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Spatial-temporal Trend Analyses of Infant Mortality Versus Chernobyl Fallout in Switzerland (1969 - 2024): Analysis of a Dose Response Association at the Canton Level

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Abstract

Background: In Switzerland from 1987 to 2022 after the Chernobyl accident in April 1986, the infant mortality proportion jumped relatively parallel to the prevailing monotone secular downward trend from 1950 to 1986. The jump odds ratio (OR) in 1987 was 1.175 (1.102, 1.253). This report aims at studying whether the canton-specific drops or jumps of the infant mortality in 1987 are associated with the average Chernobyl cesium-137 (Cs-137) fallout in the Swiss cantons.

Methods: Counts of annual live births and infant deaths under one year of age from 1969 to 2024 stratified by sex and the twenty-six Swiss cantons were obtained from the Federal Statistical Office (FSO). The Swiss Federal Office of Public Health (FOPH) provided a map of Switzerland documenting Cs-137 Chernobyl fallout (kBq/m^2) in early May 1986. Possible dose-response associations of Chernobyl fallout with infant mortality were analyzed employing five parsimonious regression techniques.

Results: The overall infant mortality proportion in the period 1969 - 2024 was 0.65%, i.e., 29,322 infant deaths in 4,524,021 live births. Restricted to the period 1987 - 2024 (with a total of 13,948 infant deaths), the jump OR in 1987 in the long-term infant mortality trend is 1.165 (1.095, 1.240), p-value < 0.0001 and translates to 1964 (1201, 2688) excess infant deaths from 1987 to 2024. The five regression techniques consistently suggest that infant mortality in Switzerland after Chernobyl increased in the order of 1% to 3% per kBq/m2 Cs-137 fallout.

Conclusion: In Switzerland after the Chernobyl accident, the positive association of canton-specific jumps in infant mortality with canton-specific Chernobyl fallout strengthens the evidence of a causal link of low dose ionizing radiation (IR) and detrimental effects on early human development.

Keywords: Infant death, Radioactive contamination, Cesium, Chernobyl

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Introduction

Infant mortality is an important global socio-medical health indicator [1]. The dramatic decline in infant mortality in Europe over the course of the last century is attributable to modern medicine – particularly neonatology – as well as to improved hygienic and social conditions. Whilst in Switzerland in the 1950s more than 30 per thousand newborns died in their first year of life, this figure now stands at around 3 per thousand [2]. Infant mortality is linked, among other things, to socio-economic status [3], the density of doctors [4], unemployment [5], income [6], urbanization [7], nitrogen dioxide concentrations in the air [8] and lead contamination in the soil (particularly in agricultural land) [9].

The biological effects of IR have been systematically studied for more than 100 years. Depending on the dose, IR leads to deterministic or stochastic changes at the organism, tissue, cell, and subcellular levels [10]. It has been shown that unborn babies, children and women are especially sensitive to radiation [11-13]. It has also been demonstrated that IR causes cancer and impairs reproduction. In the 1920s, Muller [14] landmark findings on the detrimental genetic effects of IR in Drosophila caused a sensation. In the 1950s, Stewart et al. [12] demonstrated a carcinogenic effect in children whose mothers had been exposed to radiological examination of the pelvis during

pregnancy. Even then, it was evident that exposure to low doses of IR in the order of magnitude of natural background radiation [15] posed a significant stochastic cancer risk. However, it was not until the turn of the millennium that the scientifically based linear no-threshold model [11] became generally accepted. It states that the radiation risk is proportional to the dose and that there is no harmless dose of radiation, no matter how low it may be. However, one implausible and illogical dogma prevails, namely that detrimental genetic effects in humans have not been demonstrated for radiological exposures below 1 gray (Gy; 1 Joule/kg) [11]. Contrary to this dogma it is reasonable to assume that eggs, sperm, embryos, fetuses, and infants also experience health detriment under elevated environmental radiation as Schmitz-Feuerhake et al. [16] have aptly demonstrated.

A recent large metanalysis of epidemiological studies in varying settings directly supports excess cancer risks from low-dose IR [17]. Wakeford and Bithell [18] confirmed the harmful effects of medical x-ray examinations of the pregnant mother and pointed at the fact of an almost uniformly raised relative risk for nearly all types of cancer that are most frequent in children. Even a radiation dose of around 10 millisieverts (mSv) leads to a 50% increase in cancer risk up to the age of 15. Interestingly, several recent studies have described natural background radiation as a possible risk factor for childhood cancer [13]. Large-scale, census-based cohort studies are needed to obtain reliable results in this complex area [19]. According to observations from Switzerland [20, 21], natural background IR likely contributes to the risk of leukemia and tumors of the central nervous system in children with a population attributable fraction of about 30%. In addition, Little et al. [22] stated in an extensive review that the large body of data relating to in utero and childhood exposure provides support for the existence of excess cancer and benign neoplasm risk associated with radiation doses < 0.1 Gy), and for certain groups exposed to natural background radiation, to fallout and medical X-rays in utero, at about 0.02 Gy.

Radiation-related reproductive disorders have been studied less extensively than radio-induced carcinogenicity. Nevertheless, an increase in stillbirths [23], perinatal mortality [24], infant mortality [25], congenital malformations [26, 27], reduced birth weight [28], increase in trisomy 21 (Down syndrome) [29] and a distorted sex ratio at birth [30, 31] were observed after radiation exposure from radioactive fallout, whether from atomic bomb explosions or civil nuclear accidents. Causality in relation to radiation health effects is known to be the subject of controversial debate, although Hill's classic criteria [32] are met, at least to a considerable extent. A broad variety of these reproductive pathologies have enhanced exposure to low doses of IR in common.

Recently an unusual ongoing increase in infant mortality in Switzerland was reported [33]: After the Chernobyl accident in April 1986 the infant mortality proportion increased relative to the prevailing monotone secular downward trend from 1950 to 1986. In this ecological study, which covers more than 6'186'000 live births between 1950 and 2022, nearly 2'000 excess infant deaths were identified between 1987 and 2022. The jump OR in 1987 was 1.175 (1.102, 1.253). Given the radioactive contamination of Switzerland from the Chernobyl accident, which amounted to approximately 3'500 person-Sieverts and was mainly due to Cs-137 [34, 35], we aimed at the evaluation of a possible association of the increased radioactive exposure and the increase of infant mortality after 1986. Therefore, an independent review by the Swiss Tropical and Public Health Institute was commissioned. The results were largely confirmed [36], and the authors recommended a detailed analysis of a possible dose-response relationship to clarify arguments for a causal link. Additionally, the review raised some uncertainty regarding the assumption of the specificity of the estimated and tested change-point point in 1986/1987. However, the specificity was sufficiently demonstrated using three independent statistical methods [36] that this point in time is most likely to capture the greatest jump in infant mortality during the whole period from 1950 to 2022 under discussion. We, therefore, investigated – using appropriate correlation and regression methods – if we could demonstrate whether a low dose or low exposure is associated with a slight increase in infant mortality and whether a high dose or high exposure leads to an escalated infant mortality in the 26 cantons of Switzerland experiencing considerably different Chernobyl fallout.

Materials and Methods

The Infant mortality proportion is defined as the number of resident newborns in a specific geographic area and/or period (e.g., country, state, county, year, and month) dying under one year of age divided by the number of live births for the same period and area. The FSO provides counts of annual live births and infant deaths under 1 year of age for Switzerland. Sex-specific and canton-specific live births and infant mortality data for the 26 Swiss cantons for the period 1969 – 2024 only are available since mid-2025. Such spatially more detailed canton-specific data is currently not available for the period 1950 - 1968. For comparison purposes, the 2024 analysis [33], which covers the whole of Switzerland (1950 – 2022), was therefore adjusted to cover the reduced period 1969 – 2024 as the starting point for this new study.

Radiological exposure data were based on information published by the FOPH [34, 35]. The estimate of the Cs-137 fallout levels from Chernobyl from early May 1986 in the 26 cantons is derived from a contour map from 2006 [34] according to Department for the Safety of Nuclear Facilities, calculations based on ambient dose measurements [37]. The contour map from 2006 was reproduced by the FOPH in 2026 [35]. The contour plot [34] is presented in shades of blue, which are assigned to the measured or calculated Cs-137 fallout values based on a corresponding scale: white < 3 kBq/m^2 to dark blue 26 kBq/m^2. Image processing was used to determine a color index (ci) as the average of the corresponding red, green, and blue values of each pixel (n = 240,401). The color index ci was transformed to kBq/m^2 by the following empirical formula: kBq/m^2 = 2.5 + ci/1.57 × (26 - 2.5). The Statistical Analysis System (SAS) procedure GINSIDE was employed to assign the pixels to the 26 Swiss cantons and to finally calculate the mean fallout values for the cantons. This study therefore evaluates the height of downward drops or upward jumps in the canton-specific infant mortality trends in 1987 and the associations of those long-term drops or jumps with the average Chernobyl Cs-137 fallout in the Swiss cantons from early May 1986.

Dose-response regression in epidemiology evaluates how varying levels of an exposure (dose) impact health outcome risks (response) using statistical key regression models:

- Ordinary linear least-squares regression assumes a steady, straight-line or curved increase or decreases in risk as exposure grows.
- Nonlinear and spline models use flexible curves (like restricted cubic splines) to capture complex, u-shaped, j-shaped, or threshold effects without rigid assumptions.
- Logistic or probit models are applied when the health outcome is binary (e.g., diseased vs. healthy, surviving vs. not surviving the first year of life, etc.) to map exposure levels to event probabilities.

Core objectives of causality checks are a demonstration of a gradient

in risk, which strongly supports a causal link. Trend estimation tests statistical significance across ordered exposure categories or continuous values. Meta-analysis pooling combines slope estimates across multiple independent studies to establish a consensus curve. Therefore, we analyzed possible dose-response associations of Chernobyl Cs-137 fallout levels with canton-specific infant mortality trends and 1986/1987-jump heights by five straightforward, transparent, and methodologically parsimonious regression techniques:

1. Unrestricted inverse variance weighted ordinary linear or curved least squares regression of the canton-specific drops or jumps in the infant mortality trends in 1987 on the average fallout in the cantons.

2. Intercept-restricted, i.e., intercept = 0, inverse variance weighed ordinary linear or curved least-squares regression of the canton-specific drops or jumps in the infant mortality trends in 1987 on the average fallout in the cantons. Whereby the restriction "intercept = 0" means that cantons with marginal or no fallout would not experience any significant change (drop or jump) in their individual infant mortality trends - effectively embedding the null hypothesis (no Chernobyl effects before the accident and after 1986 at zero fallout) into cantons with zero exposure and/or in the period before the Chernobyl accident.

3. Fixed effects spatial-temporal logistic regression [26, 28, 38] of the direct infant mortality proportion (not only the jump heights as above under 1 and 2) on time (1969 - 2024) and fallout. The potential Chernobyl effect is modeled, estimated, and tested by the dummy variable d1987, which is zero (0) before 1987 and one (1) from 1987 onward. This formalizes the null hypothesis of no effect on infant mortality before the Chernobyl accident and a possible fallout effect on infant mortality after the Chernobyl accident. This central main effect d1987 together with its pertinent interactions, e.g., d1987 × kBq/m^2 are estimated and tested.

4. Similarly, to point 3 above: Mixed effects spatial-temporal logistic regression of the direct infant mortality proportion on time and fallout. Here, random effects are the canton-specific intercepts and the canton-specific fallout levels, fixed effects are time and time squared. Random effects capture the heterogeneity of the 26 canton-specific intercepts and 26 fallout levels, whereas the fixed effects time and time squared are determined more precisely by 26 × 56 = 1456 spatial-temporal data points, or 2912 data points if sex is considered.

5. For a list of 22 pertinent co-variables (effect modifiers like sex, confounders like age of the mother, etc.), the potential modulating influence for each single co-variable on the dose-response relation between fallout and infant mortality was estimated and tested. More than one co-variable in the regression model was not analyzed for two reasons: combinatorial diversity and the relatively small effective sample size of only 26 cantons for most of the co-variables.

Unless otherwise noted, statistical significance is based on two-tailed tests and refers to p-value < 0.05. The code, data-analysis, and output for this paper were generated using SAS software: mainly SAS-PROCs LOGISTIC, GINSIDE, GLIMMIX, GMAP, REG, and SGPLOT. Copyright © 2021 SAS Institute Inc. Cary, NC, USA. All rights reserved SAS on demand release 3.1.0. SAS and all other SAS Institute Inc. products or service names are registered trademarks or trademarks of SAS Institute Inc.

Results

The live birth counts, the numbers of infant deaths in age category zero (0), and the infant mortality proportion by year in Switzerland are listed in table 1. The overall infant mortality proportion in the period

Table 1: Infant deaths (<1 year), live births, and infant mortality proportion in Switzerland 1969 to 2024.

Year	Death at age < 1 year	Live births	Infant mortality proportion	Year	Death at age < 1 year	Live births	Infant mortality proportion
1969	1,574	102,520	0.01535	1997	387	80,584	0.00480
1970	1,494	99,216	0.01506	1998	377	78,949	0.00478
1971	1,380	96,261	0.01434	1999	361	78,408	0.00460
1972	1,216	91,342	0.01331	2000	386	78,458	0.00492
1973	1,153	87,518	0.01317	2001	365	72,295	0.00505
1974	1,053	84,507	0.01246	2002	326	72,372	0.00450
1975	843	78,464	0.01074	2003	309	71,848	0.00430
1976	797	74,199	0.01074	2004	311	73,082	0.00426
1977	712	72,829	0.00978	2005	310	72,903	0.00425
1978	615	71,375	0.00862	2006	324	73,371	0.00442
1979	610	71,986	0.00847	2007	296	74,494	0.00397
1980	667	73,661	0.00905	2008	308	76,691	0.00402
1981	557	73,747	0.00755	2009	338	78,286	0.00432
1982	574	74,916	0.00766	2010	305	80,290	0.00380
1983	560	73,659	0.00760	2011	303	80,808	0.00375
1984	533	74,710	0.00713	2012	300	82,164	0.00365
1985	515	74,684	0.00690	2013	319	82,731	0.00386
1986	521	76,320	0.00683	2014	336	85,287	0.00394
1987	524	76,505	0.00685	2015	339	86,559	0.00392
1988	550	80,345	0.00685	2016	306	87,883	0.00348
1989	596	81,180	0.00734	2017	310	87,381	0.00355
1990	574	83,939	0.00684	2018	287	87,851	0.00327
1991	537	86,200	0.00623	2019	283	86,172	0.00328
1992	557	86,910	0.00641	2020	313	85,914	0.00364
1993	465	83,762	0.00555	2021	280	89,644	0.00312
1994	426	82,980	0.00513	2022	311	82,371	0.00378
1995	415	82,203	0.00505	2023	265	80,024	0.00331
1996	390	83,007	0.00470	2024	259	78,256	0.00331

1969 - 2024 was 0.65%, i.e., 29,322 infant deaths in 4,524,021 live births. For the period 1969 - 2024, the jump from 1986 to 1987 in the long-term infant mortality trend measures 1.165 (1.095, 1.240), p-value < 0.0001 and translates to 1964 (1201, 2688) excess infant deaths from 1987 to 2024 (Figure 1).

The canton names and codes, the overall canton-specific infant deaths and live births (1969 - 2024) in Switzerland, canton-specific Chernobyl Cs-137 fallout levels (kBq/m^2), and canton-specific jump heights 1986/1987 of the canton-specific linear-quadratic infant mortality trends analogous to figure 1 and to the previously published trend analysis for all of Switzerland [33] are given in table 2. Figure 2 depicts the information on cantonal average Chernobyl Cs-137 fallout-

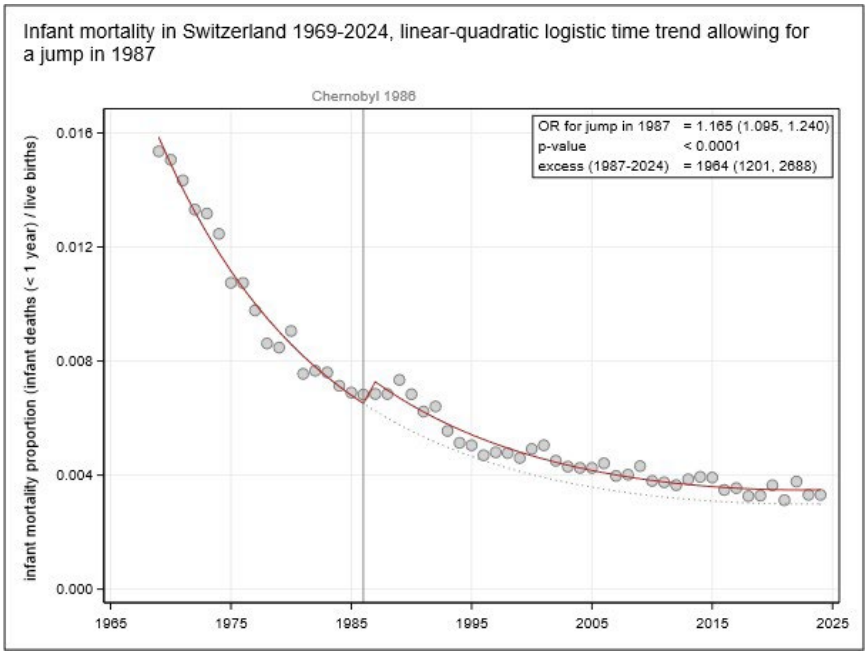


Figure 1: Infant mortality proportion in Switzerland and solid red linear logistic trend line allowing for a jump in 1987; the dotted line indicates the trend under the null hypothesis of no trend change from 1986 onward.

Table 2: Switzerland: Canton-specific infant deaths and live births (1969 - 2024), Chernobyl Cs-137 fallout (kBq/m^2), and canton-specific jump heights 1986/1987 in infant mortality trends.

Canton	Deaths at age < 1 year	Live births	Cs-137 fallout (kBq/m^2)	Jump OR	Log OR	Standard error	Weight inverse variance
Aargau	2,051	349,475	4.72	1.294	0.258	0.113	78.45
Appenzell IR	97	10,916	8.50	1.415	0.347	0.476	4.42
Appenzell OR	224	33,286	10.31	1.642	0.496	0.288	12.06
Bern	3,641	571,382	2.70	1.120	0.114	0.091	121.83
Basel-country	935	149,601	2.51	0.957	-0.044	0.152	43.11
Basel-city	712	104,766	2.50	1.627	0.487	0.192	27.18
Fribourg	1,138	163,166	2.80	1.098	0.094	0.165	36.95
Geneva	1,467	253,315	5.01	1.201	0.183	0.141	50.44
Glarus	159	24,288	3.56	1.343	0.295	0.354	7.96
Grisons	784	111,220	4.63	1.218	0.197	0.154	42.28
Jura	310	44,404	4.73	1.004	0.004	0.271	13.67
Lucerne	1,422	231,316	2.93	1.196	0.179	0.122	67.63
Neuchâtel	753	102,929	5.77	1.121	0.114	0.170	34.72
Nidwalden	170	23,549	2.50	1.082	0.079	0.330	9.21
Obwalden	130	21,329	2.50	1.667	0.511	0.429	5.44
St. Gallen	2,033	296,995	7.87	1.254	0.226	0.128	61.42
Schaffhausen	299	43,415	5.17	1.074	0.071	0.264	14.34
Solothurn	1,044	145,022	2.52	1.071	0.068	0.143	49.25
Schwyz	588	85,710	4.42	1.258	0.230	0.218	21.10
Thurgau	904	147,067	10.20	1.059	0.058	0.170	34.64
Ticino	1,148	158,132	10.14	1.334	0.288	0.163	37.87
Uri	197	23,905	2.75	0.614	-0.487	0.318	9.92
Vaud	2,416	405,762	4.65	1.090	0.086	0.115	75.61
Valais	1,353	177,047	2.51	1.034	0.034	0.138	52.74
Zug	378	64,011	5.19	1.666	0.511	0.255	15.34
Zurich	4,969	782,013	5.94	1.130	0.123	0.095	111.98
Switzerland	29,322	4,524,021	4.70	1.165	0.153	0.032	992.56

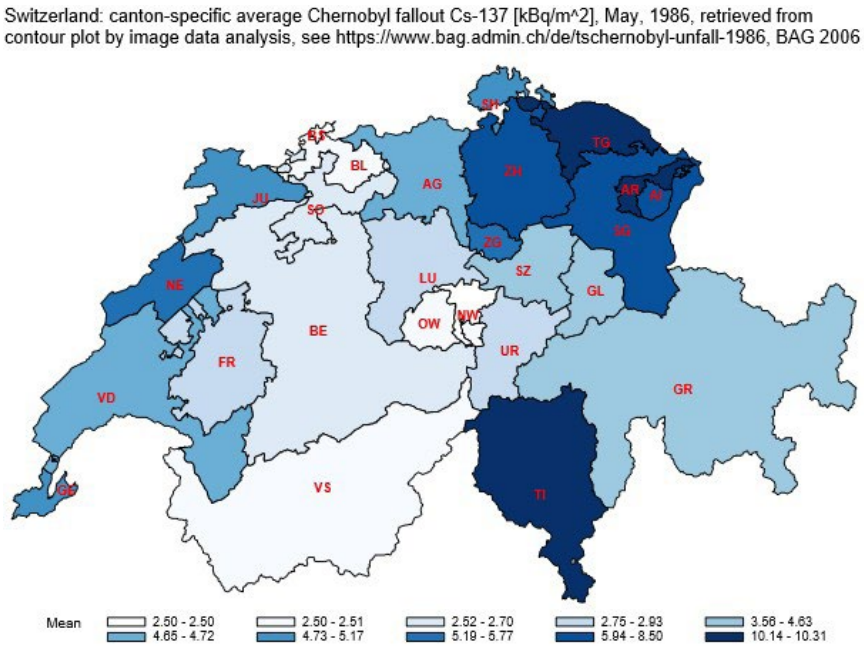


Figure 2: Map of Switzerland: canton-specific average Chernobyl fallout Cs-137 [kBq/m^2] reportedly as of early May 1986, retrieved by image data analysis from the contour plot as published by FOPH 2006.

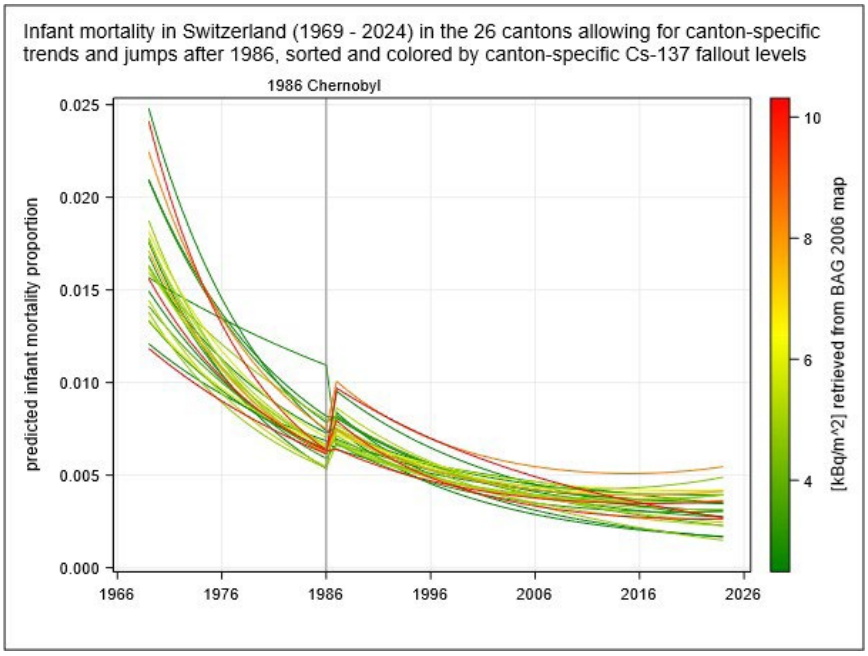


Figure 3: Predicted linear-quadratic infant mortality trends in Switzerland 1969 - 2024 in the twenty-six (26) cantons allowing for canton-specific trends and canton-specific jumps after 1986, sorted and colored by canton-specific Cs-137 fallout levels.

levels in table 2 graphically, and figure 3 shows the canton-specific predicted infant mortality trends with their jumps in 1986/1987, whereby the color gradient of the trendlines is proportional to the average canton-specific Chernobyl fallout.

Ordinary unrestricted inverse variance weighted regression of the log odds of the canton-specific jump heights on canton-specific fallout yields a jump OR of 1.0169 (0.9942, 1.0400), p-value 0.1581 per kBq/m^2, however, with an insignificant intercept at 0 kBq/m^2 p-value 0.2383. Therefore, naturally restricting the regression to intercept = 0, i.e., jump height zero at zero kBq/m^2 fallout, yields a significant dose-response association of the infant mortality jump height OR with fallout: jump OR of 1.0297 (1.0197, 1.0398) per kBq/m^2, p-value < 0.0001. Figure 4 shows the inverse variance weighted cantonal data points and the according un-restricted and restricted regression lines.

Fixed effect logistic regression yields an OR of infant mortality per kBq/m^2 of 1.0288 (1.0176, 1.0401), p-value < 0.0001. Employing canton-specific intercepts and canton-specific fallout levels as random effects and time and time squared as fixed effects, mixed effect logistic

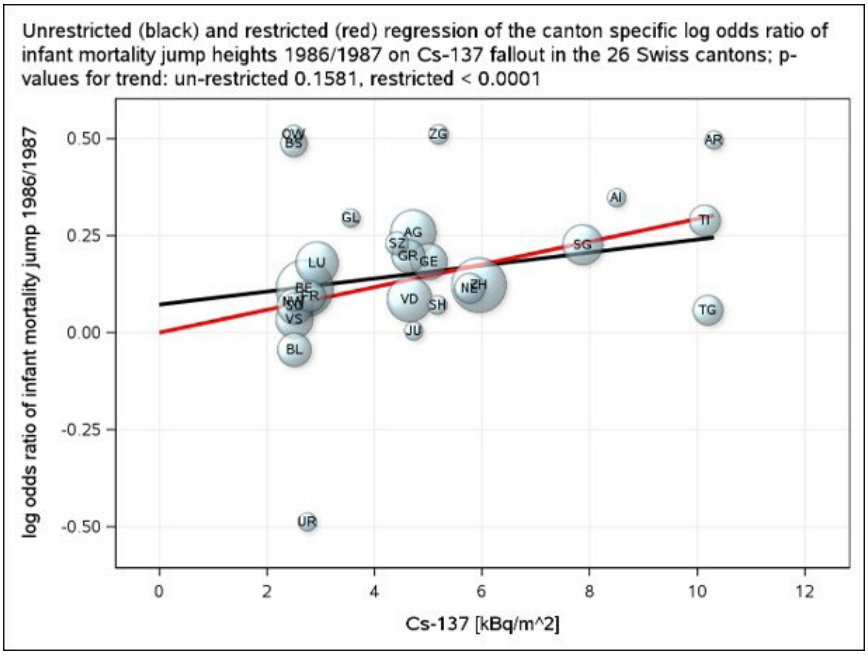


Figure 4: Unrestricted (black) and restricted (red) inverse variance weighted ordinary regression of the canton specific log OR of infant mortality jump heights 1986/1987 on Cs-137 fallout in the twenty-six Swiss cantons; p-values for trend: un-restricted 0.1581, restricted < 0.0001.

Table 3: Parameters, estimates, and pertinent statistics of the four regression techniques assessing a possible dose-response association between Chernobyl fallout and infant mortality in Switzerland.

Method		OR per kBq/m^2	Lower 95% limit	Upper 95% limit	p-value
Inverse variance weighted ordinary regression	Unrestricted	1.0169	0.9942	1.0400	0.1581
	Restricted	1.0297	1.0197	1.0398	< 0.0001
time-linear-quadratic logistic regression	Fixed effects	1.0288	1.0176	1.0401	< 0.0001
	Mixed effects	1.0288	1.0190	1.0387	< 0.0001

regression yields the very same OR compared to ordinary logistic regression with fixed effects, however with a slightly more precise interval estimate: OR of infant mortality per kBq/m^2 of 1.0288 (1.0190, 1.0387), p-value < 0.0001.

Table 3 summarizes the pertinent outcome statistics of the four regression methods applied and outlined above assessing a possible dose-response association between Chernobyl Cs-137 fallout levels in Switzerland and proportionally disturbed infant mortality trends form 1987 onward.

Altogether, 3 of those 4 applied regression techniques demonstrate a highly significant ($p < 0.0001$) positive exposure response association at the level of the 26 Swiss cantons of Chernobyl Cs-137 fallout-levels with the jumps and long-term increases in the infant mortality trends in Switzerland from 1987 onward.

An additional restricted analysis focusing on the six cantons in Central Switzerland, to which considerably radioactively contaminated milk from the canton of Ticino was shipped for food production from May 1986 onwards [37, 39], shows statistically significant higher infant mortality rates ($p = 0.0408$, if analyzed by one-sided test, which would be adequate for this situation) from 1987 compared with the 20 remaining cantons (Figure 5). This observation is consistent with the hypothesis that the consumption of radioactive food made a biologically significant contribution to the jump in infant mortality in Switzerland after 1986.

A fifth regression technique employed involves estimating and testing the potential influence of each covariate on the dose-response relationship, based on a list of 22 possible covariates (effect modifiers, confounders, etc.) (Table 4). The question arises to what extent the associations (strength and significance) presented in table 3 are modulated by possible co-variables, e.g., effect modifiers or confounders. Ideally, effect modifiers are associated with the outcome but not with the exposure, whereas confounders are associated with both the exposure and the outcome. In our situation, time is a typical confounder. Time is associated with the outcome of infant mortality since infant mortality decreases with time. And time is also associated with the exposure: different exposures before vs. after Chernobyl. On the other hand, sex would be an effect modifier if the sex ratio would (ideally) be constant over time but would be associated with the outcome: boys are subject to a considerably higher infant mortality than girls. Table 4 lists the investigated co-variables and their individual influence on the estimate and on the significance (p-value) of the target variable (Cs-137) in the ordinary logistic regression dose response model. In addition to the gender of the deceased children and the mother's age, the strongest effects shown in table 4 include terrestrial and cosmic background radiation. Both radiation components increase infant mortality by approximately 0.3% per nanosievert (nSv)/h. As a main finding it turns out that the dose response associations demonstrated in table 3 are neither inverted, nor annulled by the inclusion of single pertinent co-variables. The dose-response association remains significant whatever co-variable in table 4 is included in the dose response model. This 5th regression technique can thus be seen as a kind of sensitivity analysis.

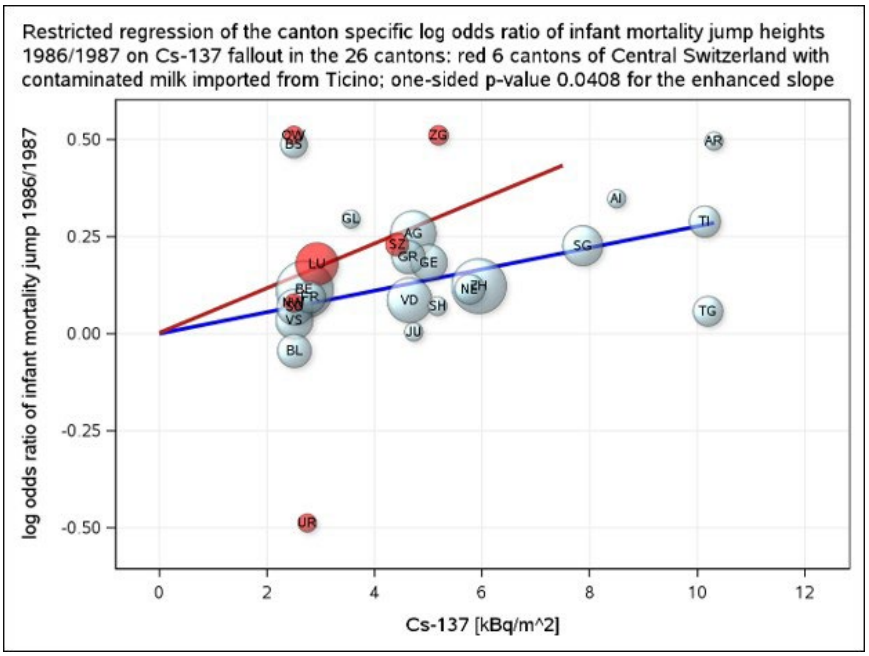


Figure 5: Inverse variance weighted ordinary restricted regression of the canton specific log OR of infant mortality jump heights 1986/1987 on Cs-137 fallout in the 26 Swiss cantons: red 6 cantons of Central Switzerland with radiologically considerably contaminated milk imported after Chernobyl; one-sided p-value 0.0408 for the enhanced slope (red line).

Table 4: Simultaneous effects of single co-variables and the target variable in the ordinary most parsimonious linear logistic regression model: infant deaths/live births = co-variables + target variable + t + t2.

Co-variable: effect modifier or confounder						Target variable: Cs-137 [kBq/m^2]			
Co-variable	**Effective sample size [n]**	**Estimate**	**SE**	**Chi-square**	**p-value**	**Estimate**	**SE**	**Chi-square**	**p-value**
None, i.e., not adjusted, i.e., the reference	-	-	-	-	-	0.0124	0.0038	10.962	0.0009
Sex (female = 0, male = 1)	2912	0.2396	0.0135	315.102	<0.0001	0.0124	0.0036	12.089	0.0005
Age of mother [year]	1092	-0.0944	0.0174	29.497	<0.0001	0.0129	0.0037	11.989	0.0005
Proportion of births to foreign mothers [%]	1430	-0.0019	0.0007	6.517	0.0107	0.0147	0.0038	14.619	0.0001
Unemployment rate [%]	1456	0.0082	0.0103	0.633	0.4261	0.0123	0.0038	10.658	0.0011
Physician per 1000 live births	156	-0.0003	0.0002	1.966	0.1608	0.0123	0.0038	10.746	0.0010
Income [Swiss Francs 1000/ month]	26	-0.0385	0.0208	3.408	0.0649	0.0105	0.0039	7.343	0.0067
GDP [Swiss Francs 100,000/ year]	26	-0.0152	0.0259	0.345	0.5571	0.0125	0.0038	11.136	0.0008
Urbanity [%]	26	-0.0040	0.0048	0.687	0.4073	0.0127	0.0038	11.423	0.0007
Population density [1000/km^2]	26	-0.0064	0.0082	0.599	0.4389	0.0123	0.0038	10.717	0.0011
Terrestrial background radiation [nSv/h]	26	0.0033	0.0006	25.743	<0.0001	0.0090	0.0038	5.657	0.0174
Cosmic background radiation [nSv/h]	26	0.0034	0.0006	28.596	<0.0001	0.0141	0.0037	14.289	0.0002
Sea level [100 m]	26	0.0072	0.0016	19.857	<0.0001	0.0098	0.0038	6.762	0.0093
Radon [Bq/m^3]	26	-0.0004	0.0002	3.022	0.0821	0.0126	0.0038	11.198	0.0008
Inverse distance from Beznau [1/100 km]	26	-0.0202	0.0051	15.751	<0.0001	0.0124	0.0037	11.019	0.0009
Inverse distance from Gösgen [1/100 km]	26	-0.0180	0.0044	16.432	<0.0001	0.0103	0.0038	7.497	0.0062
Inverse distance from Leibstadt [1/100 km]	26	-0.0249	0.0063	15.637	<0.0001	0.0122	0.0037	10.639	0.0011
Inverse distance from Mühleberg [1/100 km]	26	0.0066	0.0098	0.451	0.5021	0.0134	0.0040	11.130	0.0008
Nitrate in groundwater [mg/l]	26	-0.0059	0.0011	28.704	<0.0001	0.0132	0.0037	12.501	0.0004
Nitrogen dioxide [µg/m^3]	26	-0.0033	0.0009	14.502	0.0001	0.0129	0.0037	11.837	0.0006
Lead in soil [mg/kg]	26	0.0007	0.0006	1.299	0.2544	0.0120	0.0038	10.028	0.0015
Cadmium in soil [mg/kg]	26	0.0095	0.0474	0.040	0.8419	0.0124	0.0038	10.963	0.0009
Mercury in soil [mg/kg]	26	0.4352	0.4366	0.9936	0.3189	0.0122	0.00376	10.516	0.0012

It shows, whatever single co-variable is included in the powerful fixed effect logistic regression model does not in principle change the dose-response association between fallout and infant mortality: Therefore, this dose response association is established at an order of magnitude of 1% to 3% mortality increase per kBq/m^2 Cs-fallout in Switzerland after the Chernobyl accident.

Discussion

Based on the observation that infant mortality in Switzerland increased by 10 to 25% after 1986 corresponding to an OR for jump in 1987 of 1.175 (1.102, 1.253) p-value < 0.0001 [33] and considering specific cantonal trends and their changes over time, we were able to demonstrate a dose-response relationship between radiation exposure and infant mortality of approximately 1% to 3% mortality increase per kBq/m^2 of Cs-137 fallout. The individual cantonal jumps in infant mortality play a central role here: in 24 out of 26 cantons, there exists a positive jump ranging from approximately 0.04% to nearly 70%, which corresponds to a Swiss-wide average jump of approximately 16.5% (Figure 1 and figure 3). This confirms previous findings [33, 36]. On the other hand, five different weighted regression methods demonstrated that the individual cantonal increases in infant mortality correlate highly significantly with the average radiation exposure caused by Cs-137 fallout in the individual Swiss cantons (Table 3 and table 4). The study's objective of establishing a dose-response relationship at the ecological level has thus been achieved. Given the extensive previous findings [23-31] the existence of a dose-response relationship was to be expected, although the extent of the specific response on infant mortality was surprising.

Before we address the observed dose-response relation, we first consider the details regarding radiation dose and the aspects of causality.

There is no doubt that estimating radiation exposure across entire regions, let alone for individual people, is a highly complex task [34, 35, 37, 38, 40]. Dose calculations consider both external and internal exposure (primarily through food) to a wide variety of radioisotopes, chiefly Cs-137 and cesium-134, but also iodine-131 and strontium-90. By focusing primarily on Cs-137, international and national radiation protection authorities highlight the crucial importance of this specific radioisotope in terms of biological effects. Nevertheless, it should be borne in mind that, due to the varying properties of radioisotopes (such as physical and biological half-life, radiation spectrum, and tissue affinity), their biological effects must be regarded as highly heterogeneous. Cs-137 can therefore only be considered a practical, but crude, tracer isotope for total radiation exposure resulting from the Chernobyl fallout. Earlier Cs-137 fallout from atmospheric nuclear bomb testing in the 1950ies and 1960ies [25] complicates matters to some degree.

Food contamination and its significance for the food chain can be illustrated using the example of milk. According to the Swiss Farmers' Union [41], around 3 million tons of milk were produced in Switzerland in 1986. From Ticino, the canton with the highest Chernobyl-fallout levels, 120'000 liters of contaminated milk were transported to Central Switzerland for dilution. This course of action was chosen with the idea of protecting the public in accordance with the official regulations in force at the time [37, 39]. This milk was then processed into cream, cheese and butter. Most of the Cs-137 remained in the whey. Unlike in Germany, contaminated whey was not disposed of in Switzerland. Therefore, whilst this entire procedure allowed to reduce the intake of short-lived radioisotopes such as iodine-131, isotopes with longer half-lives, such as Cs-137 and strontium-90, remained in the food chain and thus contributed to the collective radiation exposure in Switzerland to a largely undiminished extent. According to data from the Department for the Safety of Nuclear Facilities [42] – the predecessor of the Swiss Federal Nuclear Safety Inspectorate ENSI – the average individual whole-body effective doses for children aged one year, children up to the age of ten, and adults range from 0.6 to 1.6, 1.0, and 1.1 mSv for the year 1986, respectively. According to Department for the Safety of Nuclear Facilities, however, these dose estimates apply only to the most heavily affected individuals in the hardest-hit regions. Consequently, when calculating the collective radiation dose for 1986, Department for the Safety of Nuclear Facilities used only one-tenth of these calculated radiation doses, resulting in a total of 970 person-Sieverts. By contrast, the FOPH [34, 35] estimates the collective radiation dose resulting from the Chernobyl disaster over the first 20 years at around 3'500 person-Sieverts. The FOPH therefore concludes that the average radiation dose for the Swiss population was approximately 0.5 mSv per person. Furthermore, according to the FOPH, the average radiation dose for the Swiss population in the first year following the accident was 0.2 mSv per person. The personal dose estimates provided by Department for the Safety of Nuclear Facilities and FOPH therefore differ by a factor of approximately 2 for the first 8 and 12 months respectively following 26 April 1986. Surprisingly, this difference is even more pronounced when one considers that Department for the Safety of Nuclear Facilities took all major foodstuffs into account, whereas the FOPH only included the food categories of milk, vegetables and meat, but not, for example, cereals or strontium-90 data for milk.

In the debate on causality, we hypothesize that infant deaths linked to low-dose IR (LDIR, defined by the International Commission on Radiological Protection as doses of IR as below about 100 mSv, and low dose rates as below 5 mSv/h [43]) should be interpreted as stochastic events. Just as it is impossible to attribute individual cases of – e.g. – cancer to LDIR, it is impossible to attribute individual cases of infant deaths to such exposure. The Hill criteria [32] enable a reliable assessment of causality in this classic epidemiological setting.

- The criterion of strength (effect size) is clearly met in the present study: the fact that there has been a sustained increase in infant mortality of around one-sixth in Switzerland since 1986 is highly striking.

- Secondly, consistency (reproducibility) is demonstrated both by the report already cited [36] and by a publication by Körblein [44], which show an increase in infant mortality in Switzerland after 1986. Additionally, a significant increase after 1986 in infant mortality was found in the Ukraine, Belarus, Russia, Finland, Germany, Poland, Sweden [45]. Furthermore, the higher infant mortality rate observed in this study from 1987 onwards in the 6 cantons of Central Switzerland, into which radioactively contaminated milk from the canton of Ticino was imported, is consistent with the hypothesis that the consumption of radioactive food made a biologically significant contribution to the rise in infant mortality in Switzerland after 1986.

- However, the criterion of specificity is only partially met: although a clearly defined age group is identified, this study deals with a non-specific (however most pertinent) condition such as infant death.

- The condition of temporality is sufficiently met: the observed effect (an increase in infant mortality) follows the potential trigger - namely the radioactive fallout - at the estimated and tested turning point in 1986/1987. The fact that a statistically significant effect can be detected as early as 1983 may seem puzzling [36]. A likely explanation for this is provided by the fact that, according to the International Atomic Energy

Agency, a partial core meltdown noticed only by selected personnel had already taken place at the Chernobyl nuclear power station in 1982 [46 – 48]. This accident, classified as category 5 on the International Nuclear and Radiological Event scale, was also associated with massive environmental radiation. Nevertheless, the most pronounced effect with the highest statistical significance can undoubtedly be observed at the 1986/1987 change-point (corresponding to the Chernobyl accident on 26 April 1986) [36].

- The demonstration of a dose-response relationship meets the most stringent Bradford-Hill criterion – this was established in the present study. Additionally, an observation of a dose response was published already by Mangano et al. [49]: He reported that subsequent to the shutdown of 8 US nuclear power plants after 1987 strontium-90 levels in local milk declined sharply as did deaths among infants – especially in the context of birth defects – who had lived downwind of each plant. Similarly, cancer incidence in children younger than 5 yr of age fell significantly after the shutdowns.

- Biological plausibility is supported by the fact that IR hinders reproduction. Formally, radiation exposure associated with infant deaths can occur before conception, *in utero,* or during the first year of life, or as a combination of exposures at these stages. Thus, as mentioned by International Physicians for the Prevention of Nuclear War in 2006, a wide range of resulting medical conditions may contribute to an elevated infant mortality [50]. According to Yablokov et al. [45] main causes of infant deaths in the Ukraine after the Chernobyl accident were antenatal pathologies, congenital malformations, respiratory diseases, and infections. Transgenerational radiation impacts [51] may explain pathologies such as congenital anomalies associated with early life impairment. Significant changes in all parameters of cellular immunity were observed in children born to liquidators in 1987 [52]. Stepanova [53] stated that in the Ukraine in the first 2 years following the disaster, significant immune deficiency was observed in children exposed to radiation *in utero.* Immunosuppression is a well-known consequence of exposure to IR. Studies from the Ukraine, Belarus and Russia showed suppressed immunity both after high and low doses of IR due to Chernobyl fallout [45]. Based on a review of some 150 scientific publications, Savyna and Khoptynskaya [54] concluded that impaired thymus function plays the primary role in post-irradiation pathology of the immune system. Petrova et al. [55] report that antibody production and neutrophil activity were significantly lower in newborns during the first year of their lives in areas where levels of Cs-137 exceeded 5 Ci/km². Furthermore, Busby [56] documented an increase in cases of leukemia among infants born in Europe following exposure to very low doses of IR due to the Chernobyl accident, which may have contributed to the rise in ID after 1986. Of particular interest is the finding by Röösli et al. [36], according to which the highest rise in infant mortality in Switzerland after 1986 is observed during the post-neonatal period (deaths occurring between the 2nd and 12th month). Death during this very period may be linked to impaired immune function, leading to an increased susceptibility to fatal infections.

- Furthermore, arguments in favor of coherence and analogy are supported for decades by further significant dose-response observations of the harmful effects caused by low-dose IR on reproductive capacity [23 – 31].

- Finally, the criterion of experimental evidence is not applicable for stochastic events in this context.

How do our findings compare, in terms of magnitude, with the levels of natural radiation, and how do they align with existing knowledge of dose-response relationships – particularly the patterns of cancer risk – associated with low-level IR? According to the Swiss Federal Nuclear Safety Inspectorate ENSI [57] the average annual natural radiation dose amounts to around 4.3 mSv, with most of the exposure caused by cosmic and terrestrial radiation. A nearly identical figure of 4.4 mSv annually is given by the FOPH [58]. The natural background radiation dose in Switzerland over a 20-year period is therefore approximately 88 mSv per person which is more than two orders of magnitude higher than the already mentioned average individual dose of 0.5 mSv in Switzerland resulting from the Chernobyl fallout. This finding documents that even very low additional doses of IR – far below natural radiation doses – significantly increase the risk of infant mortality. At the same time, we must not overlook the possibility that official estimates of exposure and radiation dose following Chernobyl could be too low due to conflicts of interest among the relevant authorities [59]. A parallel finding is well known in oncology: according to the now-accepted linear no-threshold model [11], radiation is considered harmful to health at any dose, with no assumption of a threshold dose below which no adverse health effects are expected. Interestingly, ongoing research by a group of scientists at the Institute of Social Medicine in Bern, Switzerland [20, 21] in the field of pediatric oncology has confirmed the highly probable causal role of natural radiation in spontaneous childhood malignancies: Around one third of leukemias and brain tumors can be attributed to background radiation. These new scientifically based findings fundamentally contradict the nowadays outdated dogma that the "dose from the Chernobyl accident, with a range from 0.2 to 5mSv, is insignificant and the same can be said for its implications for public health in Switzerland" [37].

As regards the extent of the biological effects, this study suggests, based on the absolute number of deaths, that the risk of radiation-induced infant mortality is significantly higher than the lifetime risk of radiation-induced cancer mortality. Based on Swiss population figures for 1986 and recommendations by the International Commission of Radioprotection, the FOPH calculated that around 200 radiation-related cancer deaths are to be expected due to the Chernobyl fallout [34, 35]. However, as far as case numbers are concerned, we have identified statistically almost 2'000 additional radiation-related deaths among infants between 1986 and 2024. Even if a more appropriate – that is, higher – risk factor for cancer mortality is used, as suggested by the World Health Organization [60], the number of Chernobyl-related infant deaths in Switzerland is five times higher than the number of Chernobyl-related cancer deaths at any age. This circumstance must serve as a reason to fundamentally review and amend the current radiation protection guidelines – particularly about contamination of food by IR. In particular, Swiss governmental regulations aimed in the past at removing most limit values for radionuclides in non-emergency situations and at introducing specific limit values in the event of a crisis. The reasons for these changes are not comprehensible. In contrast, the lack of limits hinders the enforcement of the radiation law [40].

Conclusion

The results indicate that the increase in infant mortality observed in Switzerland after 1986 correlates with the canton specific exposure to Cs-137 fallout by the Chernobyl nuclear power plant disaster. The demonstration of a dose response at the ecological level fulfils one of the most important criteria for causality. This finding is consistent with the harmful effects of low doses of IR on reproduction, which have been recognized for decades. The extent of the risk of radiation-related infant mortality far exceeds that of the officially reported risk of cancer caused by IR. Radiation protection legislation should take these findings

into account in future, particularly in the food sector. Furthermore, a nation-wide census-based individual-level cohort study could provide more precise further insights.

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None.

Conflict of Interest

None.

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