Dose Formation and Medical Aspects

Congenital Malformation and Stillbirth in Germany and Europe Before and After the Chernobyl Nuclear Power Plant Accident

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Abstract

In large parts of central, eastern, and northern Europe, awareness of the many lasting detrimental health effects from the Chernobyl Nuclear Power Plant (ChNPP) accident of April 1986 has increased. In this paper, the authors suggest a flexible, synoptic method based on logistic regression for the analysis of national as well as district-by-district reproductive failure data. The main idea is to model a spatial-temporal (annual or monthly) data set by adjusting for country- or region-specific trend functions, and either to test for local or global temporal jumps or broken sticks (change-points) associated with the years 1986 or 1987, or to test for the spatial effects of regionally stratified exposure or dosimetry data. In numerous official data sets from central, eastern, and northern European countries or regions, absolute or relative increases of stillbirth rates after 1986 were observed. Those purely temporal change-points are supported by results from ecological exposure-response analyses involving a spatial dimension represented by region-specific exposure data. We found significant ecological relative risks in the range of 1.005 to 1.020 per kBq/m^2 ^{137}Cs for stillbirths and congenital malformations in Germany. A similar result is obtained from Finnish data. The relative risk coefficient of 1.01 per kBq/m^2 ^{137}Cs translates to a preliminary relative risk coefficient of approximately 1.60 per mSv/a. The disclosed spatial-temporal effects in Germany and Europe indicate that the radioactivity released over large parts of Europe by the Chernobyl accident had a detrimental effect on reproductivity in those areas.

Keywords: Chernobyl accident; congenital malformation; genetic effect; logistic regression analysis; mutagenicity; perinatal mortality; radiation risk; sex ratio; spatial-temporal analysis; stillbirth; teratogenicity; time trend

Abbreviations: CP: change-point model; CPr: reduced change-point model; GDR: German Democratic Republic (former); ICD: International Classification of Diseases; kBq: 1000 Bequerel; mSv: 1/1000 Sievert; SBp: stillbirth proportion; 95%-CL: 95% confidence limits; Cs: Cesium

1 Introduction

The nuclear reactor explosion in Chernobyl, Ukraine, on April 26, 1986, is to date the world's most serious accident at a nuclear power station. The accident led to a release of large quantities of radioactive material, in the range of several hundreds of megacuries over a ten-day period [24]. However, the exact amount of radioactivity released into the atmosphere is subject to ongoing debate. Depending on atmospheric conditions at the time, the extent of contamination in Europe was quite variable. Even in relatively small regions, for example Bavaria, ^{137}Cs measurements within a regular measurement program ranged from the detection limit to 120.7 kB/m^2 [5]. It is evident that the most extreme local fallout in Bavaria has not been recorded. Ukraine, Belarus, and parts of Russia and Scandinavia were highly contaminated by radioactive fallout, with markedly less contamination occurring in Great Britain, Ireland, France, Portugal, and Spain. Finland seems to be the most highly contaminated country in Scandinavia.

Numerous investigations have been carried out regarding the possible impact of the Chernobyl accident on the incidence of congenital malformations, perinatal mortality, and stillbirths. Reviews of the material from these investigations were compiled by Little [15] and by Bard et al. [2]. In most studies aimed at measuring the differences in pregnancy outcomes between regions or time periods, the authors concluded that no consistent evidence of detrimental physical effects leading to congenital anomalies (or other abnormal outcomes of pregnancy) following the accident exists. However, there has been no strong national or international effort to thoroughly investigate the possible health consequences of the Chernobyl disaster. The EUROCAT project, aimed at recording congenital malformations in Europe, covers only a few percent of the respective western and central European populations. The population coverage in the United Kingdom, for example, involves only 61,710 out of 759,041 births in 1986 [9]. No data are available for eastern European countries. For a detailed account of the problems connected with recording the health consequences of the Chernobyl accident in the former USSR, see Jaroshinskaja [13].

Official German and European reproductive failure data have not yet been investigated in sufficient detail. With this in mind, using appropriate methodology, we first studied long-term time trends in European stillbirth rates; then we studied the possible association of stillbirths and congenital anomalies with local fallout at the district level in Germany. The main result of a local spatial-temporal Bavarian analysis, adjusted for district-specific trend functions [20] was the identification, for the years 1987 and 1988, of a significant statistical association of stillbirths with ^{137}Cs deposition at the district level in Bavaria. The ecological relative risk coefficient for stillbirths was 1.0072 per kBq/m^2, 95%-CL = [1.0026, 1.0117], p = 0.0021, where p is the p-value

and CL means confidence limits. In this paper, we present a gender-specific update of this estimate, based on a large data set that combines the information from Bavaria, the former German Democratic Republic (GDR), and West Berlin. In addition, this spatial-temporal methodology is also applied to data from the 'Bavarian Congenital Malformation Study, 1984–1991.' For a description and the results of this investigation, see [22,23].

The main finding of a global synoptic spatial-temporal European analysis [19] was a marked difference in stillbirth time trends between western Europe (Belgium, France, Great Britain, Ireland, Iceland, Luxembourg, Portugal, Spain), central Europe (Austria, Denmark, Germany, Italy, Norway, Switzerland), and eastern Europe (represented by Sweden, Poland, Hungary, Greece). In contrast to the western and central European trends, the eastern European trend exhibits an absolute increase in stillbirth rate in 1986 compared to 1985, as well as an apparent upward shift of the entire trend line from 1986 onward. The result of this analysis has been criticized for being the product of a too-specific selection of European countries [4]. In this paper, we show that our initial approach can be extended to yield far more specific and clear-cut results.

2   Data and Statistical Methods

This study is based on three different kinds of population and health statistics data. First, we used official German and Bavarian annual live birth and stillbirth data at the district level made available by the Federal Statistics Office in Berlin and Wiesbaden and by the Bayerisches Landesamt für Statistik und Datenverarbeitung in Munich. Second, we used the Bavarian Congenital Malformation Data Set, 1984 to 1991 [22], made available by the Bayerisches Staatsministerium für Landesentwicklung und Umweltfragen. These monthly data are comprised of nearly all children with congenital malformations born in Bavaria from 1984 to 1991. The total number of cases with congenital malformations in these data set is 29,961 out of 984,570 live births. (The data set does not contain cases with minor congenital malformations.) Third, we used data on official national stillbirth statistics, together with the corresponding stillbirth definitions for the years 1980 to 1995, for the following 23 European countries: Austria, Belgium, Czech, Denmark, Finland, France, Germany (former FRG + former GDR), Great Britain, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Sweden, Spain, and Switzerland. More detailed information on the compilation of these data is published elsewhere [19]. We also analyzed recently published Finnish stillbirth and live birth data based on consistent stillbirth definitions from 1977 to 1992 [1]. We reproduce these data with the written permission of the editor in chief of *Environmental Health Perspectives* (Tom Goehl, personal communication, September 3, 2002).

The ecological surrogate exposure variables are defined according to district-specific mean values of ^{137}Cs measurements for the 96 districts of Bavaria and the 198 districts of the former GDR, including East Berlin and West Berlin [3,5,11,17,18]. Additionally, to adjust regression models, we used district-specific mean dose measurements of the natural background radiation for Bavaria in 1981 [3] and also district-specific statistical information on population characteristics made available by the Bayerisches Landesamt für Statistik und Datenverabeitung in Munich (for example, population density, physician density, and income). For the analysis of Finnish stillbirth data, we used mean dose equivalents of population quintiles published by Auvinen et al. [1].

The justification for applying inferential statistical procedures is based on the year-to-year or month-to-month (random) variation in stillbirth proportions or incidence of congenital malformations. To assess the underlying time trends in stillbirth proportions or incidence of congenital malformations, and to investigate whether there are significant changes in the trend functions in 1986 or later, we applied a linear logistic regression method. According to Cox [8], linear logistic regression is the most appealing method for treating binomial variables. Theoretically as well as practically, it is appropriate to model stillbirths and congenital malformations as binomially distributed random variables. Consequently, we apply linear logistic regression as a parametric method to yield quantitative effect estimates.

Many studies of possible Chernobyl health effects have been aimed at the detection of differences of pregnancy-outcome measurements between regions or time periods. These studies may generally be divided into two categories:

1. Marked geographical variations in contamination provide an opportunity to compare radiation-related outcome measures between human populations residing in different regions. Problems with regional comparisons of infant mortality data were discussed by Landau [14]. Important characteristics (environmental conditions, social class, etc.) are rarely identical between regions. Therefore, the results should be adjusted to achieve comparability.

2. Another approach is to investigate changes in the frequencies of pertinent outcome variables over time. In the case of temporal comparisons, special care must be taken to avoid possible alterations in variable definition. However, if the population characteristics of interest are relatively stable over time, and if the time periods considered are not too large, problems with this approach seem less pronounced in contrast to regional comparisons. In this case, a combination of the regional and temporal comparison seems to be the most informative method.

The main idea behind a spatial-temporal approach is to model a data set that contains regional and temporal information simultaneously by adjusting the regression model for region-specific trend functions. The great advantage of this spatial-temporal method is that by considering partial trends of regional units, these regional units are, so to speak, compared to themselves, as the target variable describing the interesting characteristic varies from year to year or from month to month. Information on several regional units is then combined in a complete spatial-temporal model, giving rise to tests of local or global change-points in time as well as spatial trends in the outcome variable with regionally determined radioactive contamination or radiation doses.

For details and examples of the change-point methodology, see Carlstein et al. [6], or Sugiura and Ogden [24]. Scherb et al. [19,20] published two variants of the spatial-temporal change-point methodology on a small-scale level (in Bavaria) and a large-scale level (in Europe).

3 Results

3.1 Spatial-temporal analysis of German reproductive data based on district-specific fallout measurements

As initial examples, **Fig. 1** and **Fig. 2** present the time trends of annual stillbirth proportions for the ten least and ten most contaminated districts in Bavaria. **Table 1** contains the data for 20 districts with mean values of ^{137}Cs measurements. In the ten districts with the lowest contamination (mean value 4.5 kBq/m^2 ^{137}Cs), no significant change-point in the stillbirth proportion trend occurred in 1987 (Fig. 1), whereas in the ten districts with the highest contamination (mean value 37.2 kBq/m^2 Cs-137), a significant upward shift of the trend line occurred from 1987 onward (Fig. 2). The p-value for the null hypothesis of no change-point in 1987 is 0.0091; the odds ratio for the change-point is 1.58, 95%-CL = [1.20, 2.22]. According to this model, approximately 100 more
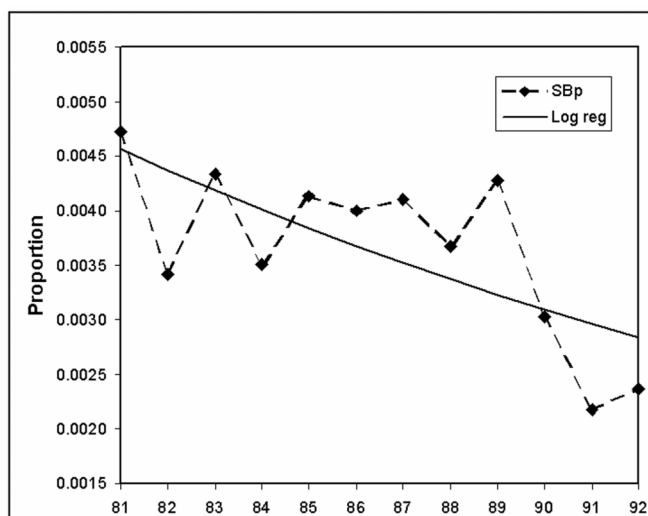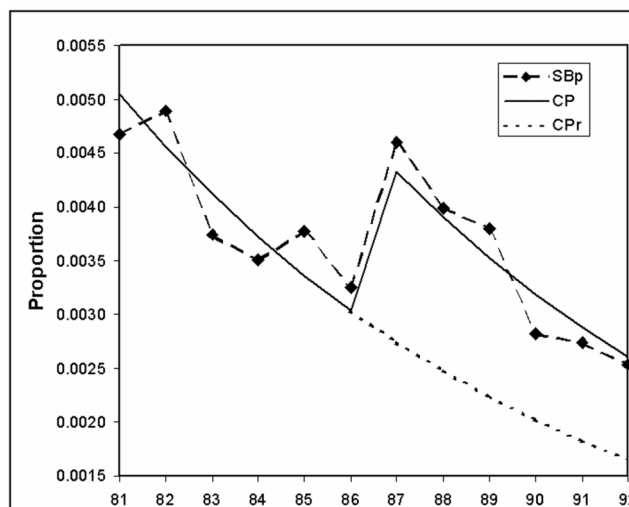

Fig. 2: Stillbirth proportion (SBp) for the ten combined, most contaminated districts in Bavaria, including change-point (CP) and reduced change-point (CPr) models based on logistic regression

stillbirths occurred between 1987 and 1992 in the ten most highly affected districts. We emphasize that the stillbirth excess after 1987 in the two most contaminated districts of Bavaria was nearly 200%. These observations are highly indicative of a distinct ecological-exposure-response association between stillbirths and ^{137}Cs fallout in Bavaria.

For all districts of Bavaria and the former GDR, including West Berlin, we computed the district-specific mean ^{137}Cs fallout. The results are displayed in **Fig. 3** and **Fig. 4**. Because rather different sampling schemes had been applied in Bavaria than were applied in the former GDR [3,5,17,18], we interactively rescaled the measurements in the former GDR to better agree with the distribution of measurements in Bavaria. Then a synoptic spatial-temporal analysis at the district level, employing logistic regression, was performed for Bavaria + GDR + West Berlin (combined). The analysis is based on 4,265,510 live births and 19,877 stillbirths from 1980 to 1993 in a total of 3,324 district years. This analysis, adjusted for district-specific intercepts and linear-time-trend parameters, yields significant gender-specific relative risks (RR) per kBq/m^2 ^{137}Cs for stillbirths:

Fig. 1: Stillbirth proportion (SBp) for the ten combined, least contaminated districts in Bavaria, including the logistic regression line

Table 1: The ten least and most contaminated districts in Bavaria, mean ^{137}Cs measurements

| 10 Most-Contaminated Districts	^{137}Cs kBq/m^2	10 Least-Contaminated Districts	^{137}Cs kBq/m^2
Augsburg, City	53.7	Schweinfurt, City	5.3
Berchtesgaden	50.3	Hof, City	5.3
Garmisch-Partenkirchen	40.5	Miltenberg	4.9
Memmingen, City	40.2	Main-Spessart	4.7
Unterallgäu	35.5	Würzburg, City	4.6
Augsburg	32.3	Würzburg	4.6
Regen	30.8	Rhön-Grabfeld	4.4
Aichach-Friedberg	30.6	Bad Kissingen	3.9
Landsberg/Lech	30.3	Weiden, City	3.7
Neuburg-Schrobenhausen	27.7	Schweinfurt	3.1
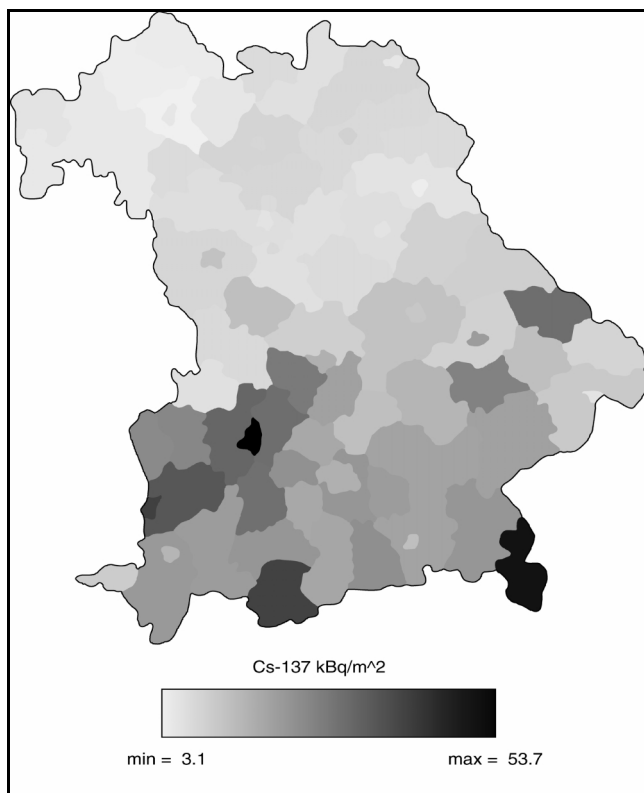
Fig. 3: Bavarian districts (n = 96), gray level according to the mean values of the ^{137}Cs (kBq/m^2) measurements in the districts after the Chernobyl accident

Male: RR = 0.0073, 95%-CL = [1.0034, 1.0113], p = 0.000245
Female: RR = 1.0048, 95%-CL = [1.0004, 1.0091], p = 0.031092
Total: RR = 1.0061, 95%-CL = [1.0032, 1.0089], p = 0.000026

Based on environmental measurements on the district level in Bavaria, a conversion coefficient from kBq/m^2 Cs to mSv/a of 0.0143 (95%-CL = [0.0124, 0.0162]) was derived. (This is in good agreement with a theoretical value of 0.0123 used in ECOSYS by the GSF [12].) Applying the conversion coefficient of 0.0143, the above relative risks per kBq/m^2 ^{137}Cs translate to preliminary relative risks per mSv/a:

Male: RR = 1.41, 95%-CL = [1.17, 1.69], p = 0.000245
Female: RR = 1.25, 95%-CL = [1.02, 1.53], p = 0.031092
Total: RR = 1.33, 95%-CL = [1.16, 1.51], p = 0.000026

Because we apply a rather crude transformation from cesium fallout (density of contamination of ^{134}Cs and ^{137}Cs, in kBq/m^2) to effective dose equivalent, in mSv/a, without considering more subtle aspects (for example, the different contribution of indoor/outdoor exposure and internal/external doses), the dose-based relative risk coefficients can be considered 'preliminary.' However, we postulate that the order of magnitude for those dose-based coefficients and their ranking should at least be valid. No such restriction is necessary for the fallout-based ecological risk coefficients, which are, of course, subject to possible misclassification bias. However, as is well known, such misclassification theoretically leads to underestimation of 'true' risks in general. We emphasize that the concept of effective equivalent dose is not
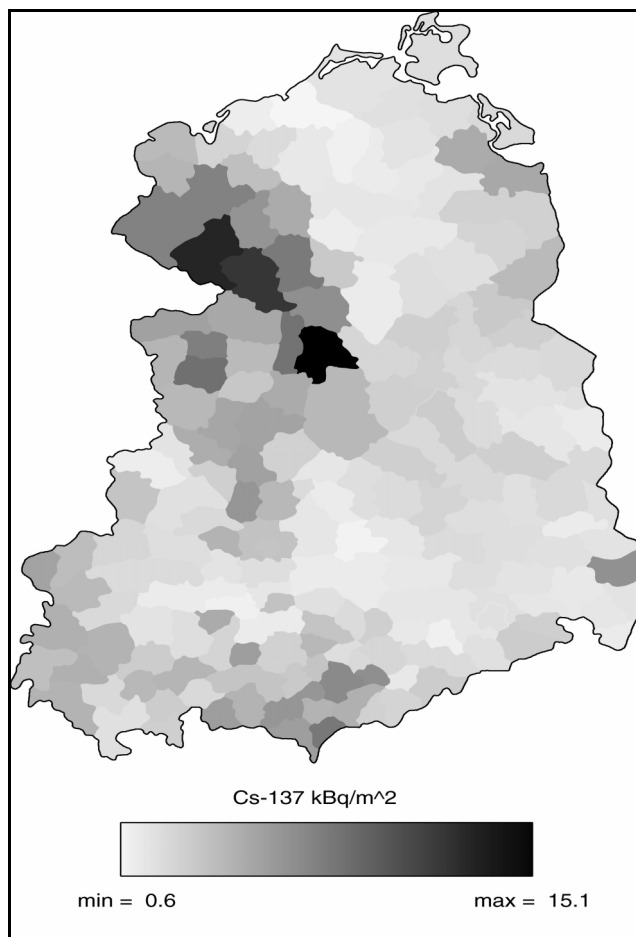

Fig. 4: Former GDR districts (n = 198) including East Berlin and West Berlin, gray level according to the mean values of the ^{137}Cs (kBq/m^2) measurements in the districts after the Chernobyl accident

without problems, because it relies on an attempt at average energy transfer at the molecular level to obtain measures of energy transfer at the macroscopic level of organs, the entire body, and even populations. Thus, the possibility exists that 'true' doses received after the Chernobyl accident are higher than those reflected by established radiobiological theories. In that case, our dose-based risk coefficients were too high. This consideration does not apply to the fallout-based risk coefficients, because they require only counting data from radioactive decay.

Next, we employed our spatial-temporal methodology to analyze the Bavarian Congenital Malformation Data Set. General descriptions and analyses of these data have been published previously, but with practically no emphasis on the Chernobyl accident [22,23]. Diagnoses were coded according to the Ninth Revision of the International Classification of Diseases (ICD-Code).

As an example, **Fig. 5** shows the annual birth incidence of two combined, relatively frequent congenital malformations of the heart, ICD7454 and ICD7455 (n = 2,797), in the ten least and ten most contaminated districts. For further illustration, the ten most contaminated districts have been split into the five uppermost contaminated districts and the five remaining districts. There is a clear increase in the preva-
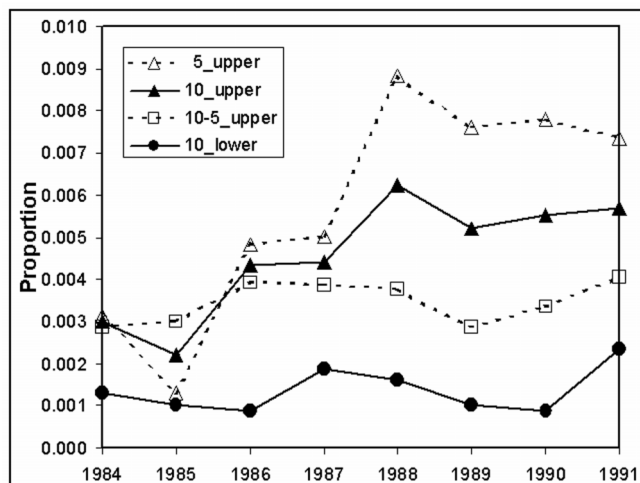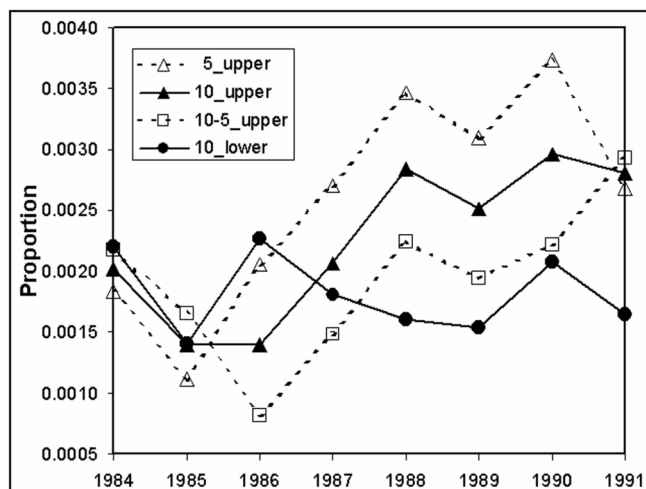
Fig. 5: Birth prevalences (proportions) of two congenital heart malformations (ICD7454+ICD7455, n = 2797) in Bavaria; stratification according to contamination of districts (see Table 1)

lence of these heart malformations with increasing Chernobyl fallout. A full spatial-temporal analysis, analogous to the spatial-temporal stillbirth analysis above, yields the following relative risk estimates for ICD7454 and ICD7455:

RR = 1.013, 95%-CL = [1.005, 1.021], p = 0.0020, per kBq/m^2 ^{137}Cs
RR = 1.830, 95%-CL = [1.250, 2.670], p = 0.0020, per mSv/a

An effect similar to the effect of the heart malformations can be seen in the nonidentifiable malformations (coded ICD9999, n = 1,817) of the Bavarian Congenital Malformation Data

Set. However, there are fewer cases in this malformation class, and the dependency on fallout seems to be somewhat weaker. **Fig. 6** is completely analogous to Fig. 5, with the spatial-temporal analysis yielding the following risk estimates:

RR = 1.007, 95%-CL = [1.002, 1.013], p = 0.0112, per kBq/m^2 ^{137}Cs
RR = 1.400, 95%-CL = [1.080, 1.817], p = 0.0112, per mSv/a

A class of malformations that seems to be strongly dependent on the Chernobyl fallout are the deformities of the skull, face, jawbone, neck, spinal column, hip joint, long bones of the legs, and feet (ICD7540, ICD7541, ICD7542, ICD7543, ICD7544, ICD7546, ICD7547, ICD7548, ICD7565, n = 3,686). This class of malformations has been completely recorded only from 1984 to 1989 for organizational reasons. Fig. 6 displays the birth incidence of this group of malformations. Our spatial-temporal analysis yields the following highly significant risk estimates:

RR = 1.018, 95%-CL = [1.009, 1.027], p = 0.000036, per kBq/m^2 ^{137}Cs
RR = 2.295, 95%-CL = [1.547, 3.405], p = 0.000036, per mSv/a

For the investigated classes of reproductive failures, **Table 2** summarizes the risk coefficients and confidence limits that we derived from German and Bavarian data, using our spatial-temporal methodology. If the disclosed relation is in fact a causal one, we provisionally estimated that the Chernobyl accident entailed congenital malformations in the range of 1,000 to 3,000 more cases in Bavaria from October 1986 to December 1991 (**Fig. 7**).

Fig. 6: Birth prevalences (proportions) of the nonidentifiable congenital malformations (ICD9999, n = 1817) in Bavaria; stratification according to contamination of districts (see Table 1)
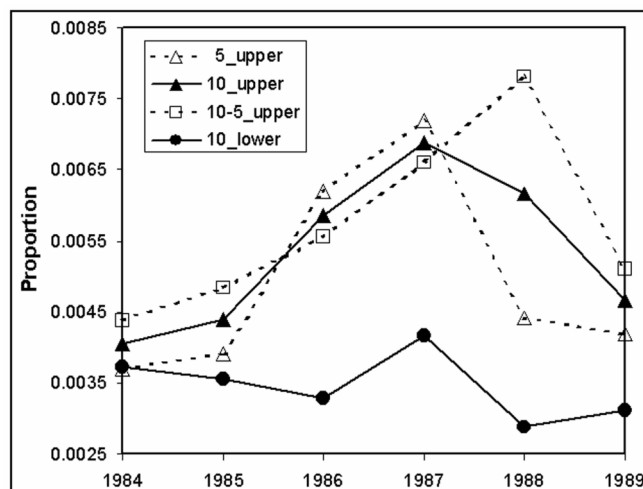

Fig. 7: Birth prevalences (proportions) of the deformities (ICD7540, ICD7541, ICD7542, ICD7543, ICD7544, ICD7546, ICD7547, ICD7548, ICD7565, n=3686) in Bavaria; stratification according to contamination of districts (see Table 1)

Table 2: Relative risks (RR) for reproductive failure per kBq/m^2 ^{137}Cs and preliminary relative risks per mSv/a

| Reproductive Failure		n	RR/(kBq/m^2)	95%-CL	RR/(mSv/a)	95%-CL
Stillbirth	male	10,580	1.0073	[1.003, 1.011]	1.41	[1.17, 1.69]
	female	9,297	1.0048	[1.000, 1.009]	1.25	[1.02, 1.53]
	total	19,877	1.0061	[1.003, 1.009]	1.33	[1.16, 1.51]
Malformations of the heart		2,797	1.0130	[1.005, 1.021]	1.83	[1.25, 2.67]
Nonidentifiable malformations		1,817	1.0072	[1.002, 1.013]	1.40	[1.08, 1.82]
Deformities		3,686	1.0180	[1.009, 1.027]	2.29	[1.55, 3.41]

3.2 Spatial-temporal analysis of European stillbirth data

We previously studied the trends of the combined stillbirth data from Sweden, Poland, Hungary, and Greece. Using a rather conservative approach, we found a significant relative overall increase in the stillbirth rate of approximately 5.6% (p = 0.0085) from 1986 to 1992. No such global detrimental effect was seen in the western and central European strata. This result has been criticized for presumably being a consequence of the special combination of selected countries [4]. If Blettner's imputation were true, it should be difficult to demonstrate the disclosed effect with data from single nations or other combinations of data. However, in practically all northern or eastern European countries with valid data, relative or absolute increases of stillbirth proportions from 1986 or 1987 onward may be observed.

In this paper, we adopted a detailed modeling strategy to obtain specific information on single countries or regions situated approximately northeast of an imaginary diagonal through Europe, from Hungary to Iceland. This is justified because it can reasonably be assumed that the northeast part of Europe was considerably more contaminated than the southwest part. We will consider, in alphabetical order, Bavaria + GDR + West Berlin (combined), Denmark, Hungary, Iceland, Latvia, Norway, Poland, and Sweden. We employed a synoptic spatial-temporal change-point model for these data. In other contaminated countries, such as the Czech Republic, Finland, Belarus, Ukraine, and Turkey, stillbirth definitions either changed shortly after the Chernobyl accident or were not available, stillbirth data were incomplete, or stillbirth data did not exist at all. A three-step modeling strategy was used. First, we estimated change-points for individual countries. The change-point years were obtained by a minimum-deviance criterion for a change-point variable, shifted through the time windows from 1981 to the end of the respective time intervals in the 1990s. Second, we modeled trends of individual countries more precisely. Specifically, we considered transformations of time t (e.g., t^2) and included significant single-year effects, if present, as well as eventual interactions of time with change-points. Third, we composed a synoptic model by including all time-dependent variables determined in the first two steps as spatial interactions with the respective countries.

Table 3 contains quantitative information on the disclosed change-points in this synoptic spatial-temporal model. **Fig. 8**

to **10** present the observed data, together with the country-specific partial regression lines (change-point models [CP]) as well as the respective reduced change-point regression lines (CPr) obtained by setting the presumed Chernobyl effect to zero. **Fig. 8** shows the data and the partial full and reduced models for Denmark, Poland, and Sweden. **Fig. 9**
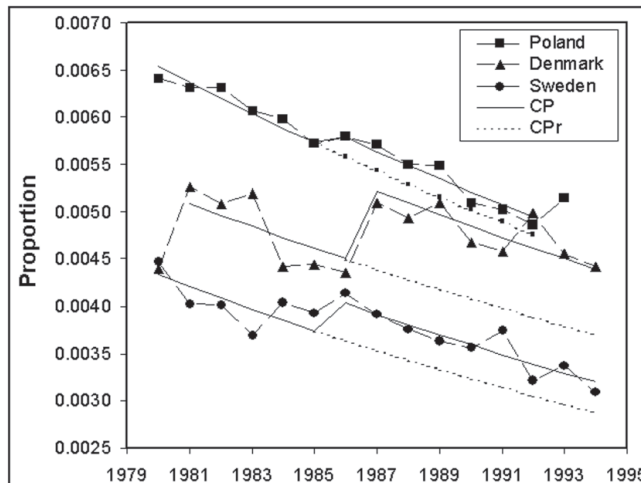

Fig. 8: Stillbirth proportions for Poland, Denmark, and Sweden, change-point (CP) and reduced change-point (CPr) models
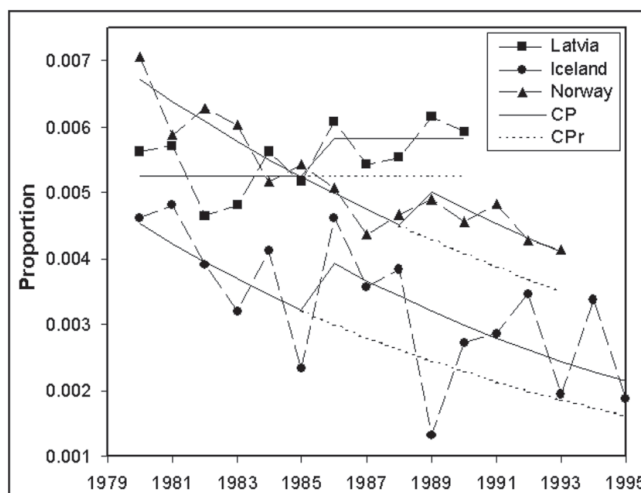
Fig. 9: Stillbirth proportions for Latvia, Iceland, and Norway, change-point (CP) and reduced change-point (CPr) models

Table 3: Point estimates, 95%-confidence limits, and p-values for the change-points (CP) of the synoptic-spatial-temporal change-point model for European countries

Country	Year of CP	Odds Ratio of CP	95%-CL	p value
Iceland	1986	1.31	[0.79, 2.15]	0.2935
Latvia	1986	1.11	[1.02, 1.20]	0.0116
Poland	1986	1.04	[1.00, 1.08]	0.0451
Sweden	1986	1.11	[1.00, 1.22]	0.0407
Bavaria+GDR+West Berlin	1987	1.10	[1.04, 1.16]	0.0008
Denmark	1987	1.19	[1.05, 1.34]	0.0064
Hungary	1987	1.31	[1.19, 1.45]	<0.0001
Norway	1989	1.17	[1.04, 1.31]	0.0108
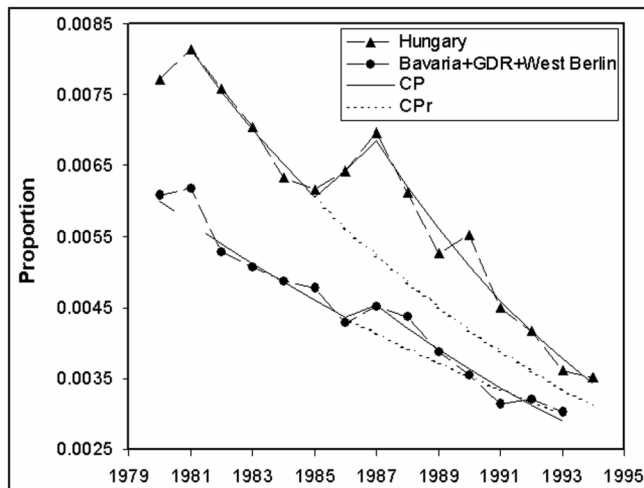
Fig. 10: Stillbirth proportions (SBp) for Hungary and Bavaria + GDR + West Berlin, change-point (CP) and reduced change-point (CPr) models.

contains the corresponding information for Iceland, Latvia, and Norway. Finally, **Fig. 10** displays data and partial models for Bavaria + GDR + West Berlin and Hungary, which are the only two regional units with significant interactions of time with change-points. This means that the slopes before and after the change-points are significantly different.

In 1986, we find significant change-points in Hungary, Latvia, Poland, and Sweden, as well as an insignificant change-point in Iceland. In 1987, there are significant change-points in Bavaria + GDR + West Berlin and in Denmark. Finally, in 1989, there is a significant change-point in Norway. The variability of the change-point years may result from random variation. The suggested model is based on 114 observations (country years), 19,056,178 live births, and 99,943 stillbirths. It employs 30 variables: one global and seven partial intercepts; linear time coefficients for all countries but Latvia; and single-year effects in 1980 for Denmark and Hungary, in 1981 for Bavaria + GDR + West Berlin, in 1986 for Hungary, and in 1993 for Poland. Interactions of time with change-points are only significant for Bavaria + GDR + West Berlin and Hun-
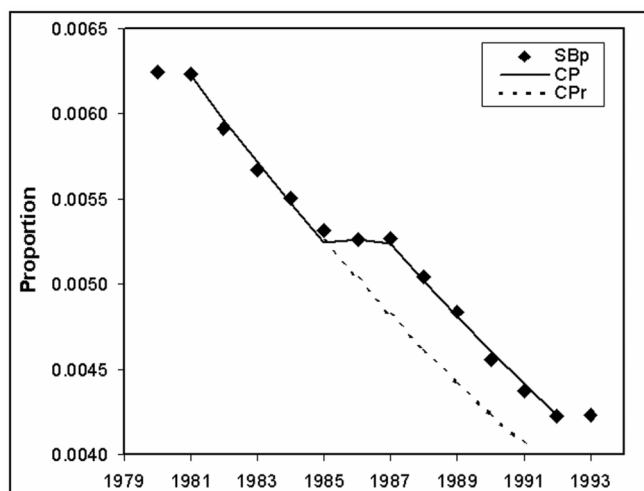
Fig. 11: Stillbirth proportion (SBp) for Bavaria + GDR + West Berlin, Denmark, Hungary, Iceland, Latvia, Norway, Poland, and Sweden combined, change-point (CP) and reduced change-point (CPr) model

gary. The model has 84 degrees of freedom and a deviance of 82.95. Thus it fits the data well.

It is also possible and informative to analyze the data of all eight countries combined. The trend from 1981 to 1992 is very smooth because of the huge numbers involved. Significant single-year effects occur in 1980, 1986, and 1993. The offset in 1987 of 8.8% is highly significant. The p-value is smaller than one in a million. According to this model, for the eight countries combined, there are theoretically 3,240 (95%-CL = [1973 ,4,560], p = 0.00000031) excess stillbirth cases from 1986 to 1992. The graphical result of this analysis is presented in **Fig. 11**.

3.3 Spatial-temporal analysis of Finnish stillbirth data

In their interesting article in the February 2001 issue of *Environmental Health Perspectives*, Auvinen et al. [1] reported a statistically significant increase in spontaneous abortion in Finland with dose of radiation and 'no marked' changes in induced abortions or stillbirths. In our analysis of official European stillbirth proportions [19], we excluded Finland because in 1987 the definition of stillbirth was changed from 28 weeks of gestational age to 22 weeks. The consequence is a sharp increase in the Finnish stillbirth proportion after 1986, such that we could not use the official Finnish stillbirth data for a meaningful trend analysis. Because Auvinen et al. [1] published Finnish stillbirth data for the pre-Chernobyl period, presumably consistent with stillbirth data for the post-Chernobyl period, and have performed longitudinal analyses, we are also able to investigate trends in Finnish stillbirth proportions. Using the annual data on live births and stillbirths in exposure quintiles by Auvinen et al. [1], and applying our spatial-temporal change-point methodology, we find that there is a relatively strong positive and significant dose-response relationship between the mean dose equivalent in May 1986 and relative risk of stillbirth from 1987 to 1992.
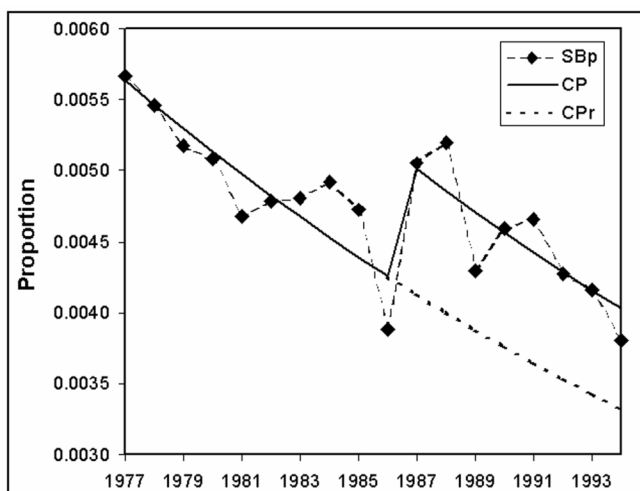
Auvinen et al. [1] obtained absolute stillbirth numbers based on 'either gestational age ≥22 weeks or weight ≥500 g' from Statistics Finland. Unfortunately, they did not address the problem of changed stillbirth definitions in sufficient detail. However, indirect evidence exists indicating that the data published by Auvinen et al. [1] is consistent with respect to the stillbirth definition: 'either gestational age ≥22 weeks or weight ≥500 g.' First, the overall sum of stillbirths in Finland from 1977 to 1986, according to Auvinen et al. [1], is 3,182. This is approximately 20% more than 2,669, the number of stillbirths (28 weeks) from 1977 to 1986 previously reported by Statistics Finland and the Finnish Statistical Yearbooks. Because this 20% excess proportion is in good agreement with other European 28- versus 22-week stillbirth data (e.g., Poland), we conclude that Auvinen et al. [1] made efforts to retrospectively obtain stillbirth data from 1977 to 1986 according to the 22-week or 500 g definition. Second, Auvinen's longitudinal analysis of stillbirth data would have been meaningless if it were based on inconsistent stillbirth definitions. Third, as a byproduct, our spatial-temporal analysis also yields evidence of a temporally consistent stillbirth definition in Auvinen et al [1]. There are no significant change-points in the trends of the stillbirth proportions in the three least contaminated quintiles in 1987 (see below).

We reproduce Finnish live birth and stillbirth data from Auvinen et al. [1] with the written permission of the editor in chief of *Environmental Health Perspectives* (Tom Goehl, personal communication, September 3, 2002). Fig. 2 in Auvinen et al. [1] yields absolute numbers of annual live births in exposure quintiles that total accurately to the published numbers of live births in all of Finland. Likewise, from Fig. 3 in Auvinen et al. [1], we can read, with sufficient accuracy, absolute numbers of annual stillbirths in Finnish exposure quintiles, which also accurately total to the well-known stillbirth figures from 1987 onward in Finland as a whole.
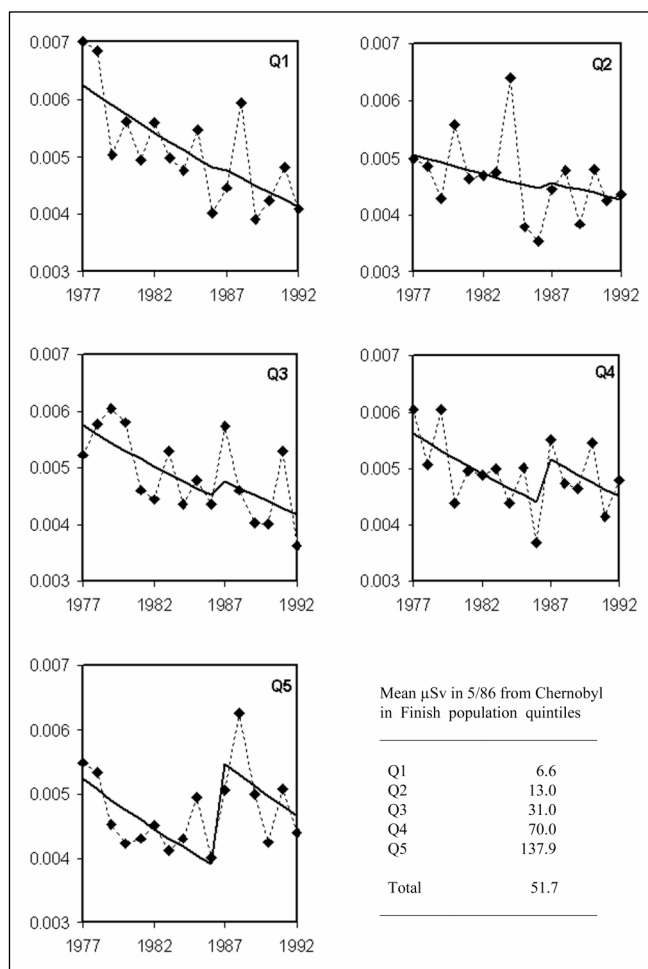
As a first step, we analyzed the overall trend of stillbirth proportions in Finland from 1977 to 1994, using a simple linear logistic change-point model with estimated change-point in 1987. **Fig. 12** shows the stillbirth proportions as well as the change-point and reduced change-point models. The relative risk of the change-point, as approximated with sufficient accuracy by the odds ratio, is 1.215, 95%-CL = [1.091, 1.352], p = 0.0004. This is approximately two times the effect in Sweden, similar to the effect in Denmark, and approximately two-thirds the effect in Hungary.

As a second step, we performed a synoptic analysis of stillbirth proportion trends in the Finnish exposure quintiles Q1 to Q5. The result is shown in **Fig. 13**. We find insignificantly increased relative risks in the three lower quintiles and significantly elevated relative risks in the upper two quintiles, with a maximum relative risk of 1.364, 95%-CL = [1.068, 1.742], p = 0.0128 in Q5. The situation in Q5 after 1986 is thus strikingly similar to the excess stillbirth proportions in the ten most contaminated districts (upper decile) of Bavaria (Fig. 2).

Finally, to obtain a quantitative effect estimate, we performed a logistic regression of stillbirth proportions over time and the mean dose equivalent in May 1986 [1, Table 1], adjusted for quintile-specific trend functions. The relative risk of stillbirth from 1987 to 1994 per 10 µSv mean dose equivalent in May 1986 is 1.027, 95%-CL = [1.012, 1.043], p = 0.0006. Assuming simple linear relationships, this is equivalent to a relative risk per mSv/a of 1.25, 95%-CL = [1.10,

Fig. 13: Stillbirth proportion for Finnish exposure quintiles; jump heights in 1987 proportional to the mean dose within the population quintiles

1.42], p = 0.0006. This finding agrees fairly well with the results gained from German district-by-district data (Table 2). According to the models and computations in this paper, we assume 409, 95%-CL = [174, 674], theoretical excess stillbirths in Finland from 1987 to 1994.

4 Discussion

We have investigated annual stillbirth proportions in Europe for the years 1980–1995, with emphasis on the possible impact of the Chernobyl disaster. In the combined data of Bavaria, GDR, West Berlin, Denmark, Hungary, Iceland, Latvia, Norway, Poland, and Sweden, we found a highly significant change-point in the linear logistic regression trend function in 1986 and 1987. The relative increase measures 4.6% (p = 0.0022) and 8.8% (p = 0.00000033) of the expected annual stillbirth proportions in 1986 and from 1987 to 1992, respectively. This finding supports our spatial-temporal relative risk estimates of stillbirth per kBq/m^2 and per mSv/a of 1.0061 and 1.33 (p = 0.000026). We also observed a certain dependency on gender within the risk coefficients. This local gender-specific finding bolsters the observation of a global gender-specific effect reported in our paper on European stillbirths. Sex ratios of live births and stillbirths, as well as the stillbirth ratios for gender, show significant changes in 1986 and 1987.

Fig. 12: Stillbirth proportion (SBp) for Finland according to the stillbirth definition 'either gestational age ≥ 22 weeks or weight ≥ 500 g,' change-point (CP) and reduced change-point (CPr) model

Further evidence showing the detrimental causal effect of Chernobyl fallout on reproductive health was obtained from spatial-temporal analyses of the Bavarian Congenital Malformation Data Set. The risk coefficients for several classes of congenital malformations are even higher than those for stillbirth. It is not implausible that certain classes of congenital malformations yield higher risk coefficients than stillbirth, because the classes of congenital malformations are perhaps more specifically linked to certain etiologic pathways than are stillbirths. The association of elevated congenital malformations with elevated fallout are of special interest, because the official stillbirth statistics in Bavaria + GDR + West Berlin and the Bavarian Congenital Malformation Data Set come from completely independent data sources. We thus have independent evidence corroborating Chernobyl's effect on perinatal mortality and previously reported stillbirths. It should also be recognized that the official stillbirth statistic is a total ascertainment, not a random sample from a larger population. The same holds true, at least approximately, for the Bavarian Congenital Malformation Data Set, for which a certain underreporting is possible. Therefore, the maximum available information is utilized. A result supporting the increased malformation rates in Bavaria after Chernobyl was published by Zieglowski and Hemprich [27]; in the former GDR, they found an overall 9.4% dose-dependent increase of the relative frequency of cleft lip and palate newborns in 1987, as compared to the mean rate from 1980 to 1986.

If the disclosed effects were attributable to the increased radioactivity in Germany and Europe after the Chernobyl accident, biological hypotheses that may be tested with experimental data and with analytical epidemiological data would then be helpful. Implicit in the hypothesis is the effect on the ovum and sperm (mutagenicity) or on the embryo and fetus (teratogenicity) at a certain stage of development. This has to be elaborated more precisely to predict during what periods of time the excess reproductive failure would appear and for what dose. We conjecture that threshold theories for low-level radiation have a weak scientific basis and cannot be used to consider our results 'implausible.' Spatial-temporal analyses could also help in establishing the connection (or lack of one) between reproductive failure (and also cancer) and fallout on a regional level in other affected countries.

The effects we observed are in strong contradiction to 'well-established' radiobiological theories. Our ecological risk coefficients for stillbirth and congenital malformation are much higher and more precisely estimated than those yet published. However, as Vogel [26] put it, the genetic risk estimates by BEIR and UNSCEAR, which are mainly based on parents exposed to atomic bombs or high background radiation, are 'extremely unreliable.' As a rule, data in previous investigations were restricted to relatively small regional units, to a few nuclear power or reprocessing plants, or to a few patients in a few hospitals [10,16,21]. The findings of such studies are constantly under debate, with eventual positive findings easily attributed to multiple sources of bias as well as pure chance, because of the low statistical power associated with only relatively few effective observations. Our results, which are based on very large numbers of cases, indicate that Chernobyl fallout had a detrimental effect on reproductive health in central, eastern, and northern parts of Europe, but causal inference is of course difficult. However, opponents of our methods and findings should bear in mind that the mere possibility of confounding is not a proof of confounding and, even more so, it is not a proof of no effect.

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