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Background Radiation and Cancer Mortality in Bavaria: An Ecological Analysis

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ABSTRACT. The authors investigated a possible association between background gamma radiation (BGR) and cancer and infant mortality rates. In an in-country ecological study, they performed a population-weighted linear regression of cancer (infant) mortality rates on BGR, adjusted for unemployment rate and population density. Crude cancer rates showed a highly significant increase with BGR: 38 excess cases per 100,000 person-years per millisievert/year ($p < .0001$). After adjusting for unemployment rate and population density, the authors found that the excess absolute risk reduced to 23.6 cases per 100,000 person-years per mSv/year ($p = .0014$). The corresponding excess relative risk was 10.2% (95% confidence interval = 3.9–16.7) per mSv/year. The excess relative risk for infant mortality rates was 24% (95% confidence interval = 9–42) per mSv/year. The cancer risk derived from this ecological study is 0.24/Sv, which compares with an International Commission on Radiological Protection value of 0.05/Sv. However, because they are based on highly aggregated data, the results should be interpreted with caution.

KEYWORDS: background radiation, cancer mortality, epidemiology, infant mortality

Cancer risk from low doses of ionizing radiation is the focus of a long-standing controversy in radiation protection. Its magnitude is the subject of an ongoing debate because epidemiological studies have not provided consistent results. Researchers often estimate the expected risks at low doses by extrapolating observed risks at higher doses down to low doses. The extrapolation model most commonly accepted is the linear no-threshold model. Other models have also been used: There is a linear quadratic model that assumes a proportionally smaller risk at low doses, and there are models that postulate increased risks at low doses. Some scientists even believe in a beneficial effect from small doses of ionizing radiation; this is called the *hormesis theory*.[1]

Because radioactive emissions from nuclear facilities, such as nuclear reactors, nuclear reprocessing plants, and nuclear weapons facilities, add to the natural background radiation, the form of the dose effect curve at the level of natural background gamma radiation (approximately 1 mSv per year) is a matter of public concern. The real risk at low doses and dose rates can only be determined by epidemiological studies. A recent study on radiation workers has shown an increased cancer risk with exposure.[2] The average occupational exposure of the workers is often comparable with exposure in areas of high natural background radiation. Most studies have failed to show excess cancer risks in areas of high natural background radiation, but these studies were often limited by small population sizes.[3–5]

A detailed in-country case-control study of childhood leukemia in the United Kingdom showed a significant positive correlation with background radiation after the researchers adjusted for several confounding factors.[6] In the present study, however, we do not deal with childhood cancers.

In 1993, the German Federal Office of Radiation Protection (Bundesamt für Strahlenschutz, or BfS) published a study on total cancer mortality rates for people of all ages in 96 districts (cities and rural areas) in the federal State of

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Bavaria, Germany, from 1979 to 1988.[7] The analysis, which included parameters for unemployment rate and population density, yielded a nonsignificant decrease of cancer mortality rates with background radiation.

In the present study, we revisit the 1993 BfS study and supplement it with additional data for the period through 1997. As in the original study, we treat unemployment rate and population density as potential confounders. Unlike the BfS study that is based on data of the outdoor background radiation from 1987, which are flawed by the fallout from Chernobyl, we use measurements for outdoor as well as indoor gamma radiation from 1981.

METHODS

The BfS provided data on cancer mortality rates for the period from 1979 through 1997 for all 96 Bavarian districts.[7,8] The reports also contain incidence rates of childhood cancers in Bavaria from 1983 through 1998. The BfS has also published measurements of outdoor and indoor gamma dose rates for 1981 on the district level.[9] In those reports, researchers measured dose rates in microroentgen per hour (μR/h). Roentgen is a unit of gamma radiation (unit of exposure dose) that is now used infrequently, so we made a conversion into a more frequently used unit of measure, the millisievert (mSv). For our conversion, we approximated 1 R as 10 mSv. We assumed effective dose rates to be 80% indoor and 20% outdoor dose rates.

We obtained data on unemployment rate and population density from the Bavarian Statistical Office (Bayerisches Landesamt für Statistik und Datenverarbeitung). We used an average of the population densities in 1981 and 1989 in all of our analyses. Because data on the unemployment rate before 1985 were not available on a district level, we used data on the unemployment rate in 1989.

First, we conducted a population-weighted linear regression of cancer mortality rates as a function of only background gamma dose rate. In a second step, we included 2 potential confounders that were identified in the BfS studies, unemployment rate and population density, in the regression model. We assigned both to 4 categories. We used the lowest quartile as a reference, whereas we estimated the excess risks in the upper 3 quartiles by using additional parameters. The regression model has the following form:

$$\text{rate} = c_1 + c_2 \times \text{emp}_1 + c_3 \times \text{emp}_2 + c_4 \times \text{emp}_3 + c_5 \times \text{pop}_1 + c_6 \times \text{pop}_2 + c_7 \times \text{pop}_3 + c_8 x, \quad (1)$$

where c_1 is the intercept; c_8 is the radiation risk factor, that is, increase of cancer mortality (rate) per unit dose rate (x); c_2–c_7 are the parameters for confounding factors; emp_1, emp_2, emp_3 are dummy variables for the second, third, and fourth quartiles of unemployment rate, respectively; and pop_1, pop_2, pop_3 are dummy variables for the second, third, and fourth quartiles of population density.

As a measure of the goodness of fit, we used the weighted sum of squares. To test whether the inclusion of unemployment rate and the inclusion of population density would each lead to a significant improvement of the model, we used an F test with 3 parameters. We applied a t test to test the significance of the radiation risk factor, and our null hypothesis was this: $c_8 = 0$.

The linear model yields an estimate of the excess absolute risk (EAR). To estimate the relative risk per unit dose rate, we used a logistic regression model:

$$\text{rate} = 1/[1 + 1/\exp(c_1 + c_2 \times \text{emp}_1 + c_3 \times \text{emp}_2 + c_4 \times \text{emp}_3 + c_5 \times \text{pop}_1 + c_6 \times \text{pop}_2 + c_7 \times \text{pop}_3 + c_8 x)]. \quad (2)$$

The excess relative risk (ERR) per unit dose rate is calculated as follows: ERR $= \exp(c_8) - 1$.

RESULTS

Cancer Mortality: Absolute Risk Model

The average cancer mortality rate in Bavaria is 240.7 per 100,000 person-years between 1979 and 1997. The weighted sum of squares obtained from a regression with a constant rate model is $\chi^2(95, N = 96) = 1407.7$. Thus the variance in the data is nearly 15 times greater than one would expect from a purely random distribution.

A model allowing for a linear dependency on background radiation yields $\chi^2(94, N = 96) = 1028.1$. The improvement of the sum of squares is highly significant ($p = .0001$, F test). Figure 1 shows the cancer mortality rates in all 96 Bavarian districts, as well as the regression line.

In addition to all cancers, we analyzed the subgroup of all cancers except lung cancers to reduce the impact of smoking as the dominant risk factor for lung cancer. Table 1 contains the estimates for the radiation risk (in cancer deaths per 100,000 person-years), the 95% confidence interval (95% CI), and the p values that we obtained for all cancers, for lung cancers, and for all cancers except lung cancer. For all cancers and the 2 subgroups, the effect of background radiation is significant.

Next, we investigated the effects of the potential confounders of unemployment rate and population density individually. Unemployment rate, which uses 3 parameters, reduced the sum of squares to 820.7 ($p < .0001$, F test), and population density, also with 3 parameters, yields $\chi^2(92, N = 96) = 1183.0$ ($p = .001$, F test). Thus both confounders have a significant individual effect on cancer rates.

Eventually, we applied the complete regression model. The sum of squares reduced to 719.2 ($df = 88$). The estimates for the parameter are given in Table 2, together with standard deviations, t values, and p values.

The main result of including the confounders is that the radiation effect on cancer mortality rates remains highly significant ($p = .0014$). The radiation risk is $c_8 = 23.6 \pm 7.2$ excess cancer deaths per 100,000 person-years per 1 mSv/year.

Table 3 summarizes the results obtained by regressions to all subgroups.

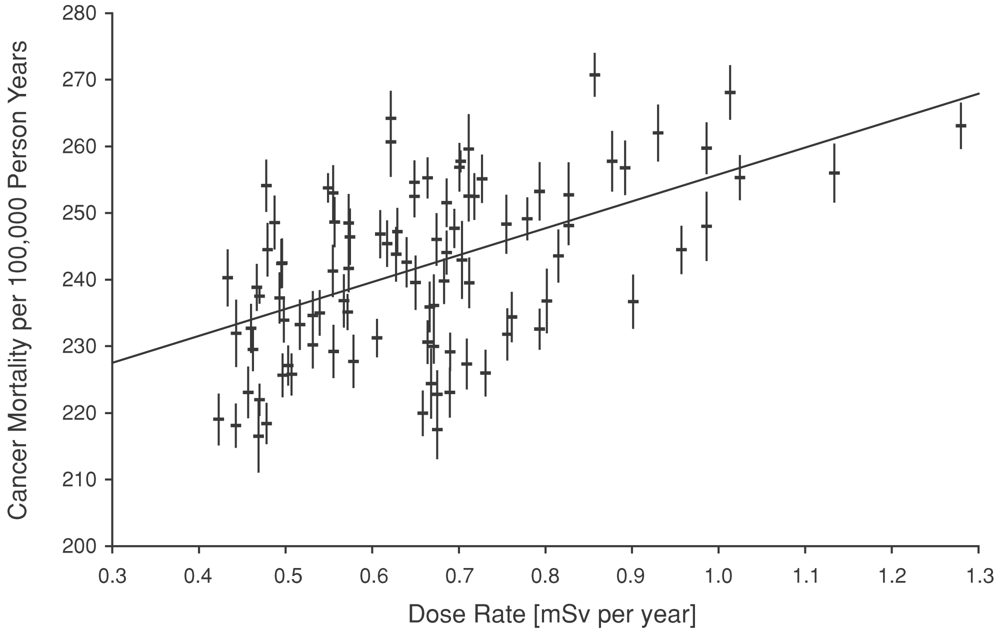

Fig. 1. Crude cancer mortality rates in all 96 Bavarian districts, and the regression line. The error bars indicate 1 *SD*.

Table 1.—Excess Absolute Cancer Risk Among Bavarians Between 1979 and 1997, Without Confounders

Data set	EAR/100,000 person-years	95% CI	*p*
All cancers	37.9	25.1–50.7	$< .0001$
Lung cancers	7.8	3.0–12.6	.0020
All cancers except lung cancers	31.2	20.6–41.8	$< .0001$

Note. EAR= excess absolute risk; CI = confidence interval.

Cancer Mortality: Relative Risk Model

Table 4 shows the results of regressions with a relative risk model as in equation (2), but without confounders. Regressions with model 2, that is, with the confounders of unemployment rate and population density, yield the ERRs per mSv/year given in Table 5.

Infant Mortality Rates

We evaluated infant mortality rates with the relative risk model shown in equation (2), and we found a significant increase of infant mortality rates with background radiation (p = .0024, t test). Figure 2 shows the infant mortality rates in the 96 Bavarian districts, as well as the regression line.

Table 2.—Results for All Cancers Among Bavarians Between 1979 and 1997, With Unemployment Rate and Population Density as Confounders: Absolute Risk Model

Parameter	Meaning	Estimate	*SE*	*t*	*p*
c_1	Intercept	220.6	5.024	43.911	$< .0001$
c_2	Effect of unemployment	2.533	2.787	0.909	.3658
c_3		9.549	3.341	2.858	.0053
c_4		11.87	3.956	3.000	.0035
c_5	Effect of population density	–1.649	2.919	–0.565	.5735
c_6		–4.573	3.130	–1.461	.1476
c_7		1.840	2.851	0.646	.5203
c_8	Radiation risk	23.57	7.165	3.289	.0014

Table 3.—Excess Absolute Cancer Risk Among Bavarians Between 1979 and 1997, With Unemployment Rate and Population Density as Confounders

Data set	EAR/100,000 person-years	95% CI	p
All cancers	23.6	9.3–37.8	.0014
Lung cancers	5.2	0.3–10.1	.0372
All cancers except lung cancers	20.0	8.0–32.1	.0014

Note. EAR = excess absolute risk; CI = confidence interval.

Table 4.—Excess Relative Cancer Risk Among Bavarians Between 1979 and 1997, Without Confounders

Data set	ERR/(mSv/a)	95% CI	p
All cancers	16.7	10.9–22.9	$<.0001$
Lung cancers	22.6	8.7–38.2	.0012
All cancers except lung cancers	15.7	10.1–21.6	$<.0001$

Note. ERR = excess relative risk, shown as a percentage; CI = confidence interval.

Table 5.—Excess Relative Cancer Risk Among Bavarians Between 1979 and 1997, With Unemployment Rate and Population Density as Confounders

Data set	ERR (%)/(mSv/a)	95% CI	p
All cancers	10.2	3.9–16.7	.0014
Lung cancers	14.6	1.2–29.7	.0318
All cancers except lung cancers	9.9	3.8–16.3	.0014

Note. ERR = excess relative cancer risk; CI = confidence interval.

We found that the inclusion of population density ($pop_1 - pop_3$) as a potential confounder leads to a highly significant improvement of the goodness of fit ($p = .0002$, F test), whereas the inclusion of unemployment rate yields no substantial additional improvement ($p = .324$, F test). The regression model thus reduced to

$$\text{rate} = 1/[1 + 1/\exp(c_1 + c_2 \times \text{pop}_1 + c_3 \times \text{pop}_2 + c_4 \times \text{pop}_3 + c_5 x)]. \quad (3)$$

The results of the regression analysis are given in Table 6. Parameters $c_2 - c_4$ estimate the relative increases of infant mortality in the districts belonging to categories $pop_1 - pop_3$, and c_5 estimates the relative increase of infant mortality rate for an increase of background radiation by 1 mSv/year where x is defined as a continuous variable. From $c_5 = 0.2154 \pm 0.0668$, we determined an ERR of 24.0% per mSv/year ($p = .0018$; 95% CI = 8.6–41.6).

We obtained a still better fit when we defined background radiation as a categorical variable (four quartiles). The weighted sum of squares is 421.8 ($df = 92$) for the model with only population density and 345.7 ($df = 89$) when background radiation is introduced as a categorical variable. This is a highly significant improvement of the goodness of fit ($p = .0005$, F test).

Table 7 lists the regression results. Parameters c_2–c_4 estimate the effect of population density on infant mortality rates. Infant mortality is increased in the 24 districts with the highest population density and decreased in the districts of the second highest category. Parameters c_5–c_7 estimate the ERR in the 3 upper categories of background radiation relative to the lowest category. Infant mortality rates are increased only in the highest dose category ($p = .0007$).

COMMENT

Our main finding in this study is a highly significant increase of total cancer mortality, for Bavarians of all ages, with background gamma radiation ($p = .0014$). The significance of the finding does not change when we evaluate all cancers except lung cancers ($p = .0014$), although the risk for lung cancers alone is slightly greater than the risk for cancers of all sites. A separate evaluation for children's cancers yielded a nonsignificant 11% increase per mSv/year, which agrees with the 10% increase per mSv/year observed for all ages. Infant mortality rates show a significant increase with background radiation, but this is limited to the highest dose category.

The results for cancer contradict a previous analysis by the BfS in which researchers found no significant association between cancer rates and background radiation in Bavaria. The BfS study, however, used outdoor background radiation measurements from 1987, and these measurements were influenced by the fallout from the Chernobyl accident in 1986. Our evaluation is based on data for 1981, that is, before the Chernobyl accident. Furthermore, we used both outdoor and indoor measurements. This can be important when one is deriving an ecological risk factor because indoor radiation exposure can differ significantly from outdoor exposure, and the values are not necessarily correlated.

The definition of *radiation risk*, that is, excess cancer rate per year divided by dose per year, is numerically equal to the excess cancer rate per unit dose that is the definition of the EAR. The result that we obtained herein for cancers of all sites, 0.236/Sv (see Table 3), is approximately 5 times greater than the International Commission on Radiological

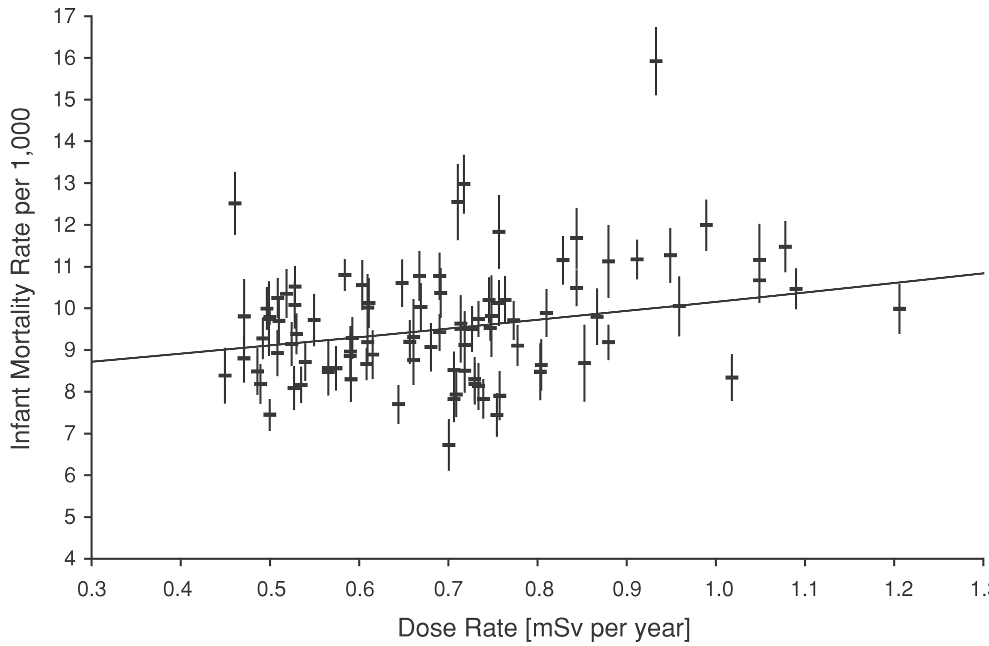

Fig. 2. Crude infant mortality rates in all 96 Bavarian districts, and the regression line. The error bars indicate 1 *SD*.

Table 6.—Results for Infant Mortality Rates Among Bavarians Between 1979 and 1997: Continuous Dose Variable

Parameter	Meaning	Estimate	*SE*	*t*	*p*
c_1	Intercept	–4.7792	0.0574	–83.28	< .0001
c_2	Effect of population density	–0.0324	0.0327	–0.989	.3251
c_3		–0.0897	0.0329	–2.728	.0076
c_4		0.0527	0.0315	1.673	.0978
c_5	Radiation risk	0.2154	0.0668	3.223	.0018

Table 7.—Results for Infant Mortality Rates Among Bavarians Between 1979 and 1997: Categorical Dose Variable

Parameter	Meaning	Estimate	*SE*	*t*	*p*
c_1	Intercept	−4.6519	0.0313	−148.72	< .0001
c_2	Effect of population density	−0.0350	0.0312	−1.122	.2649
c_3		−0.0892	0.0325	−2.743	.0074
c_4		0.0608	0.0312	1.945	.0549
c_5	Excess risk in dose categories 2–4	0.0086	0.0310	0.277	.7824
c_6		−0.0305	0.0295	−1.035	.3035
c_7		0.1080	0.0307	3.514	.0007

Protection (ICRP) value of 0.05/Sv. On the basis of the ICRP risk estimate, we would not expect to find a significant result.

Other studies failed to find radiation risks from background radiation, but they often do not provide information on the test power. An evaluation of data from Kerala, India,[4] yields an EAR of 0.0035 ± 0.0168/Sv, much less than the ICRP value 0.05/Sv. Because the average cancer mortality rate in Kerala, however, is much lower than that in Bavaria, it may be more appropriate to compare the relative risks. The increase of relative risk with dose in Kerala is 0.95% ± 4.6% per mSv/year, but the 95% CI is large (from –9.3% to 11.2%). Therefore, the Kerala data do not disagree with the observed relative increase of 10.2% per mSv/year in the Bavarian data.

Confounding can either increase or decrease the association between cancer and background radiation. Multiple risk factors tend to obscure the association and therefore rather underestimate the effect. In Bavaria, however, the geographical distribution of background radiation happens to correlate with both unemployment rate and population density. Therefore, the radiation effect is somewhat reduced when we include these confounders in the analysis. Because both parameters are ecological, we cannot exclude a certain extent of residual confounding.

The differences of cancer rates in the present analysis are small: The average cancer rates in the 10 districts with the highest exposure (1.08 mSv/year), after we adjusted for the effect of unemployment and population density, are only about 6% higher than those in the 10 districts with the lowest exposure (0.49 mSv/year) to background radiation. However, because of the large number of cancer cases in our study (N = 536,392), this difference reaches statistical significance. Although we cannot exclude confounding as an explanation for this association, it appears unlikely that the observed dose-response relationship was caused completely by confounding through unemployment and population density. Alternatively, our results may indicate that possible effects from background radiation on cancer rates are only detectable by in-country ecological studies on large homogeneous populations with little mobility, which are conditions approximately met in the study for Bavaria.

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