plus stillbirths.

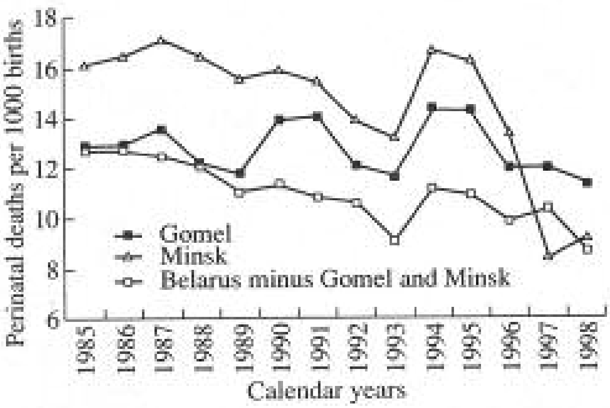

Fig. 3. Perinatal mortality in the oblasts of Gomel and Minsk City and in Belarus without Gomel and Minsk City.

RESULTS

Data from Ukraine

Individual regressions to the data from Kiev (Kiev City plus Kiev region) and Zhitomir oblast yielded the following results. Both the increase in 1987 (parameter c_3) and the prefactor in the strontium term (parameter c_4) are significant in Zhitomir but not in Kiev. The slopes of the trend curves (parameter c_2) agree within the limits of error in the two data sets. Therefore a combined regression was performed. This is, first, a way to increase the test power, but also, to make the strontium effects comparable to one another. The combined regression model has the following form:

$$p = (c_1\text{kiev} + c_2\text{zhitomir})\exp(-c_3t) + (c_4\text{kiev} + c_5\text{zhitomir})d87 + (c_6\text{kiev} + c_7\text{zhitomir})\text{Sr}. \qquad (4)$$

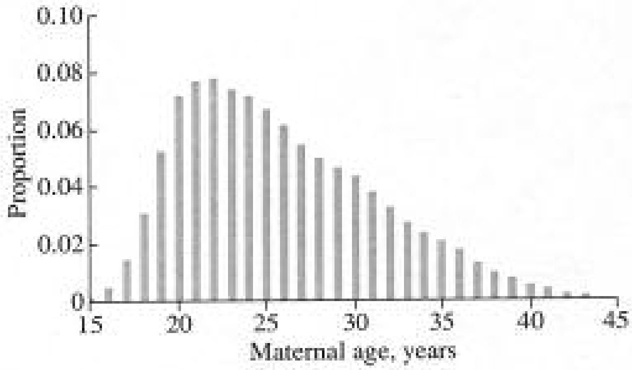

Fig. 4. Maternal age distribution from St. Petersburg averaged over 1990–1999.

Table 5. Combined regression analysis for Ukraine

Parameter	Estimate	SD	t-value	p-value
c_1	18.98	0.47	40.39	<0.0001
c_2	12.90	0.53	24.43	<0.0001
c_3	0.0714	0.0148	4.829	0.0010
c_4	1.054	0.669	1.576	0.0795
c_5	2.662	0.961	2.771	0.0138
c_6	5.448	2.115	2.576	0.0184
c_7	13.65	2.041	6.689	0.0001

Table 6. Combined regression analysis for Belarus

Parameter	Estimate	SD	t-value	p-value
c_1	13.24	0.57	23.22	<0.0001
c_2	13.02	0.36	36.19	<0.0001
c_3	0.0328	0.0155	2.119	0.0288
c_4	1.058	1.085	0.975	0.1754
c_5	0.314	0.508	0.618	0.2747
c_6	3.256	1.913	1.702	0.0584
c_7	–0.300	1.577	–0.190	0.4262

Table 7. Combined regression analysis for Belarus – reduced model

Parameter	Estimate	SD	t-value	p-value
c_1	13.11	0.263	49.87	<0.0001
c_2	0.0362	0.0046	7.812	<0.0001
c_3	1.241	0.926	1.341	0.1015
c_4	0.307	0.447	0.686	0.2523
c_5	3.852	0.867	4.444	0.0003

Here "kiev", "zhitomir" are dummy variables that identify the two data sets.

The model fits the data well: the sum of squared residuals is 8.2 with 7 degrees of freedom ($p = 0.315$, chisquare-test). The results are given in Table 5. In 1987, there is a significant 24% increase of perinatal mortality in Zhitomir ($p = 0.014$); the excess perinatal mortality is 2.66 ± 0.96 per 1000 births. In Kiev, the excess perinatal mortality in 1987 is only 1.05 ± 0.67 ($p = 0.080$), 2.5-times less than in Zhitomir. The strontium effect is also 2.5 times greater in Zhitomir (parameter c_7, $p = 0.0001$) than in Kiev (parameter c_6, $p = 0.0184$).

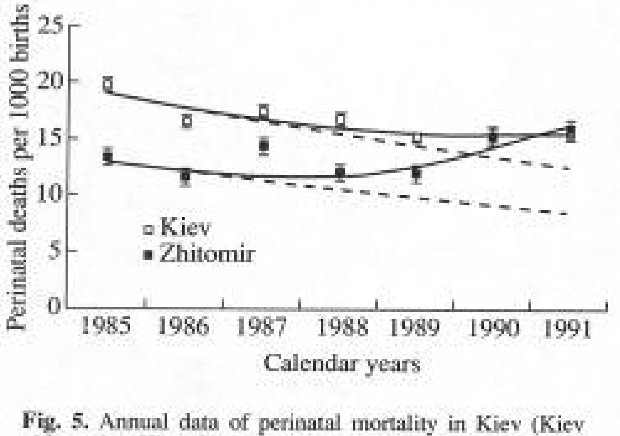

Fig. 5. Annual data of perinatal mortality in Kiev (Kiev oblast plus Kiev-City) and in Zhitomir oblast. The solid lines are the results of a combined regression analysis. The interrupted lines show the undisturbed trend lines.

Data from Belarus

For Belarus, the range of available perinatal mortality data extends to 1998. The data for the oblasts Gomel and Minsk City, together with the data for Belarus minus Gomel and Minsk City, are shown in Fig. 5. In all data sets, there is a significant increase in 1994 which is caused by the change of stillbirth definition in that year. In Minsk City, perinatal mortality is higher than in the other oblasts until 1996, but then suddenly drops to a level smaller than in the other oblasts. This behaviour is unlikely to have biological reasons.

The trend analysis for the data from Ukraine is hampered by the change of definition of stillbirth in 1994. Therefore the data can only be analysed until 1993. For the individual regressions to the data of Gomel (study area) and Belarus minus Gomel and Minsk City (control area) the model in equation 2 is used. For the reasons mentioned above, Minsk City is not included in the control area.

Since the slopes agree within the limits of error, a combined regression of the two data sets with the model in equation 4 is performed. The results are given in Table 6. Now parameter c_1 and c_2 coincide and parameter c_6 is zero within the limits of error. Therefore the model is modified as follows.

$$p = c_1\exp(-c_2 t) + (c_3\text{gomel} + c_4\text{rest})d87 + c_5\text{gomelSr}. \quad (5)$$

Now the undisturbed trend is the same in the study and in the control area. The effect from caesium in 1987 is estimated individually for the two sub data sets ("gomel" and "rest", respectively). A possible effect from strontium is only allowed for in Gomel.

The sum of squared residuals (ssq) obtained with model 5 is ssq = 20.1 with 13 degrees of freedom ($df = 13$), the chisquare test yields $p = 0.093$. Thus model 5 fits the data better than model 4 (ssq = 19.8, $df = 11$, $p = 0.048$). The results of the regression with model 5 are given in Table 7. The excess perinatal mortality in 1987 is 1.24 ± 0.96 per 1000 in Gomel ($p = 0.102$) and 0.31 ± 0.45 per 1000 in the control area ($p = 0.252$). The strontium term is highly significant ($p = 0.0003$).

The trend of the data in Gomel and in the control area is shown in Fig. 6. While the data essentially coincide in the two regions until 1989, they are considerably increased in Gomel oblast relative to the control area after 1989.

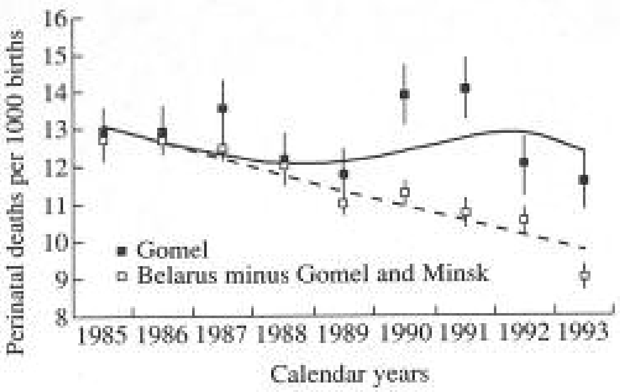

Fig. 6. Perinatal mortality in oblast Gomel (study area) and in Belarus minus Gomel and Minsk City (control area) 1985–1993, and results of a combined regression (solid line for Gomel, interrupted line for control area).

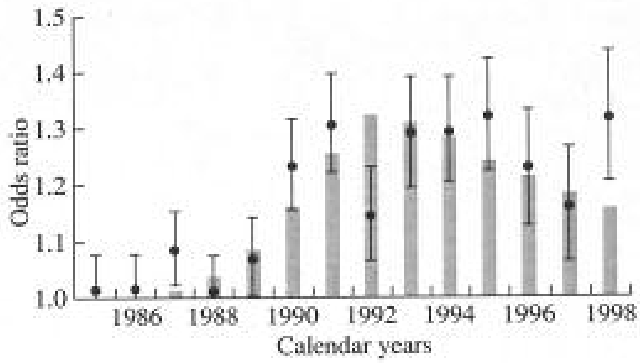

Fig. 7. Odds ratios of perinatal mortality in the oblast of Gomel vs. Belarus minus Gomel and Minsk City (dots). The error bars indicate one standard deviation. The grey columns display the fit result for the strontium term.

Trend analysis of the odds ratios

In an alternative approach, perinatal mortality rates in Gomel were compared to the rates in the control area. The change in the definition of stillbirths and other factors which may have a global impact on the data should not influence the ratio of the mortality rates which are defined by:

$$\text{odds ratio} = (p_1/(1-p_1))/(p_0/(1-p_0)). \quad (6)$$

Here p_1 and p_0 are the perinatal mortality rates in Gomel oblast and the control area, respectively. The advantage of this approach is that no assumptions are needed for the long-term trend, nor for the influence of the change of stillbirth definition on perinatal mortality rates.

The regression model has the following form:

$$\ln(\text{odds ratio}) = c_1 + c_2 d87 + c_3 \text{Sr}. \quad (7)$$

Parameter c_0 accounts for an odds ratio different from 1 before Chernobyl, c_1 estimates a possible increase in 1987 and parameter c_2 the strontium effect. The use of the logarithms simplifies the calculation of the variances σ^2:

$$\sigma^2 = 1/n_1 + 1/(N_1 - n_1) + 1/n_0 + 1/(N_0 - n_0), \quad (8)$$

where n_1, n_0 are the numbers of perinatal deaths and N_0, N_1 the numbers of live births plus stillbirths in Gomel (1) and in the control area (0).

The model fits the data well. The sum of squared residuals (ssq) is 8.0 ($df = 11$). Without the strontium-term in the model, the sum of squares is 29.7 ($df = 12$). The improvement of the fit is highly significant ($p = 0.0007$, F-test). The results of the regression analysis are given in Table 8. Parameter c_1 is not different from zero, i.e., without the caesium and strontium influence there is no significant difference of perinatal mortality rates in the study and the control area. The increase in 1987 (parameter c_2) is not significant ($p = 0.207$), but the strontium term (parameter c_3) is highly significant ($p = 0.0001$). A chisquare test shows that a regression without parameter c_1 yields a better fit (ssq = 8.4, $df = 12$, $p = 0.752$) than the full model 7 (ssq = 8.0, $df = 11$, $p = 0.714$).

The trend of the odds ratios is displayed in Fig. 7. Before 1990, perinatal mortality in Gomel equals the perinatal mortality in the control region within the limits of error, except for a small increase in 1987, the year following Chernobyl. During 1990–1998, however, the odds ratios increase to about 1.3, i.e., perinatal mortality in Gomel is 30% higher than in the control area. The columns in Fig. 7 give the fit result for the strontium term with parameter $c_1 = 0$.

DISCUSSION

Though the approach used for the data evaluation is rather simplified, and only sparse data were available for Ukraine, a significant effect from strontium on perinatal mortality in Ukraine and Belarus is shown within the limitations of the model. There is a temporal correlation of the observed effect with the calculated development of the strontium concentration in pregnant women, and the effect is more pronounced in regions with higher strontium deposit. To further confirm the results, data from Ukraine over an extended time are needed.

The data were analysed using an approach that was successfully applied to determine the effect of stron-

Table 8. Fit results for odds ratios in Belarus

Parameter	Estimate	SD	t-value	p-value
c_1	0.021	0.028	0.774	0.2277
c_2	0.049	0.058	0.848	0.2073
c_3	0.357	0.065	5.475	0.0001

tium on perinatal mortality in West Germany following the atmospheric bomb tests, where the peak of perinatal mortality appeared in 1970, seven years after the maximum strontium fallout in 1963. In the data from Belarus, the maximum effect from strontium is found in the 1990's. The present study finds 520 excess perinatal deaths in the oblast of Gomel 1987–1998, out of which 32 can be attributed to the action of caesium in 1987.

Internal doses from ^{90}Sr ingestion in Gomel oblast during 1986–2001 are estimated 10–30 times smaller than from Cs ingestion for the same time period [9]. In a recent German article which summarises the consequences of the Chernobyl accident, strontium is not even mentioned as a possible reason of concern [10]. But, as shown above, the effect from strontium on perinatal mortality far outweighs the effect from caesium. Hence, the dose factors presently used seem to severely underestimate the effect of strontium on perinatal mortality.

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Выпадение стронция после Чернобыля и пренатальная смертность на Украине и Беларуси

А. Корбляйн

Мюнхенский институт окружающей среды, Мюнхен, Германия

Интенсивность пренатальной смертности в областях Украины и Беларуси вокруг зоны аварии на ЧАЭС выросла в 1987 году. В том же году выросла пренатальная смертность в Германии и Польше, и этот эффект можно связать с цезиевой нагрузкой у беременных женщин. После 1989 года неожиданно появился второй "пик" пренатальной смертности в Беларуси и на Украине. Это увеличение, как показано здесь, коррелирует с содержанием стронция в организме беременных женщин. Эти результаты согласуются с тем, что было обнаружено в Германии после испытаний атомного оружия в атмосфере в 1950–1960-е годы. Если эффект от цезия ограничивается, в основном, 1987 годом, то эффект от стронция оставался существенным вплоть до конца периода исследования в 1998 году. Кумулятивный эффект от стронция в областях вокруг Чернобыля превосходит эффект от цезия по меньшей мере в 10 раз. Таким образом, использование имеющихся дозовых нагрузок для оценки пренатальной смертности может приводить к недооценке эффекта.