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RESEARCH ARTICLE

The human sex odds at birth after the atmospheric atomic bomb tests, after Chernobyl, and in the vicinity of nuclear facilities

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Abstract

Background, aim, and scope Ever since the discovery of the mutagenic properties of ionizing radiation, the possibility of birth sex odds shifts in exposed human populations was considered in the scientific community. Positive evidence, however weak, was obtained after the atomic bombing of Japan. We previously investigated trends in the sex odds before and after the Chernobyl Nuclear Power Plant accident. In a pilot study, combined data from the Czech Republic, Denmark, Finland, Germany, Hungary, Norway, Poland, and Sweden between 1982 and 1992 showed a downward trend in the sex odds and a significant jump in 1987, the year immediately after Chernobyl. Moreover, a significant positive association of the sex odds between 1986 and 1991 with Chernobyl fallout at the district level in Germany was observed. Both of these findings, temporality (effect after exposure) and dose response association, yield evidence of causality. The primary aim of this study was to investigate longer time periods (1950–2007) in all of Europe and in the USA with emphasis on the global atmospheric atomic bomb test fallout and on the Chernobyl accident. To obtain further evidence, we also analyze sex odds data near nuclear facilities in Germany and Switzerland.

Data and statistical methods National gender-specific annual live births data for 39 European countries from 1975 to 2007 were compiled using the pertinent internet data bases provided by the World Health Organization, United Nations, Council of Europe, and EUROSTAT. For a synoptic re-analysis of the period 1950 to 1990, published data from the USA and from a predominantly western and less Chernobyl-exposed part of Europe were studied additionally. To assess spatial, temporal, as well as spatial–temporal trends in the sex odds and to investigate possible changes in those trends after the atomic bomb tests, after Chernobyl, and in the vicinity of nuclear facilities, we applied ordinary linear logistic regression. Region-specific and eventually changing spatial–temporal trends were analyzed using dummy variables coding for continents, countries, districts, municipalities, time periods, and appropriate spatial–temporal interactions.

Results The predominantly western European sex odds trend together with the US sex odds trend (1950–1990 each) show a similar behavior. Both trends are consistent with a uniform reduction from 1950 to 1964, an increase from 1964 to 1975 that may be associated with delayed global atomic bomb test fallout released prior to the Partial Test Ban Treaty in 1963 and again a more or less constant decrease from 1975 to 1990. In practically all of Europe, including eastern European countries, from 1975 to 1986, and in the USA from 1975 to 2002, there were highly significant uniform downward trends in the sex odds with a reduction of 0.22% to 0.25% per 10 years. In contrast to the USA, in Europe there was a highly significant jump of the sex odds of 0.20% in the year 1987 following Chernobyl. From 1987 to 2000, the European sex odds trend reversed its sign and went upward, highly significantly so, with 0.42% per 10 years relative to the downward trend before Chernobyl. The global secular trend analyses are corroborated by the analysis of spatial–temporal sex odds trends near nuclear facilities (NF) in Germany and Switzerland. Within 35 km distance from those NF, the sex odds increase

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significantly in the range of 0.30% to 0.40% during NF operating time.

Conclusions The atmospheric atomic bomb test fallout affected the human sex odds at birth overall, and the Chernobyl fallout had a similar impact in Europe and parts of Asia. The birth sex odds near nuclear facilities are also distorted. The persistently disturbed secular human sex odds trends allow the estimation of the global deficit of births in the range of several millions.

Keywords Atomic bomb test · Chernobyl · Distance trend analysis · Ecological study · Environmental health · Environmetrics · Logistic regression · Low-level ionizing radiation · Male proportion · Nuclear facility · Radiation epidemiology · Radiation-induced genetic effect · Sex ratio · Spatial–temporal analysis

1 Introduction

1.1 Detrimental reproductive effects

In recent years, evidence and concern that exposure to the great diversity of chemical or physical occupational and environmental pollution has detrimental reproductive effects increased. Among those factors considered are endocrine disruptors, persistent chlorinated or brominated organic pollutants, and non-ionizing and ionizing radiation (James 1994). It has been demonstrated that prenatal exposure to some pesticides can adversely affect male reproductive health in animals. A possible association between maternal exposure to organochlorine compounds used as pesticides and cryptorchidism among male children has been investigated recently (Damgaard et al. 2006; Shen et al. 2008).

1.2 Sex odds as a reproductive health indicator

According to Neel and Schull (1991), the sex odds is unique among the genetic indicators. Its uniqueness arises from the fact that maternal exposure would be expected to produce an effect different from paternal exposure. For methodological reasons, we prefer “sex odds” over “sex ratio” (see Section 2.4). When investigating changes in the sex odds, a number of determinants of this trait have to be taken into account (Maconochie and Roman 1997; Jacobsen et al. 1999). However, when undisturbed, the birth sex odds is remarkably constant (Ein-Mor et al. 2010). According to James (1997), “ionizing radiation is the only reproductive hazard, which causes” (irradiated) “men to sire an excess of sons”. Conversely, irradiated mothers, so the theory goes (Schull and Neel 1958), would give birth to an increased proportion of girls. Therefore, one may anticipate eventual changes in the overall sex odds after local or global releases of genotoxic pollutants in case the presumed disturbances of the sex odds were not completely balanced between to the two genders of exposed parents.

1.3 Sex odds and chemical pollutants

Altered human sex odds at birth may be indicative of general health detriment or genetic damage under untoward environmental conditions for parents before conception, embryogenesis, pregnant women, or the fetus (Mocarelli et al. 2000; James 2006; Beratis et al. 2008; James 2008, 2010; Ruckstuhl et al. 2010). A distinct, however unexplained, seasonality of the monthly sex odds was reported by Lerchl (1998). Maternal exposure to polychlorinated biphenyls (PCBs) may be detrimental to the success of male sperm or to the survival of male embryos. Findings could be due to contaminants contained in industrial PCB products to metabolites of PCBs or to PCBs themselves (Hertz-Picciotto et al. 2008). Hence, more girls were born. In a commentary entitled “Where the boys aren’t: dioxin and the sex ratio”, Clapp and Ozonoff (2000) summarized the results of several studies where the exposure to dioxins entailed an alteration of the sex odds towards fewer boys. Hence, more girls were born. In a study performed in the state of Michigan in a well-defined period of PBB or PCB parental exposure, the odds of a male birth increased (Terrell et al. 2009). Hence, more boys were born.

1.4 Sex odds and statistical inference

While being easily accessible, the sex odds is often difficult to measure with sufficient precision for the scientific inquiry in mind. An important, however often neglected, aspect in the analysis of gender proportions is the number of cases considered and the resulting statistical power or precision. As a sobering rule, most publications on the human sex odds do not contain any information concerning the statistical power of the study. Consequently, positive results often fail to be replicated in subsequent investigations, resulting in irrelevant work due to low statistical power (Boklage 2005). On a population level, available datasets are large, with sizes in the range of hundreds of thousands or even millions. However, interesting differences in the sex odds may be small, in the range of a few tenth of a percent to a few percent. Even for 100,000 exposed and 100,000 non-exposed births, the power is only 54% to detect an increase from a normal sex odds of 1.06 to a disturbed sex odds of 1.08. Nevertheless, approximately 900 female concepti are affected detrimentally in the hypothetical situation of a disturbed sex odds of 1.08 in 100,000 exposed births under the conservative assumption that only the female gender was susceptible (Scherb and Voigt 2009).

1.5 Sex odds and other genetic traits and ionizing radiation

Following the explosions of the atomic bombs on Hiroshima and Nagasaki in 1945, an attempt had been made to organize an ongoing project on human genetics. Experiences after those bombings yielded some, but not entirely convincing, evidence of a certain shift in the human sex odds at birth (Schull and Neel 1958; Vogel and Motulsky 1986). The atmospheric atomic bomb tests, essentially terminated in 1963, injected huge amounts of radioactive materials into the biosphere. Radiation-induced genetic effects in rodents (fetal death in the offspring in utero) were observed by Luning et al. (1963), and radiation-induced genetic effects in humans (perinatal mortality and infant mortality) were reported by Sternglass (1971) and Whyte (1990). Based on these observations, a report of the European Committee on Radiation Risk (2003) drew further attention to the effects of the weapons fallout on infant mortality and concluded that there was a significant 2–3% increase per milliSievert of exposure over the 5-year period 1959–1963. This corresponds to a relative risk of 1.1 to 1.2/mSv per year. Consequently, these findings are in the same order of magnitude as the results reported by Scherb and Weigelt (2003). The ecological dose-specific relative risks for stillbirths and several distinct birth defects were in the range of 1.3 to 2.3/mSv per year.

The Chernobyl catastrophe has also created concern regarding the genetic effects of ionizing radiation resulting from fallout dispersed over large parts of Europe in Spring and Summer 1986 (Dubrova et al. 2002; Lazjuk et al. 2003). Although it has long been recognized by the scientific community that congenital malformation, stillbirth, neonatal death, and a disturbed human sex odds at birth are possible adverse genetic effects of ionizing radiation (Sperling et al. 1991; Neel et al. 1989; Dickinson et al. 1996; James 1997; Schull and Neel 1958; Padmanabhan et al. 2004; Muller 1927; Schull et al. 1966, 1981), there has been practically no national or international effort to thoroughly investigate genetic consequences after Chernobyl. The Chernobyl accident entailed radioactive exposure of large populations that varied substantially in time and in space as well, creating a new situation for epidemiology. We developed a spatial–temporal methodology for analytical ecological studies based on logistic regression to identify exposure response relations of untoward pregnancy outcomes in spatially stratified time series (Scherb and Voigt 2007, 2009; Scherb and Weigelt 2003). Particularly suited for epidemiological studies on radiation-induced genetic effects is the sex odds, i.e., the ratio of male to female human live births in a given region or time period.

Utilizing spatial–temporal approaches, long-term dose-dependent impacts of radioactive fallout after Chernobyl on stillbirths, birth defects, and the human sex odds at birth have been found. For example, nearly all published data concerning Down's syndrome show long-term increases after Chernobyl (Zatsepin et al. 2004; Sperling et al. 1994; Metneki and Czeizel 2005; Bound et al. 1995; Ramsay et al. 1991). Significant ecological relative risks for stillbirths and birth defects are in the range of 1.005 to 1.020/kBq m^{-2} ^{137}Cs. A relative risk coefficient of 1.010/kBq m^{-2} ^{137}Cs translates to a preliminary relative risk coefficient of 1.60/mSv per year (Scherb and Weigelt 2003). Furthermore, there are striking jumps or changes in slope (broken sticks) in the secular human birth sex odds trends in 1987 in practically all central and eastern European countries. No jumps or less pronounced jumps in the sex odds trends are visible in less exposed western European countries (e.g., France, Portugal, Spain) and in the USA. More specifically, superimposed on a downward trend in male proportions in the combined Czech Republic, Denmark, Finland, Germany, Hungary, Norway, Poland, and Sweden between 1982 and 1992, there was a significant upward jump in the sex odds in 1987 of 0.47%. A positive association of the male proportion in Germany between 1986 and 1991 with radioactive exposure at the district level is reflected by an increase in the sex odds of 1.45%/mSv per year (Scherb and Voigt 2007). Consequently, a long-term chronic impact of radioactive fallout on the secondary sex odds has been found.

1.6 Aim and scope

In our paper, we will analyze sex odds data with respect to global atmospheric atomic bomb test fallout, with respect to fallout due to nuclear accidents and with respect to radioactive releases of nuclear facilities (NF) under normal operating conditions. We synoptically study sex odds time trends in the USA and in a predominantly western European data set from 1950 to 1990 considering the possibility that those trends could have been disturbed by the delayed atmospheric atomic bomb test fallout globally released prior to the atmospheric atomic bomb test ban in 1963 (Partial Test Ban Treaty—PTBT). Then, we analyze essentially complete European sex odds trends from 1975 to 2007 with emphasis on the Chernobyl accident. Moreover, we will extend and re-analyze recently published data on spatial trends of the sex odds in the vicinity of nuclear facilities (including nuclear power plants) in Germany and Switzerland (Kusmierz et al. 2010).

2 Data and statistical methods

2.1 Europe and USA 1950 to 1990

For the synoptic re-analysis of the USA data and the western European data, we used figures published by Martuzzi et al. (2001) and Mathews and Hamilton (2005). A disadvantage of the European data published by Martuzzi et al. with respect to the Chernobyl issue is the restriction to only 23 European countries with predominantly western and less eastern European coverage (in Martuzzi et al., Czechoslovakia counts one country and Germany counts two countries: FRG and GDR; in our data, it is the other way around). The complement of our essentially complete "Europe" (39 countries; see Section 2.2) and the one by Martuzzi et al. consists of Albania, Belarus, Estonia, Latvia, Lithuania, Luxembourg, Malta, San Marino, The Russian Federation, Ukraine, and Yugoslavia. However, for a secular global synoptic analysis of the European and USA sex odds trends, 1950 to 1990, the Martuzzi et al. data are informative and sufficient.

2.2 Europe 1975 to 2007 and USA 1975 to 2002

This portion of our study is based on official, national, and gender-specific annual live births statistics compiled and provided by the WHO, United Nations, Council of Europe, and EUROSTAT, e.g., the data base http://data.euro.who.int/hfadb managed within the WHO framework 'health for all data base (hfadb)' turned out to be especially useful, complete, and user-friendly. In Table 1, we list 39 European countries with complete data from 1975 to 2007. Note that the former Czechoslovakia now comprises two and the former Yugoslavia six countries. For some republics of the former Soviet Union, no gender-specific birth data were available prior to 1980. As there are two such republics with territory in Europe, Kazakhstan and Moldova, those republics had to be excluded from the overall European trend analysis from 1975 to 2007. Also, no data or essentially incomplete data were available for Andorra, Liechtenstein, Monaco, Turkey, and Vatican. In case of incomplete, inconsistent, or doubtful data, the corresponding national statistical offices were successfully asked for help in several instances. Note that most data in Table 1 originate from the "hfadb" Internet data base by the WHO. The US data from 1975 to 2002 were again obtained from Mathews and Hamilton (2005).

2.3 German and Swiss municipalities 1969 to 2009

Kusmierz et al. (2010) compiled official gender-specific annual live births statistics for all municipalities in Switzerland and for all municipalities in the following states of Germany: Baden-Württemberg, Bavaria, Lower Saxony, North Rhine-Westphalia. For Rhineland-Palatinate, provisional data at the level of 36 districts only were available at that time. As we are now able to extend the data set utilizing 2,312 municipalities of Rhineland-Palatinate instead of the corresponding 36 districts (Table 2), a more powerful analysis can be carried out. To calculate the distances of the municipalities from nuclear facilities, we determined uniform coordinates for the geographic positions of those municipalities including the geographic positions of 28 pertinent nuclear facilities including all nuclear power plants in Germany and Switzerland (Kusmierz et al. 2010). All in all, our extended data set comprises 9,596 municipalities, 361,056 municipality-years, and 20.4 million live births with a total sex odds of 1.0552 (Table 2).

2.4 Statistical methods

To assess time trends in the occurrence of boys among all live births and to investigate whether there have been significant changes in the trend functions in 1987 or later, we applied ordinary linear logistic regression. This involves considering the male proportion among all male (m) and female (f) births: $p_{\mathrm{m}} = m/(m + f)$. The important and useful parameters in this context are the sex odds: SO = $p_{\mathrm{m}}/(1-p_{\mathrm{m}}) = m/f$, and the sex odds ratio (SOR), which is the ratio of two interesting sex odds if those two sex odds have to be compared, e.g., in exposed versus non-exposed populations. We used dummy coding for single points in time and for time periods as well. For example, the dummy variable for the time window from 1987 on is defined as $d_{87}(t)=0$ for $t<1987$ and $d_{87}(t)=1$ for $t \geq 1987$. The simple and parsimonious logistic model for a trend and a jump in 1987 has the following form (LB = live births):

$$\mathrm{Boys}_t \sim \mathrm{Binomial}(\mathrm{LB}_t,\ \pi_t)$$
$$\log\ \mathrm{odds}(\pi_t) = \mathrm{intercept} + \alpha * t + \beta * d_{87}(t)$$

To allow for changing sex odds trend slopes (broken sticks) after Chernobyl, we used dummy coding of time windows and interactions of those time windows with time. The data in this study were processed with Microsoft Excel 2003. For statistical analyses, we used R 2.11.1, MATHEMATICA 5.0 and mostly SAS 9.1 (SAS Institute Inc.).

3 Results

3.1 Analysis of European and US data 1950 to 1990

The Chernobyl accident and its possible consequences have sometimes been discussed in perspective of the experiences

Table 1 European gender-specific live births from countries with complete data from 1975 to 2007; USA from 1975 to 2002 (Mathews and Hamilton 2005)

Country	Births 1975–2007			
	Country number	Male	Female	SO
Albania	1	1,130,199	1,040,746	1.0860
Austria	2	1,458,550	1,386,074	1.0523
Belarus	3	2,170,667	2,050,534	1.0586
Belgium	4	2,060,708	1,955,233	1.0539
Bulgaria	5	1,686,699	1,595,331	1.0573
Czechoslovakia (f.)	6–7	3,396,664	3,222,748	1.0540
Denmark	8	1,057,854	1,003,118	1.0546
Estonia	9	314,547	297,105	1.0587
Finland	10	1,045,181	998,718	1.0465
France	11	12,840,000	12,210,308	1.0516
Germany	12	13,488,891	12,774,421	1.0559
Greece	13	1,977,369	1,850,287	1.0687
Hungary	14	2,099,904	1,988,257	1.0562
Iceland	15	72,914	69,321	1.0518
Ireland	16	1,024,334	966,373	1.0600
Italy	17	10,120,009	9,542,422	1.0605
Latvia	18	507,329	481,021	1.0547
Lithuania	19	779,998	740,959	1.0527
Luxembourg	20	82,544	77,845	1.0604
Malta	21	85,225	79,638	1.0702
Netherlands	22	3,174,069	3,023,245	1.0499
Norway	23	950,341	900,220	1.0557
Poland	24	9,007,557	8,496,847	1.0601
Portugal	25	2,201,456	2,061,412	1.0679
Romania	26	5,148,669	4,876,409	1.0558
Russian Federation	27	30,980,409	29,371,349	1.0548
SanMarino	28	2,988	2,757	1.0838
Spain	29	7,938,940	7,425,565	1.0691
Sweden	30	1,721,411	1,627,973	1.0574
Switzerland	31	1,305,459	1,238,886	1.0537
Ukraine	32	10,118,805	9,572,157	1.0571
United Kindom	33	12,371,861	11,741,276	1.0537
Yugoslavia (f.)	34–39	5,170,407	4,832,146	1.0700
All European		147,491,958	139,500,701	1.0573
USA (1975 to 2002)		54,256,593	51,683,339	1.0498

f. former

after the atomic bombings of Japan in World War II and the above-ground atomic bomb tests from 1945 to 1963, the year of the PTBT. Therefore, an analysis of the human birth sex odds before and after the atmospheric atomic bomb tests is also self-evident. Figure 1 displays the trends of the live births sex odds in Europe and in the USA published by Martuzzi et al. (2001) and by Mathews and Hamilton (2005), respectively. The synoptic analysis behind Fig. 1 is based on 420 million births and covers the period from 1950 to 1990. Both trends are similar in that they are consistent with a uniform reduction from 1950 to 1964, an increase from 1964 to 1975, and again a more or less constant decrease from 1975 to 1990. We conjecture that the increases in Europe and USA are a consequence of the globally emitted and dispersed atmospheric atomic bomb test fallout prior to the test ban in 1963 that affected large human populations overall after a certain delay. The synoptic trend components are highly significant ($p<0.0001$) due to the large number of births involved.

3.2 Analysis of European data 1975 to 2007 and US data 1975 to 2002

Figure 2 presents the sex odds trends of the USA from 1975 to 2002 and the corresponding European trend from 1975

Table 2 Gender-specific live births that are available from Germany and Switzerland at the municipality level

Region	Municipality	Available	Municipality-years	Births	Male	SO
Baden-Württemberg	1,102	1975–2008	37,468	3,498,211	1,795,839	1.0549
Bavaria	2,056	1972–2008	76,072	4,366,993	2,241,831	1.0549
Lower Saxonia	1,024	1971–2009	39,936	2,927,455	1,503,478	1.0558
North Rhine-Westphalia	396	1980–2008	11,484	5,033,665	2,584,664	1.0554
Rhineland-Palatinate	2,312	1972–2009	87,856	1,404,742	721,059	1.0547
Switzerland	2,706	1969–2008	108,240	3,182,400	1,633,929	1.0552
Combined	9,596		361,056	20,413,466	10,480,800	1.0552

to 2007. The synoptic analysis behind Fig. 2 is based on 393 million births. In the USA, we can see a rather smooth, uniform, and undisturbed downward trend during the whole time span of 28 years. The trend is a highly significant reduction of the sex odds of 0.22% per 10 years, 95% CI (0.17, 0.27), $p<0.0001$. In Europe, from 1975 to 1986, compared to the USA, we can see a similar downward trend with a sex odds reduction of 0.25% per 10 years (0.14, 0.35), $p<0.0001$. In contrast to the USA, in Europe in the year 1987 following Chernobyl, there was a highly significant jump of the sex odds of 0.20% (0.10, 0.30), $p=0.0001$. From 1987 to 2000, the European sex odds trend changed its sign and went upward relative to the downward trend before Chernobyl with 0.42% per 10 years (0.34, 0.51), $p<0.0001$. From 2000 onward, the European trend changed its sign again then decreased with 0.48% per 10 years (0.24, 0.71), $p<0.0001$. This means that we detected a significant gender gap in Europe after Chernobyl whereas no such similar effect is seen in the USA less exposed by Chernobyl fallout.

The question immediately arises whether the jump and the trend reversal in the European sex odds after Chernobyl (1986) are caused by the ionizing radiation released. Evidence of causality is strengthened if the disturbance of the sex odds trends were stronger or weaker in countries with more or less Chernobyl fallout, respectively. This can easily be checked by considering medium-sized or large countries with sufficient statistical power at lower or greater distances from Chernobyl, e.g., France, Germany, and the Russian Federation. Figure 3 shows these data, including appropriate parsimonious jump models. Whereas there is practically no jump in 1987 in France (sex odds ratio of jump (SOR)=1.0003; $p=0.8489$), there is after all a noticeable, however insignificant, jump in Germany (SOR=1.0019; $p=0.2133$) and an extremely significant jump in the Russian Federation (SOR=1.0088; $p<1.0\text{E}{-25}$). Because France was less exposed than Germany and Germany was less exposed than the Russian Federation (Drozdovitch et al. 2007), we observe a qualitative dose–response association between the fallout levels and the sex odds jump heights from 1987 onward. Together with the fact that the jumps in the sex odds trends follow the exposure in time, strong evidence of causality is obtained. A formal and quantitative dose–response analysis at the district level in Germany yielding a preliminary ecological SOR/mSv per year of 1.0145 has previously been published (Scherb and Voigt 2009, 2007).

3.3 Further evidence: increased sex odds near nuclear facilities

A significantly elevated human sex odds at birth has been found in the vicinity (< 35 km) of nuclear facilities in Germany and Switzerland (Kusmierz et al. 2010). In this

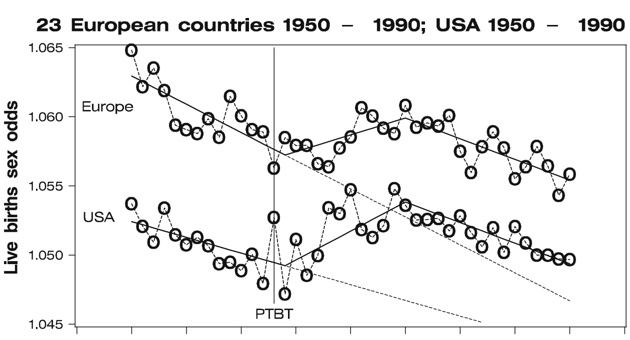

Fig. 1 Trends of the live births sex odds (male/female) in Europe and in the USA, 1950 to 1990 (Martuzzi et al. 2001; Mathews and Hamilton 2005)

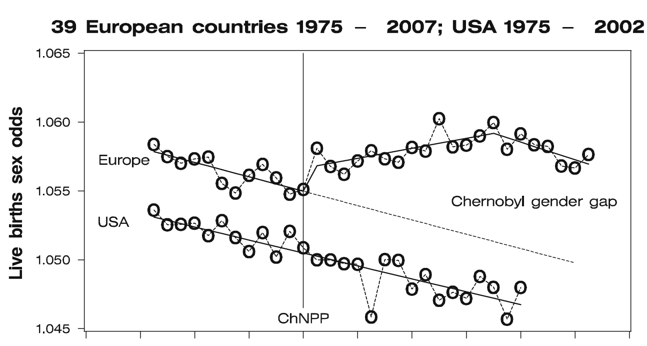

Fig. 2 Trends of the live births sex odds (male/female) in the USA, 1975 to 2002, and in 39 European countries; see Table 1 and Mathews and Hamilton (2005)

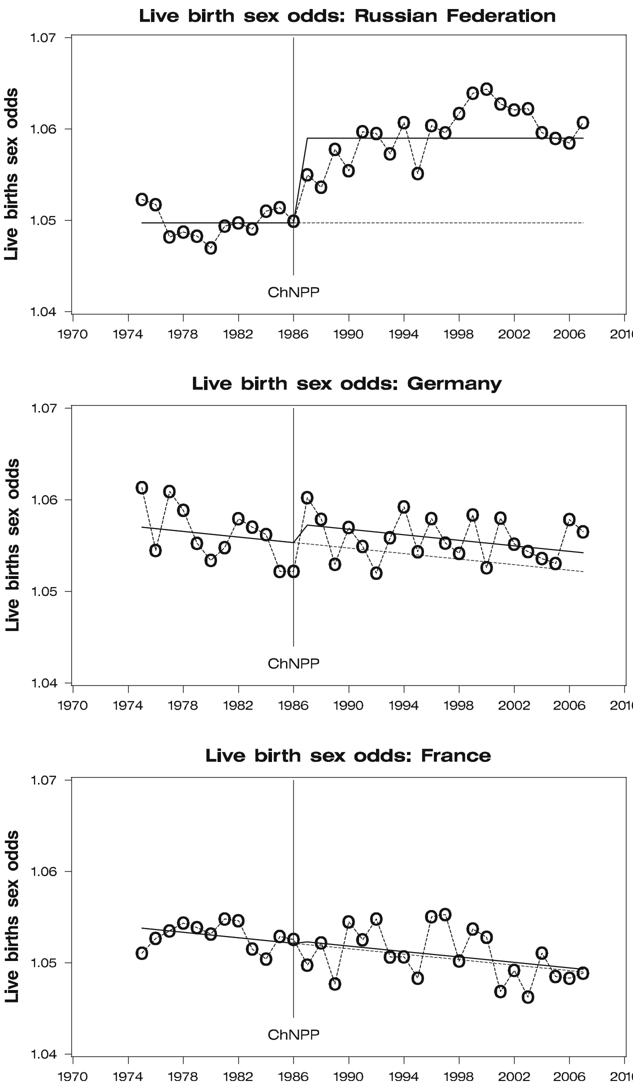

Fig. 3 Trends of the live births sex odds (male/female) in France, Germany, and the Russian Federation

paper, we improved the data base (see Section 2.3), resulting in a somewhat more powerful analysis displayed in Fig. 4. The simple jump model for distances below 35 km yields a sex odds base-line level of 1.0543, 95% CI (1.0532, 1.0553) and a sex odds ratio for the jump at 35-km distance of 1.0036, 95% CI (1.0015, 1.0056), p=0.0003. Using a more impartial Rayleigh function (p=0.0014), the estimated sex odds peaks at 14.3 km, 95% CI (9.1, 19.5) with a SOR peak=1.0052, 95% CI (1.0022, 1.0082). This finding qualitatively supports the recently reported increased childhood cancer and childhood leukemia incidences near nuclear power plants in Germany (Spix et al. 2008; Nussbaum 2009). A sensitivity analysis displacing all nuclear facilities' original geographic positions 50 km to the west or 50 km to the east yields insignificant (p>0.5) Rayleigh functions (Fig. 5). One may expect such a behavior in case a real causation by NF was indeed behind the observed significant effects in Fig. 4, and no corresponding causative agent is present at arbitrary dummy locations without nuclear facility installations.

3.4 More or less boys or girls?

In this section, we address the question on whether there is empirical evidence that the increased male birth proportions after the atomic bomb tests, after Chernobyl, and in the vicinity of nuclear facilities are in fact due to a reduced frequency of female births and not due to an increased number of male births. In principle, it seems reasonable to assume that, if radioactive fallout has any influence on human reproductive health at all, it would not increase the number of live births relative to a prevailing (positive or negative) live births trend in a given region or time period. Indirect evidence of somewhat decreased live births results from increased spontaneous abortions observed in Finland (Auvinen et al. 2001) and from increased stillbirth proportions in several parts of Europe after Chernobyl (Scherb et al. 1999). An obvious approach is the inspection of trends of absolute numbers of gender-specific births. An interesting example is Denmark. Figure 6 shows the gender-specific live births trends in Denmark from 1984 to 1990. In this period of monotonically increasing births, we notice certain impressions of the male and female trend functions, especially in 1987 and 1988. Compared to the hypothetically undisturbed straight and parallel trend lines, there were deficits of approximately 500 male and approximately 1,800 female births from 1986 onward. This yields a raw and very preliminary estimate of the sex odds in the hypothetical deficit of births in Denmark of 3/10. Admittedly, this is a crude approach, but it may nevertheless be a valid consideration. However, it is also possible that fear to conceive after Chernobyl led to this apparent deficit of births in Denmark, and if the decision not to conceive was associated with several sex-determining factors in the population (age, social class, etc.), the difference between the male and female birth trends could be independent of ionizing radiation. Therefore, this observation has to be interpreted with care and further independent information concerning this issue should be sought. As yet, we have not found other countries with such a seemingly clear behavior. In most cases, the trends of absolute numbers of births are more irregular and less smooth compared to those Danish trends in Fig. 6.

With the assumption of a sex odds in the birth deficit of 3/10, all unknown parameters are determined and it is possible to estimate the apparent gender gaps in Figs. 1 and 2 by straightforward arithmetic. The combined European and USA gender gaps after the PTBT (1963) to 1990 in

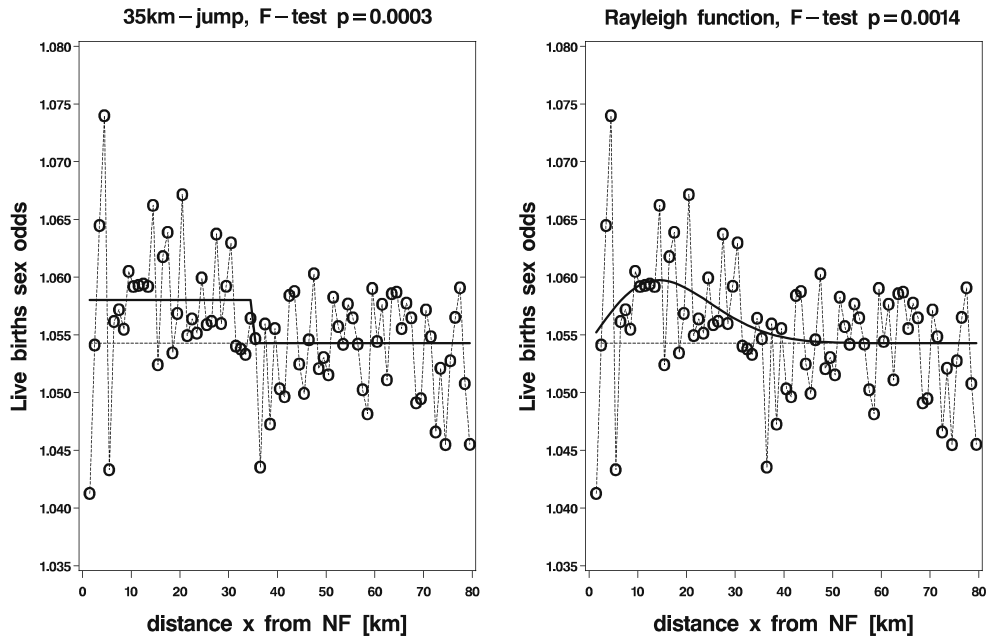

Fig. 4 Improved 35-km jump function and Rayleigh function models for the live births sex odds (male/female) depending on distance from nuclear facilities (NF) in Germany and Switzerland (Kusmierz et al. 2010)

Fig. 1 theoretically represent approximately 1.2 million children. Analogously, the European gender gap from 1987 onward to 2007 in Fig. 2 theoretically amounts to approximately 800,000 children.

Based on our previous analysis of birth defects and stillbirth after Chernobyl, i.e., assuming an approximate dose-specific relative risk of 1.5/mSv per year, it is possible to conjecture that the number of impaired children is in the same order of magnitude as the deficit of births after Chernobyl (Scherb and Weigelt 2003). Therefore, assuming that our approach is valid and realistic, it becomes clear that the deficit of births and the number of stillborn or impaired children after the global releases of ionizing radiation taken together may be in the range of several millions.

Note that our data yield only an incomplete account of contaminated regions and contaminated time periods on the globe. Given that the European and USA trends in Fig. 2 are both representative of the past as well as of the future, it seems possible that the deficit of births and the cumulative number of impaired children will still be increasing in many years to come because a complete recovery of the disturbed human sex odds is presently not foreseeable. However, a partial recovery is already visible by the significant downward trend in Europe from 2000 onward (Fig. 2).

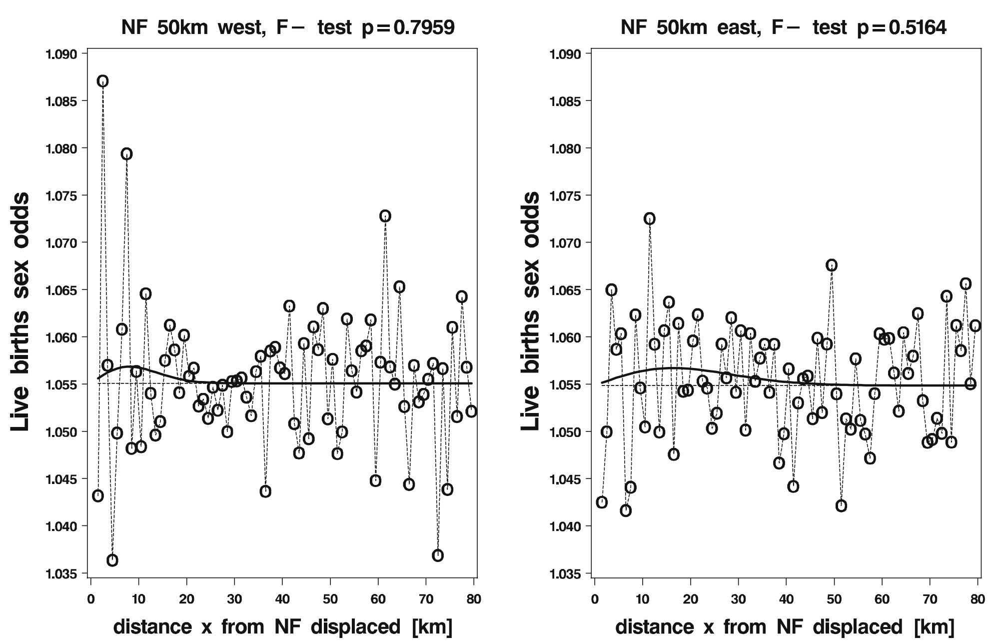

Fig. 5 Insignificant distance trends (Rayleigh functions) near fictitious positions of nuclear facilities NF obtained by dis placing all original positions of German and Swiss NF 50 km to the west (*left*) or 50 km to the east (*right*)

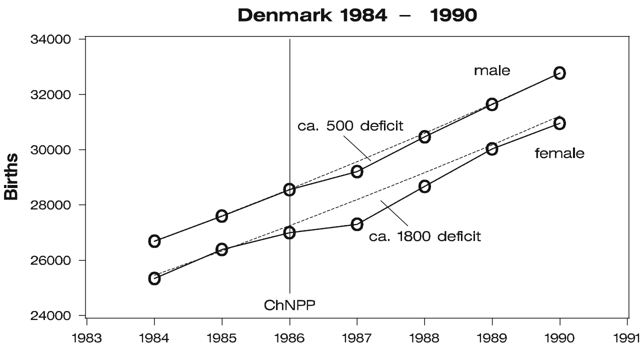

Fig. 6 Trends of gender-specific births in Denmark and preliminary estimation of the sex odds in the deficit of births: 500/1,800 ≈3/10

4 Summary and discussion

In this paper, we analyzed large data sets with respect to possible alterations of the human birth sex odds after local or global releases of ionizing radiation. The sex odds increase under elevated exposure to ionizing radiation. Straightforward time trend analyses of official and essentially complete USA and European gender-specific birth statistics reveal certain disturbances of the sex odds after the atmospheric atomic bomb testing on the whole globe, after the Chernobyl accident in Europe, and in the vicinity of nuclear facilities during their operating periods in Germany and Switzerland. It is unlikely that, among the many determinants of the sex odds discussed in the literature, any one single factor or several factors in common acted synchronously with the Chernobyl event from 1986 onward. Even if there were secular coincidences of other sex-determining factors with the aftermath of Chernobyl, it is unlikely that those factors occurred or changed in a parallel abrupt manner in 1987, the year immediately after this nuclear catastrophe in Europe. Therefore, because of its well-known mutagenic properties, ionizing radiation released by the atomic bomb tests, by the Chernobyl accident and by operating nuclear facilities, is the most parsimonious explanation for the disturbed birth sex odds trends observed.

Following the explosions of the atomic bombs on Hiroshima and Nagasaki, an attempt had been made to organize an ongoing project on human genetics (Vogel and Motulsky 1986). Experiences after the bombings yielded some, but not entirely convincing, evidence of a certain shift in the human sex odds at birth. For all categories, the sex odds showed changes in the expected direction: Under the assumption that only one parent was affected, irradiation of mothers would result in less male and irradiation of fathers would ensue less female offspring. However, based on the Hiroshima and Nagasaki data, it does not seem possible to predict the direction of an effect in case both parents or the conceptus had been exposed more or less uniformly. Vogel and Motulsky (1986) state: “When both parents were exposed, the maternal appeared to exceed the paternal effect.” However, with only approximately 12,000 exposed parents, this could as well have been a chance result because of insufficient statistical power (see “Section 1.4”). Our results concerning uniform exposures of very large populations consistently show increased sex odds. Moreover, this increase of the male proportion turned out to be dose dependent at the ecological level (Scherb and Voigt 2007). Dubrova et al. (2002) reported that the paternal mutation rate at eight minisatellite loci in exposed families from Ukraine is elevated, and they found no evidence of elevated mutation rates in the germline of exposed mothers: “A statistically significant 1.6-fold increase in the paternal mutation rate was found in the exposed families from Ukraine, whereas maternal mutation rate in this cohort was not elevated.” If one may speculate that the genetic information in fathers is more susceptible to damage by ionizing radiation compared to mothers, then one could perhaps explain why in uniformly irradiated populations the paternal effect exceeds the maternal effect with the consequence of more female than male lost concepti or children and, thus, increased sex odds.

5 Conclusions and outlook

Our observations add evidence to findings in the field of radiation epidemiology indicating considerably underestimated health risks of the so-called low-level (< 100 mSv) ionizing radiation (Bandazhevski et al. 2009; Ericson and Kallen 1994; Huether et al. 1996; Lazjuk et al. 2003; Muerbeth et al. 2004; Ramsay et al. 1991; Zatsepin et al. 2007; Auvinen et al. 2001; Wertelecki 2010). The International Commission on Radiological Protection (ICRP) has assessed the risk of severe hereditary diseases (e.g., hemophilia, Down’s syndrome) in a general population exposed to low doses and low dose rates. ICRP estimated a risk factor of 1 in 100 per Sievert for severe hereditary diseases appearing at any time in all future generations (i.e., relative risk per Sievert (Sv)=1.01). A more specific risk estimate, in the same order of magnitude however, has been propagated by the United Nations Scientific Committee on the Effects of Atomic Radiation (2001): “The estimate of risk” (at 1 Gy) “for congenital abnormalities is about 2,000 cases per million live births (compared to 60,000 cases per million live births).” Note that 1 Gy is equivalent to 1 Sv (Sievert) for gamma radiation. The UNSCEAR 2001 risk translates to a relative risk per Sievert of 1.03 (= 62,000/60,000). In sharp contrast to that, our estimated effects are in the order of magnitude of 1.50/mSv per year for birth defects and stillbirths and 1.02/mSv per year for the sex odds (Scherb and Voigt 2007; Scherb and Weigelt 2003).

This means that the internationally established radiation risk concept based on average absorbed dose is in error at three to four orders of magnitude or, more likely, it is conceptually wrong.

Our results suggest that the global deficit of births and the increased number of stillborn or impaired children due to the atmospheric atomic bomb tests and due to the Chernobyl catastrophe may be in the range of several millions. This is a large absolute number although it is a small relative number with respect to all births in the range of several hundreds of millions considered here, as well as with respect to risks like accidents, diseases, or naturally occurring unfavorable pregnancy outcomes, etc. However, the detected adverse genetic effects point to an enhanced impairment of humankind's genetic pool by artificial ionizing radiation. Moreover, our results contribute to disproving the established and prevailing belief (UNSCEAR 2000) that radiation-induced hereditary effects have yet to be detected in human populations.

We will focus our future research efforts on underestimated reproductive health effects associated with low-dose ionizing radiation by extending and specifying our spatial–temporal methodology. Further data sources will be explored with the aim of complementing our findings. Important data on neglected environmental and health topics are partly available. However, often there is no (optimum) utilization of the existing data bases. Thus, greater input from mathematicians and statisticians is urgently needed to scrutinize those data. To achieve this goal, the full spectrum of different data analysis approaches should be considered and applied appropriately. Improved interdisciplinary skills are needed at all stages of environmental health research. More research should be initiated to strengthen the evidence achieved and, importantly, to open minds to the danger of ionizing radiation.

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