Original Scholarship

Long-Term Consequences of the Chernobyl Radioactive Fallout: An Exploration of the Aggregate Data

FRANCESCA MARINO and LUCA NUNZIATA

University of Padua

Policy Points:

- Policymakers should invest more on researching the long-term health effects of low-ionizing radiation exposure, as we are far from reaching a consensus on a topic that is of enormous importance for public health and safety.
- Public policies such as those limiting the import of contaminated food from areas hit by a radioactive disaster or those regulating the resident population's access to such areas should follow a precautionary approach.
- Neoplasm diagnosis and medical care should be designed in order to take into account the possible role of long-term, low-dose radiation exposure.
- Health care policies should provide effective screening and prevention strategies with a specific focus on the regions that were hit most severely by the Chernobyl nuclear fallout.
- Health care expenditure should be targeted, taking into account the geographical dispersion of the fallout in order to attenuate its possible effect on neoplasm incidence.

Context: This study investigates the association between the radioactive ¹³⁷Cesium fallout originated by the 1986 Chernobyl nuclear accident and dispersed over Western Europe, as a result of a combination of radioactive cloud passage days and rainy days over a 10-day period, and long-term health patterns and related costs. Since the half-life of ¹³⁷Cesium is 30.17 years, part of the

radioactivity in the affected regions is still present today, and it is usually still detected in the food chain, although at lower concentration levels.

Methods: We match longitudinal data on neoplasm incidence over the time span 2000-2013 in a number of European regions not immediately adjacent to Chernobyl with the randomly distributed levels of cesium deposition after the nuclear disaster in order to assess whether we can detect an association with the long-term health effects on the European population through a random effects model.

Findings: Considering 3 levels of fallout deposition—low, medium, and high—hospital discharges after treatment for neoplasms are, respectively, 0.36, 0.44, and 0.98 discharges over 100 inhabitants higher compared to regions with no fallout, with the population average being around 1.7 hospital discharges by neoplasms over 100 inhabitants. We checked the robustness of our findings to a number of tests including a placebo simulation and different model specifications.

Conclusions: Radioactive fallout is positively associated with a higher incidence of hospital discharges after treatment for neoplasms almost 30 years after its release, with larger effects in regions where the radioactivity was more intense. Our estimates are comparable to the findings of the largest-scale study on the long-term health effects of continuous low levels of radiation exposure among workers in the nuclear industry and suggest that more research is needed on this topic, given its enormous importance for public health and safety.

Keywords: Chernobyl nuclear accident health, radioactive fallout, neoplasm, epidemiology of radiation-induced cancer.

THE HEALTH CONSEQUENCES OF THE EXPOSURE TO radioactive fallout resulting from the Chernobyl nuclear disaster in 1986 are still debated in the medical literature, as reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).¹⁻³ The lack of consensus can be explained by the intrinsic difficulty in identifying the causal effect of exposure to radioactive fallout on health patterns decades later, especially in those regions in Europe that were only moderately affected by the plume, and where the radioactive exposure was not as severe as in the areas immediately adjacent to the disaster site. Such low levels of exposure may, however, have relevant health consequences in the long run in cases of prolonged exposure, as shown by the decades-long extensive study of workers in the nuclear industry.⁴

After the explosion of the Chernobyl nuclear reactor, the continuous release of radioactivity into the atmosphere over a 10-day period and the accompanying meteorological conditions resulted in a scattered dispersion pattern across Europe. Considering that the half-life of ^{137}Cs (^{137}Cs) is 30.17 years, part of the radioactivity in the affected regions is still present today, and it is usually still detected in the food chain, although at lower concentration levels. For example, a report by the Regional Agency for Environmental Prevention and Protection of the Veneto region in Italy (a region only mildly affected by the fallout in 1986) detected up to 0.12 Bq/l ^{137}Cs concentration in milk in 2016, 0.36 Bq/kg in beef, 0.14 in vegetables, 12 in mushrooms, 2.9 in strawberries and 1.8 in blueberries (the units of measure for the amount of radiation emitted by a radioactive material are, in the SI and conventional system, respectively, *becquerels*, or Bq, and *curies*, or Ci).⁵

Most European regions were exposed to the radioactive fallout in a random fashion, as a result of the combination of winds and precipitation in the days following the disaster, producing a natural experiment setting in which the random treatment of radiation exposure should in principle be uncorrelated with any potential confounding factor at the individual or regional level. If that were the case, any association between the fallout and health could be interpreted as causal. However, in reality things may not be so straightforward, for a number of reasons. First of all, the geographical dispersion of the fallout covered most of the European continent through a finite number of regional clusters, whose characteristics can be observed only in part. The fallout deposition may therefore spuriously correlate with unobservable confounding area characteristics (eg, prevalence of a genetical predisposition to develop certain diseases, tendency to have a healthy lifestyle and diet, average skills of physicians and doctors or quality of the health care system in general). Moreover, the areas under investigation may be either too small to provide a precise match between deposition, actual exposure, and health patterns, or large enough but limited in number. As a consequence, despite the quasi-experimental nature of the fallout deposition, unobservable confounding factors may still play a role in both individual-level and aggregate analyses. For example, the effect of radiation exposure may interact with other factors and conditions, resulting in complex patterns that can be hard to detect.

Second, the information on radiation exposure is usually inferred through the matching of residency with the geographical dispersion

of the fallout. This may result in an imprecise matching due, for example, to the geographical detail and numerical approximations in the fallout dispersion measurements, and typically does not account for the individual mobility across areas and the ingestion of contaminated food originated elsewhere.

Third, the information on health outcomes, both at the individual and aggregate levels, may be imprecise, or it may be collected in a nonhomogeneous fashion, resulting in limited comparability.

As a result, we typically cannot precisely observe the exact amount of radiation exposure at the individual level, before and after the disaster, and the exposed individuals' living conditions over the decades. These problems complicate the job of the empirical researcher.

Some recent country-specific studies have focused on collecting more precise data on fallout deposition to be matched with better estimates of individual-level exposure and observed health outcomes in countries such as Finland and Sweden that were hit by the plume and where health registries and fallout maps are detailed enough to allow such analysis.⁶⁻⁸ These investigations provide a well-crafted framework to investigate the causal impact of the Chernobyl disaster on health in the medium to long term. However, their mixed findings are an indication of how even in such detailed individual-level analysis some of the problems outlined earlier may still be present, especially considering that the smaller the area under investigation is, the higher the probability that the radioactive fallout deposition in the area of residence may not correspond to the actual exposure to radioactive agents, for example, because of the ingestion of food and water contaminated elsewhere.

In this study we adopt a different approach that can be considered complementary to the previously cited studies. Our aim is to provide an exploratory analysis of whether the aggregate data can reveal an association between the Chernobyl fallout and health patterns. We concentrate on aggregate regional data in order to exploit the fact that some of the problems outlined here may be attenuated by the regional averaging. However, since we are aware of the role of potential confounding factors at the regional level, we also provide an extensive battery of robustness and falsification checks to investigate how reliable our findings are and what we can and cannot learn from this type of analysis, helping set a guidance for further research.

Using data provided by the *Atlas of Caesium Deposition on Europe After the Chernobyl Accident*, published by the European Commission,⁹ we

compare the pattern of health consequences of radioactivity about 30 years after the accident in several European regions that were characterized by heterogeneous ^{137}Cs fallout deposition.

We find that the regions that experienced more intense radioactive fallout than others are characterized by a higher incidence of neoplasms today. The association is sizable, statistically significant, and increasing with the intensity of the fallout; it does not depend on gross domestic product (GDP) per capita, population density, age patterns, distance from Chernobyl, life expectancy in 1985, the environmental characteristics of the regions, or the observable characteristics of the health care sector. It is also robust to a number of robustness and falsification checks, including dropping observations from each single country or excluding smoking-related neoplasms from the analysis. In addition, a placebo test confirms that our findings are unlikely to result from randomness. Finally, we show that our findings are comparable with those of Richardson et al.,⁴ with our models predicting larger point estimates for low doses of external radiation and similar effects for higher doses. Taking our estimates at face value, we show that such higher levels of hospital discharges are associated with a substantial increase in curative-care expenditure in affected countries. The article is complemented by an extensive online appendix.

The Chernobyl Nuclear Disaster as a Natural Experiment

The notorious accident at the Chernobyl nuclear power plant happened on April 26, 1986, during the scheduled shutdown of one of the plant's least powerful reactors. Even though some 30 years have passed since the accident, the debate about its health effects on the populations of the affected countries continues.

According to UNSCEAR's official reconstructions, the explosion destroyed the core of the reactor and the building that contained it.¹ Besides the immediate release of radioactive materials in the proximity of the plant, the disaster resulted in a diffused release of nuclear particles over vast territories for several days.²

Various factors contributed to the disposition of radionuclides in the soil, with 4 main mechanisms determining the conditions of the fallout: the release of radioactive materials over a 10-day period; the height

dispersion of radionuclides inside the plume, depending on their form and weight; winds blowing in different directions on different days interacting with plume heights;¹ and the plume's exposure (or not) to rain during its passage over each territory.¹⁰ The combination of these factors created the conditions of a random deposition of the radioactive fallout on European regions.

The significant differences in disposition of radionuclides in European soil are explained by the presence or absence of precipitation during the passage of the cloud. The composition of the cloud, depending on the chemical forms of the radionuclides and the distance from the explosion, also affected how those elements were deposited on the ground. When deposition was not caused by rainfall, the radioactivity levels were lower but the presence of radio-iodine isotopes was more intense. In the areas where disposition was caused by rain, the fallout composition was similar to that of the originating radioactive cloud. The result was a fragmented deposition of radionuclides over the European soil with different concentrations of ^{137}Cs . Surveys undertaken in May 1986, immediately after the accident, using dose rate meters and airborne gamma spectrometers, measured the soil deposition of ^{137}Cs in several European and Asian countries. Of the radionuclides dispersed by the fallout, ^{137}Cs was comparatively easy to measure and of radiological significance, especially considering its long radiological half-life.¹⁰

A ^{137}Cs soil deposition greater than or equal to 37 kBq per square meter qualifies the area as officially contaminated according to UNSCEAR.² This level corresponds to a yearly radioactivity absorption of 1 millisievert (mSv) during the first year after the accident, that is, the yearly limit of radioactivity absorption prescribed in the United States and Canada, and about 10 times the deposition from global fallout (in the SI and conventional system, respectively, the radiation absorbed by an individual is measured in *gray*, or Gy, and *rad*, whereas the biological impact of exposure, which depends on the type of radiation, is measured in *sievert*, or Sv, and *rem*). Belarus, Russia, and Ukraine were the most severely impacted countries; according to the data released by the European Commission, they received 30%, 23%, and 18% of the estimated ^{137}Cs deposition from the nuclear accident, respectively.⁹ However, many other European countries, including Finland, Sweden, Romania, Germany, and Austria, experienced high levels of ^{137}Cs concentration as well.

Since ionizing radiations are among the environmental extrinsic factors that constitute a major determinant of the probability of developing neoplasms, since they cause DNA damage,¹¹ the health consequences of the Chernobyl accident have been widely discussed in the medical literature, and the accumulation of knowledge about the long-term health effects of the accident is an ongoing process.¹⁻³ Many studies have concentrated on the health implications for the populations that lived close to the site of the accident in Belarus, Russia, and Ukraine.^{12,13} A report by the European Commission suggests that the accident may have caused an increase in the incidence of thyroid cancer cases in the European countries that were hit by the radioactive fallout.⁹ Unlike ¹³⁷Cs, which is characterized by a half-life of 30 years, iodine isotopes like ¹³¹I have a half-life of 8 days. Nevertheless, they have been shown to be an important factor in explaining the incidence of thyroid neoplasms in people who were directly exposed to the explosion or who were living in heavily contaminated regions in the days immediately following the disaster.

Ionizing radiation is known to cause most types of cancers¹⁴; however, a unanimous agreement over the broad health consequences for the populations in areas contaminated by the cesium fallout has not been reached yet. One immediate reason for the lack of consensus could be the long latency periods needed to detect the effects. Baverstock and Williams noticed how research on the topic had focused primarily on the effects of iodine exposure, neglecting the potential effects of solid cancers and non-cancer health effects that could appear even decades after the explosion, as happened in Japan after the atomic bombs were dropped on Hiroshima and Nagasaki.¹⁵ Besides the immediate exposure to the radioactive plume and the inhalation of the related radionuclides, the 2 main channels of contamination for people who were living in the areas affected by the fallout could be the continuous radiation exposure from radionuclides deposited in the soil and ingestion of contaminated food and water. The need to study Chernobyl-related health outcomes long after the explosion depends on the characteristics of the illnesses under scrutiny: if the effect on the populations of Belarus, Russia, and Ukraine was a clear increase in thyroid neoplasms and leukemia, effects on other types of solid cancers may manifest over the longer term.

Cardis et al. estimated an increase in neoplasms in Europe that may be attributable to radiation exposure after Chernobyl,¹⁶ although the predicted increase was very small at the time of the study and subject to substantial uncertainty, especially considering the limited knowledge

of the dose-response relationship when the doses of radiation are very low, like in most European countries after Chernobyl. The assumption behind these predictions is that radiations can affect individuals' health even at very low doses through continuous absorption of radionuclides deposited in the soil and ingestion of contaminated foods. The authors emphasize that, because of long latency periods, we may observe an increase in all cancer cases long after the disaster, with only 14% of the total excess cases predicted to 2065 occurring in the first 20 years after the disaster. Jaworowski criticizes the use of this linear-no-threshold approach to estimate the effect of absorbed radiation on health, claiming that no increase in neoplasms took place after the disaster.¹⁷ Cardis and Hatch provide a review of the evidence on the health consequences of the Chernobyl accident with a particular focus on the most affected countries, ie, Belarus, Russia and Ukraine, calling for further investigation of the long-term effects on the involved populations.¹⁸ Similar conclusions can be found in Moysich et al.¹⁹

Other studies find evidence in favor of an increase in the incidence of neoplasms in Sweden based on the recorded ¹³⁷Cs fallout intensity. Using data up to 1996 and comparing 8 Swedish counties, some severely impacted by the fallout and some not, Tondel et al. found an excess relative risk of total neoplasm incidence of 0.11 per 100 kBq/m².²⁰ Tondel et al. expand the study to 1999 and confirms the correlation between the total incidence rate of neoplasms and the amount of radioactive fallout.²¹ Both studies account for possible confounding effects, such as age, population density, and some proxies for overall incidence of neoplasms. A more recent Swedish cohort study, taking into account the exposed individuals' changes in residence in the first 5 years after the incident and controlling for pre-Chernobyl cancer incidence, reports a significant effect of the fallout on the incidence of neoplasms, with point estimates increasing with the intensity of the fallout.⁸ This study is a refinement of an earlier study by the same authors that did not detect any significant effect of the fallout on cancer incidence using the exposition in 1986 only.²²

A recent study of Finnish data, with detailed information on radiation exposure across a grid of 8-by-8-square-kilometer cells and shielding by type of housing, dividing the population into 4 exposure groups, reports instead no significant effects of the fallout on neoplasm incidence after an initial latency period and considering as outcome any forms of neoplasm, except those located in breast, prostate, and lung.⁶ However, when the

effect is reassessed on the same data for different types of cancer, a significant effect is found on colon cancer among females.⁷

An important cohort study that is relevant for our purposes is the International Nuclear Workers Study (INWORKS), which provides an extensive analysis of the effects of occupational exposure to ionizing radiation on cancer deaths among 308,297 workers in the nuclear industry in France, the United Kingdom, and the United States.⁴ The study covers the largest, oldest, and most informative cohort of nuclear industry workers ever analyzed in the literature. These workers are typically exposed to low-dose external radiation levels for a prolonged period of time in a similar fashion to individuals subject to a low to moderate fallout after a nuclear accident. The study findings highlight a linearly increasing effect of radiation exposure on mortality for all solid cancers, with a cancer risk per unit of radiation dose that is in line with estimates derived from studies of Japanese atomic bomb survivors, despite the fact it is commonly thought that high radiation doses are more harmful than prolonged low-dose-rate exposures.

Exposure to the Chernobyl nuclear accident and to the consequent fallout has been exploited by other authors to assess its effect on various outcomes. Danzer and Danzer analyze Ukrainian data and estimate the effect of being exposed to the nuclear disaster on life satisfaction, finding that individuals more exposed to the accident are more likely to show higher depression and trauma rates 20 years later compared to those in areas with less exposure.²³ The study by Lehmann and Wadsworth shows that Ukrainians living in the areas that received the highest levels of radiation have a worse perception of their health status and they are more likely to have worse labor-market outcomes than those with less exposure.²⁴

For what concerns Western European countries, Almond et al. show that prenatal exposure to radioactive fallout in children born in Sweden in 1986 may have impaired their cognitive abilities later in life.²⁵ Similar effects are detected by Black et al. using variation in radioactive exposure throughout Norway resulting from the abundance of nuclear weapon testing in the 1950s and early 1960s.²⁶ Along similar lines, Halla and Zweimüller examine the compensating investment behavior of parents as a response to a human capital shock from exposure to the Chernobyl fallout in Austria.²⁷

Summarizing all of these findings, we conclude that a body of evidence is emerging that suggests significant increases in neoplasms and

secondary effects not only in Belarus, Russia, and Ukraine, but also in other European countries that were reached by the radioactive plume. The intensity of these effects is still debated and a consensus has not yet been reached. Our aim is to contribute to this debate by examining the aggregate evidence on health patterns across European regions 30 years after the Chernobyl accident. To our knowledge, this is one of the first attempts to investigate the relationship between the Chernobyl fallout and health patterns using aggregate data collected in those regions that were not immediately adjacent to Chernobyl.

Our data on the concentration of ^{137}Cs on European soil are gathered from the information provided by the *Atlas of Caesium Deposition on Europe After the Chernobyl Accident*, published by the European Commission. From these data we construct a set of dummy variables that indicate the intensity of the fallout for each European region in our sample. The first dummy (D_{F1}) indicates fallout deposition of 2-10 kBq/m², the second dummy (D_{F2}) is 10-40 kBq/m², and the third (D_{F3}) is greater than 40 kBq/m². However, some areas have only spotty ^{137}Cs concentrations greater than 40 kBq/m², while other areas have been widely affected. For this reason in 1 specification we use a fourth dummy, D_{F4} , to distinguish the regions that recorded a ^{137}Cs soil deposition greater than 40 kBq/m² in more than 50% of their territories (Supplementary Table S.1). Our sample consists of those European regions for which homogeneous information on the incidence of neoplasms is available from Eurostat (see the next section for details).

Our estimated baseline model on the longitudinal data is:

$$\begin{aligned} \text{Health}_{jt} = & \alpha_0 + \alpha_1 D_{F1j} + \alpha_2 D_{F2j} + \alpha_3 D_{F3j} \\ & + \alpha_4 X_{jt} + \alpha_5 \lambda_j + \varepsilon_{it} \end{aligned} \quad (1)$$

where X_{jt} is a vector of time-varying controls for each region j , including GDP per capita, population density, the proportion of residents aged over 60, and a set of health care sector characteristics, and λ_j is a random component to account for unobservable regional characteristics. In addition to the random effects model presented earlier, in our baseline tables we also report our estimates under 2 alternative specifications: a pooled ordinary least squares (OLS) regression specification on the longitudinal data (excluding random effects) and an OLS specification on the time averages by country, using a much smaller number of observations.

In principle, the random nature of the cesium deposition after the accident created the conditions of a natural experiment in that the fallout deposition resembles the experimenter's random treatment allocation. Indeed, the literature suggests that most European citizens did not engage in any particular protective action after the disaster and, if present, the countermeasures were only temporary, resulting in a homogeneous long-term behavioral response of the affected and unaffected areas.²⁸⁻³¹ As a result, our dummy variables of interest should be uncorrelated with the stochastic component ε_i of model 1 and the estimated coefficients may be given a causal interpretation. Nevertheless, especially considering the small number of observations in our sample, we cannot exclude that some unobserved factors may correlate with the fallout dummies. As a result, we control for a number of time-varying confounding factors, and we model unobserved regional characteristics through a random component when we use longitudinal data. We also provide a battery of robustness checks in an attempt to check whether our findings are spurious or determined by chance.

The Data

In addition to the data on the radioactive fallout in Europe, our analysis is based on regional-level health data from Eurostat.³² Since neoplasms are the most frequent form of illness associated with exposure to radioactivity, we focus on the number of hospital discharges after treatment of neoplasms, standardized for resident population, observed in a large number of European regions characterized by a certain degree of homogeneity in cancer-related treatment and diagnosis practices. The regions belong to 13 European countries—Austria, the Czech Republic, Denmark, Estonia, France, Germany, Ireland, Latvia, Lithuania, Luxembourg, Netherlands, Portugal, and Spain—for a total of 80 regions. The pool of regions is a balanced mix of areas with varying degrees of fallout intensity.

Our measure of health is objective, rather than self-reported, and it is aggregated at the regional level. By adopting an aggregate measure of health at the regional level, we can provide a comparatively precise match between the average fallout and health outcomes that would be difficult to achieve using individual-level data. Indeed, not all of the inhabitants in the regions were exposed to the fallout in the same way.

However, these differences are likely to cancel out when we consider regional averages. In addition, the wide extension of the geographical area under study allows us to overcome some of the possible limitations of country-specific studies that are confined to much smaller areas where the treatment of external exposure to radioactivity may be confounded if, for example, food and water supplies from a contaminated area are accessed by individuals living in less contaminated areas. In that case the differences in external exposure across areas, however well defined, may be smaller than the actual total exposure. In our data, instead, we compare the average per capita incidence of neoplasms across regions that are far apart and received very different amounts of radioactive fallout, possibly reducing the importance of the problems outlined. We consider the total number of hospital discharges for neoplasms using the *International Statistical Classification of Diseases and Related Health Problems*, 10th Revision (ICD10 code), focusing on the diseases coded C00-D48. In some robustness checks we exclude neoplasms related to smoking or other unhealthy behavior. The measures are standardized as percentages of the resident population (ie, the number of hospital discharges by neoplasms over 100 inhabitants). In our analysis we use the annual longitudinal region-specific hospitalization data as well as the regional averages over the period 2000-2013 in order to eliminate short-term nuisance. Regional data are aggregated at the Nomenclature of Units for Territorial Statistics (NUTS) 2 level whenever possible. (See the online Appendix for further details on data construction.) We also use the information on deaths by neoplasms over 100,000 inhabitants, provided by Eurostat for the period 2000-2010.

We also observe regional GDP per capita, population density, the proportion of residents aged over 60, the tendency toward hospitalization, the number of physicians or doctors, and the number of beds in hospitals at the regional level, all of which can affect health patterns in general and the neoplasm incidence in particular at the regional level. All variables are provided by Eurostat. Other controls include the regions' distance from Chernobyl, longitude, life expectancy measured at the national level in 1985 (ie, before the nuclear disaster), proportion of wooded areas in the region, and health care expenditure by financing agent and by function at the national level. Supplementary Table S.2 contains a detailed description of data definitions and sources. Summary statistics are displayed in Supplementary Table S.3. The geographical

Figure 1. Fallout Dummy Specification [Color figure can be viewed at wileyonlinelibrary.com]

representation of the dummies created from the data on the radioactive fallout's dispersion is displayed in Figure 1.

Empirical Findings

Baseline Model

Table 1 reports the estimated regressions, under 3 alternative specifications: (1) a pooled OLS model in which we retain all annual observations on regional hospital discharges; (2) a random effects model on the resulting longitudinal data, in which we control for regional unobservable characteristics through a random component; and (3) an OLS cross-sectional specification in which all variables are expressed as time averages in order to eliminate short-term nuisance. The baseline specifications in the first 3 columns include 3 dummies for the different degrees of the observed fallout intensity, whereas the last 3 columns in

Table 1. Fallout Effect on Hospital Discharges, Different Fallout Specifications

	(1) Pooled OLS	(2) Random Effects	(3) T.A. OLS	(4) Pooled OLS	(5) Random Effects	(6) T.A. OLS
D_{F1}	0.518*** (0.0422)	0.587*** (0.152)	0.556*** (0.174)	0.503*** (0.0421)	0.581*** (0.150)	0.543*** (0.174)
D_{F2}	0.829*** (0.0366)	0.685*** (0.133)	0.952*** (0.137)	0.808*** (0.0374)	0.682*** (0.131)	0.936*** (0.140)
D_{F3}	1.379*** (0.0640)	1.368*** (0.223)	1.460*** (0.226)	1.181*** (0.0643)	1.165*** (0.236)	1.279*** (0.228)
D_{F4}				2.136*** (0.0520)	2.101*** (0.117)	2.146*** (0.124)
GDP	0.320*** (0.0403)	0.187 (0.212)	0.348** (0.155)	0.265*** (0.0372)	0.156 (0.199)	0.292** (0.144)
Population density	0.359*** (0.0267)	0.393*** (0.0724)	0.363*** (0.107)	0.380*** (0.0276)	0.403*** (0.0726)	0.386*** (0.116)
Proportion 60+	9.301*** (0.530)	2.565* (1.325)	8.901*** (2.072)	9.548*** (0.527)	2.904** (1.315)	9.148*** (2.079)
Medical obs.	0.140 (0.155)	0.0137 (0.459)	0.107 (0.399)	0.201 (0.155)	0.0160 (0.447)	0.171 (0.393)
Doctors	1.162*** (0.250)	0.917*** (0.342)	1.019 (1.010)	1.081*** (0.240)	0.925*** (0.337)	0.926 (1.008)
Non-curative beds	0.600*** (0.149)	0.943*** (0.253)	0.718 (0.534)	0.667*** (0.149)	0.974*** (0.258)	0.779 (0.531)
Observations	1,021	1,021	80	1,021	1,021	80
R^2	0.691	0.600	0.739	0.716	0.633	0.761
Number of id		80			80	

Robust standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Baseline fallout dummy specification: F1 Fallout >2 kBq/m² and <10 kBq/m², F2 Fallout >10 kBq/m² and <40 kBq/m², F3 Fallout >40 kBq/m², F4 Fallout >40 kBq/m² (more than 50%). Dependent variable expressed in hospital discharges over 100 inhabitants. Baseline controls: GDP per capita, population density, proportion of population aged over 60, and per capita number of hospital discharges by medical observation and evaluation for suspected diseases and conditions, number of doctors in the area and number of available non-curative-care beds in the area, all standardized for 100 inhabitants. Results are obtained through pooled OLS model (columns 1 and 4) with year fixed effects (not reported), random effects model with robust standard errors (columns 2 and 5) with year fixed effects (not reported), and OLS model using time averages (T.A.) over 2000-2013 and robust standard errors (columns 3 and 6).

the table also include a fourth dummy for the 2 regions where the fallout was most severe, Upper Austria (Oberösterreich) and Salzburg.

In all specifications we control for GDP per capita, population density, and the proportion of residents aged over 60 as well as for health-related controls measured at the regional level. Indeed, some could argue that the higher number of hospital discharges in some regions could be due not to the exogenous fallout but to a greater tendency toward hospitalization in general or a more diffused presence of hospitals in the region. This is controlled for by including the standardized number of hospital discharges from medical observation, the standardized number of doctors, and the standardized number of beds in hospitals not classified as for curative care, to avoid possible endogeneity, since the number of curative-care beds in the regions may respond to changes in the regional incidence of neoplasms. All specifications include robust standard errors.

Our estimates indicate that the radioactive fallout is positively and significantly associated with the incidence of hospital discharges for neoplasms and that the incidence increases with the intensity of the fallout, under all specifications. The preferred random effects model in column 2 of Table 1 indicates that in the regions where the ^{137}Cs soil concentration was 2-10 kBq/m² hospital discharges after treatment for neoplasms are around 0.59 percentage points higher compared to regions with no fallout. The effect associated with a ^{137}Cs soil concentration of 10-40 kBq/m² is around 0.68 percentage points. The area most affected by the fallout, captured by the dummy D_{F3} , experiences higher levels of hospital discharges after treatment for neoplasms, with a point estimate around 1.37 percentage points. When we include the dummy D_{F4} as well, as in column 5, the point estimates of D_{F3} and D_{F4} are around 1.16 and 2.1, respectively. P-values are lower than 1% across all specifications.

These coefficients do not necessarily measure the increase in the incidence of neoplasms among resident populations in absolute terms since they refer to hospital discharges, and 1 patient may be associated with more than 1 hospitalization during the course of the disease. However, the effects are large considering that hospital discharges after treatment for neoplasms over 100 inhabitants are on average equal to around 1.7% of the resident population.

Similar findings are obtained using alternative specifications of the fallout dummies based on the extension of the regional area exposed to the fallout (Supplementary Table S.4). We also performed an estimate of a quadratic parametric model specification in which we input either

the lower bound or the average value of the fallout to each region. The estimates reported in Supplementary Table S.5 confirm our baseline findings and show that the radioactive fallout is positively and significantly associated with the incidence of hospital discharges for neoplasms with an effect that increases with the intensity of the fallout. For example, using the lower bound we find that the increase in hospital discharges associated with each fallout intensity is, respectively, 0.14, 0.71 and 1.22 percentage points.

GDP per capita, population density, the proportion of residents aged 60 or more, and the presence of doctors and non-curative hospital beds are all positively associated with the incidence of neoplasms, as expected. Although when we control for regional unobservable characteristics through random effects, GDP per capita loses its statistical significance.

In Supplementary Table S.6 we provide alternative ways of accounting for the different propensity to hospitalization across regions, controlling, respectively, for non-curative beds only, as in the baseline model of Table 1; for curative-care beds only; for the total number of hospital beds; and for a measure of hospital discharges for all other causes other than neoplasms (all variables are standardized over 100 inhabitants). However, some of these controls are likely to be endogenous. For example, we cannot exclude that a change in hospital discharges for neoplasms affects the number of available hospital curative beds in the region or the number of discharges for other medical conditions as a result of the hospitals' allocation of their scarce resources. We also cannot exclude that exposure to ionizing radiations may affect medical conditions other than neoplasms, as suggested by various studies in the literature and reported in the next section. Still, we find a positive, statistically significant (at the 1% level) association between the fallout dummies and discharges for neoplasms, increasing with the intensity of the fallout, after controlling for each of these indicators, with smaller point estimates when we control for all other discharges.

Robustness Checks

Additional Regional Controls. Our findings reveal a strong association of the actual radionuclide soil concentration with the incidence of neoplasms, measured by hospitalization rates. Still, there are a number of issues that deserve attention. Figure 1 shows that the geographical

distribution of the regions with no fallout is concentrated in those areas that are more distant from Chernobyl (Portugal, Spain, and the western French regions). Despite the randomness of the geographical dispersion of the fallout, the concentration of the no-fallout areas in the west of Europe may still constitute a problem for our estimates if those regions have unobservable characteristics that correlate with health patterns. Therefore, we re-estimate our model to determine whether our findings disappear when we include additional controls, such as a measure of regional distance from Chernobyl; longitude; life expectancy measured at the national level in 1985, ie, before the nuclear disaster; and a measure of anthropization, ie, the proportion of wooded areas in the region. Our findings are robust to the inclusion of all these additional controls, as displayed in Table 2. The point estimates are generally smaller, but hospital discharges are still positively and significantly correlated with the fallout, and the association increases across the 3 levels of intensity of the fallout, with a point estimate equal to 0.36, 0.44, and 0.98 percentage points, respectively. Not surprisingly, the incidence of neoplasms is generally negatively associated with the distance from Chernobyl, with life expectancy in 1985 (only in cross-sectional models excluding random effects) and with the percentage of woods in the region and is positively associated with longitude.

We also check whether our findings are affected by the immigration flows from Russia, Belarus, and Ukraine, the countries that suffered the most from the fallout. As Lehmann and Wadsworth and Danzer and Danzer point out,^{23,24} at the time of the accident Soviet Union citizens' mobility was severely restricted. However, our estimates could be biased by the migration flows that followed the disruption of the Soviet Union. Fortunately, we can control for the presence of immigrants from those ex-Soviet countries using migration penetration data by origin country from Eurostat in the 2000s, for all countries in our sample. The data indicate a very low share of immigrants from Russia, Belarus, and Ukraine over total resident population in all countries in our sample, except for Estonia and Latvia where, respectively, 6.28% and 0.98% of the resident population are foreign nationals from Russia. In all other countries the shares are generally much smaller. Our estimates (not reported, available upon request) indicate that our findings are basically unchanged after controlling for immigration from Russia, Belarus, and Ukraine.

Excluding Smoking-Related Neoplasms. In Table 3 we re-estimate our model excluding those types of neoplasms that may be related to

Table 2. Fallout Effect on Hospital Discharges, With Additional Controls

	(1) Pooled OLS	(2) Random Effects	(3) OLS	(4) Pooled OLS	(5) Random Effects	(6) OLS
D_{F1}	0.353*** (0.0453)	0.362** (0.169)	0.450** (0.174)	0.318*** (0.0427)	0.403** (0.167)	0.380** (0.180)
D_{F2}	0.435*** (0.0506)	0.438** (0.189)	0.542** (0.250)	0.443*** (0.0463)	0.521*** (0.171)	0.447* (0.245)
D_{F3}	0.899*** (0.0835)	0.984*** (0.271)	1.013*** (0.352)	0.860*** (0.0762)	1.007*** (0.252)	0.873** (0.354)
GDP	0.380*** (0.0426)	0.155 (0.212)	0.499*** (0.174)	0.447*** (0.0441)	0.198 (0.212)	0.579*** (0.174)
Population density	0.184*** (0.0311)	0.305*** (0.0779)	0.139 (0.117)	0.186*** (0.0280)	0.309*** (0.0778)	0.126 (0.110)
Proportion 60+	7.655*** (0.462)	2.052 (1.325)	8.698*** (1.742)	8.005*** (0.460)	2.185 (1.335)	9.155*** (1.788)
Medical obs.	-0.520*** (0.138)	-0.0910 (0.444)	-0.745 (0.451)	-0.520*** (0.137)	-0.0944 (0.440)	-0.787* (0.438)
Doctors	1.460*** (0.267)	0.970*** (0.306)	1.255 (1.043)	1.260*** (0.255)	0.927*** (0.301)	1.029 (0.994)
Non-curative beds	0.118 (0.165)	0.654*** (0.252)	-0.0406 (0.676)	0.243 (0.154)	0.692*** (0.258)	0.00718 (0.640)
Life expectancy in 1985	-0.0387* (0.0224)	0.105* (0.0619)	-0.0685 (0.0623)	-0.0293 (0.0212)	0.120* (0.0642)	-0.0693 (0.0624)

Continued

Table 2. *Continued*

	(1) Pooled OLS	(2) Random Effects	(3) OLS	(4) Pooled OLS	(5) Random Effects	(6) OLS
Percentage woods	-1.018*** (0.159)	-0.379** (0.158)	-1.015** (0.400)	-1.161*** (0.158)	-0.389** (0.157)	-0.994** (0.392)
Distance (thousands km)	-0.361*** (0.0589)	-0.502*** (0.182)	-0.265 (0.203)			
Longitude				0.0359*** (0.00354)	0.0440*** (0.0126)	0.0316* (0.0166)
Observations	1,021	1,021	80	1,021	1,021	80
R^2	0.754	0.675	0.796	0.760	0.675	0.800
Number of id		80			80	

Robust standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Baseline fallout dummy specification: F1 Fallout > 2 kBq/m² and < 10 kBq/m², F2 Fallout > 10 kBq/m² and < 40 kBq/m², F3 Fallout > 40 kBq/m², F4 Fallout > 40 kBq/m² (more than 50%). Dependent variable expressed in hospital discharges over 100 inhabitants. Baseline controls: GDP per capita, population density, proportion of population aged over 60, and per capita number of hospital discharges by medical observation and evaluation for suspected diseases and conditions, number of doctors in the area, and number of available non-curative-care beds in the area, all standardized for 100 inhabitants. Further controls: distance indicates the area's distance from Chernobyl's nuclear power plant (in kilometers), longitude accounts for the area's meridian (positive numbers correspond to meridians east of Greenwich's, negative numbers are located west), life expectancy in 1985 (pre-accident) at country level is expressed in years, percentage of woods controls for the proportion of the area covered by woods. For Pooled OLS and Random Effects models, year fixed effects are not reported in the table.

Table 3. Fallout Effect on Hospital Discharges, Excluding Neoplasms of Trachea, Bronchus, and Lungs

	(1) Pooled OLS	(2) Random Effects	(3) OLS	(4) Pooled OLS	(5) Random Effects	(6) OLS
D_{F1}	0.442*** (0.0375)	0.520*** (0.135)	0.472*** (0.153)	0.295*** (0.0395)	0.309*** (0.147)	0.370*** (0.151)
D_{F2}	0.725*** (0.0323)	0.611*** (0.122)	0.836*** (0.120)	0.367*** (0.0445)	0.368*** (0.165)	0.450*** (0.215)
D_{F3}	1.225*** (0.0574)	1.225*** (0.198)	1.298*** (0.202)	0.786*** (0.0748)	0.860*** (0.240)	0.876*** (0.313)
GDP	0.283*** (0.0366)	0.166 (0.193)	0.302*** (0.140)	0.343*** (0.0384)	0.138 (0.193)	0.448*** (0.155)
Population density	0.322*** (0.0260)	0.355*** (0.0731)	0.324*** (0.103)	0.160*** (0.0296)	0.271*** (0.0792)	0.120 (0.111)
Proportion 60+	8.289*** (0.474)	2.280* (1.214)	7.888*** (1.839)	6.838*** (0.411)	1.808 (1.217)	7.707*** (1.523)
Medical obs.	0.120 (0.133)	0.0102 (0.398)	0.114 (0.344)	-0.501*** (0.118)	-0.0952 (0.380)	-0.659* (0.382)
Doctors	1.113*** (0.227)	0.869*** (0.305)	1.057 (0.912)	1.403*** (0.243)	0.917*** (0.275)	1.252 (0.927)
Non-curative beds	0.643*** (0.129)	0.841*** (0.238)	0.779* (0.450)	0.187 (0.142)	0.550*** (0.239)	0.0904 (0.564)
Distance (thousands km)				-0.323*** (0.0524)	-0.463*** (0.163)	-0.242 (0.181)

Continued

Table 3. *Continued*

	(1) Pooled OLS	(2) Random Effects	(3) OLS	(4) Pooled OLS	(5) Random Effects	(6) OLS
Life expectancy in 1985						
Percentage woods				-0.0401** (0.0199)	0.0919 (0.0575)	-0.0667 (0.0545)
Observations	1,012	1,012	79	1,012	1,012	79
R ²	0.694	0.606	0.743	0.760	0.684	0.801
Number of id		79			79	

Note: Robust standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Baseline fallout dummy specification: F1 Fallout > 2 kBq/m² and < 10 kBq/m², F2 Fallout > 10 kBq/m² and < 40 kBq/m², F3 Fallout > 40 kBq/m², F4 Fallout > 40 kBq/m² (more than 50%). Dependent variable expressed in hospital discharges over 100 inhabitants. Dependent variable calculated as the difference between total hospital discharges by neoplasms (ICD10 code: C00-D48) and hospital discharges by neoplasms of trachea, bronchus and lungs (ICD10 code: C33-C34). Baseline controls: GDP per capita, population density, proportion of population aged over 60, and per capita number of hospital discharges by medical observation and evaluation for suspected diseases and conditions, number of doctors in the area, and number of available non-curative-care beds in the area, all standardized for 100 inhabitants. For Pooled OLS and Random Effects models, year fixed effects are not reported in the table.

smoking, since we do not explicitly control for heterogeneous smoking patterns across regions. These are neoplasms of the trachea, bronchus, and lungs. Our findings are robust to this check and the radioactive fallout's coefficients are still significant, positive, and increasing with the fallout intensity.

Additional Health-Related Controls. Another dimension that could affect our estimates is the regional internal allocation of health care expenditure. The incidence of hospitalizations and, more generally, the procedures by which neoplasm treatments are administered to the patients could be affected by health care policies at the national level. We control for financing agents of the total health care expenditure as share of GDP and for the specific type of health care provision per inhabitant (Supplementary Tables S.7 and S.8). For simplicity we decided to report only the results obtained using random effects; however, similar findings are obtained with pooled OLS and OLS on time averages as well. Our results are robust to the inclusion of all of these controls, therefore excluding the possibility that the findings are due to the characteristics of health care expenditure at the national level.

Sensitivity to Country Exclusion. Our findings are also robust to the exclusion of any country in the sample, as displayed in Table 4A, where we report the resulting estimated coefficients from the random effects model. In all cases the effect of the fallout is positive and increasing with the intensity of the fallout. Similar results from the OLS cross-sectional model are reported in Supplementary Table S.9. Not surprisingly, we observe some variation in the point estimates of some of the fallout coefficients when we exclude the countries with more extreme values of the fallout. These are Spain and Portugal, the countries that received the lowest levels of contamination, and Austria and the Czech Republic, which are the most contaminated. Indeed, Spain and Portugal are the only countries in the sample that were not affected by the fallout at all, and Spanish regions make up a large share of the zero-fallout areas. Despite ending up with much lower variability in the data when we eliminate Spain, all fallout dummies are still statistically significant with an effect that increases with the intensity of the fallout. Similar findings are reported when we exclude heavily contaminated areas.

Another possible factor that could affect our estimations is the geographical location of the regional clusters characterized by the highest and the lowest levels of fallout intensity. We test whether the inclusion of specific groups of countries is the main driver of our

Table 4A. Fallout Effect on Hospital Discharges Over 100 Inhabitants, Excluding One Country at A Time (Random Effects)

	(1) Excl. AT	(2) Excl. CZ	(3) Excl. DE	(4) Excl. DK	(5) Excl. EE	(6) Excl. ES	(7) Excl. FR	(8) Excl. IE
D_{F1}	0.549*** (0.152)	0.681*** (0.170)	0.186* (0.0974)	0.593*** (0.156)	0.588*** (0.151)	0.457*** (0.137)	1.115*** (0.205)	0.556*** (0.153)
D_{F2}	0.557*** (0.119)	0.925*** (0.147)	0.473*** (0.172)	0.678*** (0.134)	0.681*** (0.138)	0.567*** (0.143)	0.899*** (0.148)	0.818*** (0.115)
D_{F3}	0.637*** (0.148)	1.573*** (0.212)	1.420*** (0.248)	1.344*** (0.222)	1.369*** (0.223)	1.246*** (0.234)	1.555*** (0.239)	1.347*** (0.214)
GDP	0.0153 (0.168)	0.169 (0.173)	0.162 (0.195)	0.189 (0.216)	0.182 (0.213)	0.0705 (0.183)	0.209 (0.287)	0.318 (0.254)
Population density	0.469*** (0.121)	0.373*** (0.0851)	0.422*** (0.0743)	0.386*** (0.0741)	0.394*** (0.0727)	0.371*** (0.0670)	0.310*** (0.0949)	0.369*** (0.0719)
Proportion 60+	3.098** (1.297)	2.604* (1.406)	0.0874 (1.129)	2.587** (1.299)	2.581* (1.327)	5.518*** (1.666)	3.685** (1.454)	2.625* (1.481)
Medical obs.	0.213 (0.554)	0.164 (0.575)	0.103 (0.395)	0.819* (0.437)	0.0122 (0.458)	-0.515* (0.267)	-0.750*** (0.336)	-0.0980 (0.429)
Doctors	0.813*** (0.277)	1.222*** (0.365)	0.901*** (0.334)	0.929*** (0.335)	0.923*** (0.344)	1.231* (0.642)	0.653*** (0.313)	0.871*** (0.352)
Non-curative beds	1.207*** (0.273)	0.876*** (0.255)	0.889*** (0.212)	0.861*** (0.260)	0.942*** (0.254)	0.704*** (0.272)	0.219 (0.455)	1.063*** (0.265)
Observations	913	909	813	1,011	1,012	817	727	993
Number of id	71	72	64	79	79	63	59	78
R^2	0.595	0.666	0.681	0.604	0.601	0.543	0.645	0.633

Continued

Table 4B. Fallout Effect on Hospital Discharges Over 100 Inhabitants, Excluding One Country at A Time (Random Effects)

Variables	Dependent Variable: Hospital Discharges by Neoplasms										(16) Excl. AT CZ ES PT
	(9) Excl. LT	(10) Excl. LV	(11) Excl. LU	(12) Excl. NL	(13) Excl. PT	(14) Excl. AT CZ	(15) Excl. ES PT				
D _{F1}	0.596*** (0.159)	0.631*** (0.160)	0.590*** (0.159)	0.615*** (0.157)	0.589*** (0.152)	0.606*** (0.167)	0.445*** (0.137)	0.429*** (0.147)			
D _{F2}	0.685*** (0.133)	0.701*** (0.143)	0.683*** (0.133)	0.685*** (0.132)	0.688*** (0.133)	0.764*** (0.144)	0.555*** (0.148)	0.588*** (0.164)			
D _{F3}	1.369*** (0.223)	1.340*** (0.204)	1.368*** (0.224)	1.364*** (0.222)	1.371*** (0.223)	0.918*** (0.0773)	1.233*** (0.237)	0.656*** (0.0741)			
GDP	0.177 (0.216)	0.414** (0.207)	0.177 (0.215)	0.210 (0.222)	0.188 (0.213)	0.0406 (0.140)	0.0700 (0.183)	0.0141 (0.122)			
Population density	0.392*** (0.0728)	0.346*** (0.0677)	0.394*** (0.0727)	0.390*** (0.0749)	0.393*** (0.0724)	0.450*** (0.157)	0.370*** (0.0670)	0.310*** (0.100)			

Continued

Table 4B. *Continued*

Variables	Dependent Variable: Hospital Discharges by Neoplasms								(16) Excl. AT CZ ES PT
	(9) Excl. LT	(10) Excl. LV	(11) Excl. LU	(12) Excl. NL	(13) Excl. PT	(14) Excl. AT CZ	(15) Excl. ES PT		
Proportion 60+	2.547* (1.322)	1.884 (1.281)	2.533* (1.323)	2.616* (1.351)	2.570* (1.326)	3.611*** (1.359)	5.528*** (1.665)	7.109*** (1.693)	
Medical obs.	0.00322 (0.455)	-0.0367 (0.488)	0.0294 (0.467)	0.0249 (0.475)	0.0141 (0.459)	0.409 (0.724)	-0.513* (0.268)	-0.500 (0.369)	
Doctors	0.930*** (0.344)	0.781** (0.327)	0.911*** (0.339)	0.891*** (0.342)	0.914*** (0.342)	1.049*** (0.311)	1.233* (0.646)	2.945*** (0.570)	
Non-curative beds	0.938*** (0.253)	0.850*** (0.258)	0.957*** (0.253)	0.946*** (0.261)	0.943*** (0.253)	1.148*** (0.274)	0.697** (0.273)	0.243 (0.266)	
Observations	1,010	1,009	1,013	1,010	1,015	801	811	591	
Number of id	79	79	79	79	79	63	62	45	
R ²	0.600	0.595	0.600	0.607	0.598	0.619	0.539	0.575	

Abbreviations: AT, Austria; CZ, Czech Republic; DE, Germany; DK, Denmark; EE, Estonia; ES, Spain; FR, France; IE, Ireland; LT, Lithuania; LV, Latvia; LU, Luxembourg; NL, Netherlands; PT, Portugal. Robust standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Baseline fallout dummy specification: F1 Fallout > 2 kBq/m² and < 10 kBq/m², F2 Fallout > 10 kBq/m² and < 40 kBq/m², F3 Fallout > 40 kBq/m², F4 Fallout > 40 kBq/m² (more than 50%). All columns are obtained by the same Random Effects specification; used controls are only the ones reported in the table with the addition of year fixed effects. Dependent variable expressed in hospital discharges over 100 inhabitants.

findings. In the final columns of Table 4A we repeat the analysis after excluding Austria and the Czech Republic (column 14), Spain and Portugal (column 15), and lastly all 4 countries: Austria, the Czech Republic, Portugal, and Spain (column 16). The positive and increasing pattern of neoplasm incidence with the fallout intensity is confirmed even excluding “extreme” countries.

Placebo Test: Randomly Assigned Fallout Dummies. In another robustness test, we check for the likelihood that our findings are produced by chance, a necessary test given the relatively small number of regions in our sample. We perform a placebo test in which our fallout dummies are substituted with a set of randomly assigned placebo dummies that respect the proportions of the fallout intensity areas in the baseline fallout specification. After simulating 1,000 distinct random fallout patterns, we checked the results delivered by the baseline random effects specification in Supplementary Table S.10. After 1,000 replications, in not even 1 case are all dummies’ coefficients positive, statistically significant, and increasing with the intensity of the fallout. The probabilities of 3, 2 and only 1 dummy being positive and significant are 0%, 0%, and 1.6% respectively. In other words, our placebo test shows that our empirical findings are unlikely to have been determined by chance. (See the online Appendix for more details.)

Effect on Different Types of Neoplasms, Unrelated Illnesses and Other Medical Conditions. Previous studies that investigated the link between ionizing radiations and neoplasms emphasized the effect on various types of neoplasms, including neoplasms of the stomach and pancreas,³³ skin,^{34,35} breast,³⁶⁻³⁸ kidney,³⁹⁻⁴¹ thyroid,⁴²⁻⁴⁴ and lymphoma and leukemia.^{38,45-48} In our data we find that the radioactive fallout is positively and significantly associated with any type of malignant neoplasms, although the intensity varies according to the type, as displayed in Supplementary Table S.11. No effect is found for benign neoplasms of the colon, rectum, and anus.

We also check whether we find similar patterns of association between the fallout and hospital discharges related to forms of illness and condition that in principle should not be directly related to the harmful effects of radioactivity. Table 5 shows that we do not find a similar fallout pattern when we consider other causes of hospitalization, such as tuberculosis, alcoholic liver disease, pregnancy and child birth, and poisoning. Comparing our random effects model’s findings with the baseline results on total discharges for neoplasms reported in columns 1, we see that the

Table 5. Fallout Effect on Hospital Discharges Over 100 Inhabitants by Other Causes

Hospital Discharges by: ICD10 Code:	Neoplasm		Tuberculosis		Alcoholic Liver Disease		Pregnancy and Childbirth		Poisoning by Drugs and Medicaments	
	C00-D48		A15-A19_B90		K70		O00-O99		T36-T65	
	(1) RE	(2) T.A. OLS	(3) RE	(4) T.A. OLS	(5) RE	(6) T.A. OLS	(7) RE	(8) T.A. OLS	(9) RE	(10) T.A. OLS
D _{F1}	0.587*** (0.152)	0.536*** (0.174)	0.00837 (0.00556)	-0.000581 (0.00189)	-0.00182 (0.00417)	-0.00348 (0.00478)	0.0687 (0.0750)	-0.00280 (0.0770)	0.00933 (0.0161)	-0.0256 (0.0191)
D _{F2}	0.685*** (0.133)	0.952*** (0.137)	-0.00498* (0.00285)	-0.00470 (0.00323)	0.000834 (0.00341)	0.00347 (0.00414)	0.177 (0.108)	-0.0348 (0.0600)	-0.0231 (0.0162)	-0.0479*** (0.0163)
D _{F3}	1.368*** (0.223)	1.460*** (0.226)	0.00574*** (0.00272)	0.00620* (0.00332)	0.000897 (0.00379)	0.00679 (0.00469)	-0.0213 (0.0492)	0.0192 (0.0620)	-0.0250* (0.0133)	-0.0238* (0.0138)
GDP	0.187 (0.212)	0.348*** (0.155)	-0.0130* (0.00701)	-0.0187** (0.00835)	-0.00860 (0.00559)	0.000964 (0.00537)	0.0788 (0.0964)	-0.131* (0.0658)	-0.0162 (0.0139)	-0.0168 (0.0173)
Population density	0.393*** (0.0724)	0.363*** (0.107)	-3.82e-05 (0.00172)	0.00213 (0.00214)	0.00785*** (0.00228)	0.0124*** (0.00208)	0.00774 (0.0332)	0.0977* (0.0506)	-0.00296 (0.00452)	0.0250*** (0.00863)
Proportion 60+	2.565* (1.325)	8.901*** (2.072)	-0.0306 (0.0377)	-0.0206 (0.0361)	0.0202 (0.0536)	0.144** (0.0603)	-5.662*** (1.136)	-5.328*** (0.892)	-0.115 (0.127)	-0.392* (0.197)

Continued

Table 5. Continued

Hospital Discharges by: ICD10 Code:	Neoplasm		Tuberculosis		Alcoholic Liver Disease		Pregnancy and Childbirth		Poisoning by Drugs and Medicaments	
	C00-D48		A15-A19_B90		K70		O00-O99		T36-T65	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	RE	T.A. OLS	RE	T.A. OLS	RE	T.A. OLS	RE	T.A. OLS	RE	T.A. OLS
Medical obs.	0.0137 (0.459)	0.107 (0.399)	-0.00466 (0.00486)	0.0161* (0.00886)	0.0702* (0.0406)	0.0190* (0.00977)	0.184 (0.339)	0.265* (0.145)	0.0292 (0.0327)	0.151*** (0.0400)
Doctors	0.917*** (0.342)	1.019 (1.010)	0.0337*** (0.0134)	0.0588*** (0.0244)	-0.0102 (0.0110)	-0.0833*** (0.0265)	0.424 (0.319)	0.492 (0.470)	-0.0335* (0.0199)	-0.222*** (0.102)
Non-curative beds	0.943*** (0.253)	0.718 (0.534)	-0.00998 (0.00610)	0.00954 (0.00893)	0.0422*** (0.0145)	0.0481*** (0.0143)	0.408** (0.192)	1.118*** (0.306)	0.157*** (0.0291)	0.370*** (0.0844)
Observations	1,021	80	1,006	79	1,021	80	1,021	80	1,021	80
R ²	0.600	0.739	0.328	0.737	0.234	0.449	0.429	0.722	0.395	0.570
Number of id	80		79		80		80		80	

Robust standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Baseline fallout dummy specification: F1 Fallout > 2 kBq/m² and < 10 kBq/m², F2 Fallout > 10 kBq/m² and < 40 kBq/m², F3 Fallout > 40 kBq/m², F4 Fallout > 40 kBq/m² (more than 50%). Dependent variables expressed in hospital discharges over 100 inhabitants. Random effects estimations (RE) include year fixed effects. Estimations over 2000-2013 averages made using an Ordinary Least Squares specification with robust standard errors (T.A. OLS). All specifications include baseline controls: GDP per capita, population density, proportion of population aged over 60, and per capita number of hospital discharges by medical observation and evaluation for suspected diseases and conditions, number of doctors in the area, and number of available non-curative-care beds in the area, all standardized for 100 inhabitants. Tuberculosis data are not available for EE (Estonia).

only case where we find a point estimate that is significant at the 5% level is for D_{F3} on tuberculosis. The absence of any consistent effect of the fallout on tuberculosis, increasing in intensity, leads us to speculate that such a finding may be related to specific tuberculosis patterns in the regions that were most contaminated.

We also check whether the fallout deposition correlates with other medical conditions observed in our data. (See the online Appendix for details on the list of medical conditions observed in the data.) Even though the literature suggests a connection between radioactive exposure and certain conditions other than neoplasms (eg, cardiovascular problems^{49,50} and cataract⁵¹), our estimates (not reported, available upon request) find some significant correlations; these, however, tend to disappear when we augment our model with additional controls.

Comparison of Our Findings With the Existing Literature

How do these estimates compare to previous findings in the literature? Table 6 provides a direct comparison between the findings of the INWORKS study⁴ and the random effects models reported in column 2 of Tables 1 and 2, respectively, ie, excluding and including additional controls. To calculate an excess relative risk (ERR) measure from our estimates to be compared with the INWORKS ERR, we rescale our point estimates by the average of hospital discharges in no-fallout regions, equal to 1.08. (See the online Appendix for further details on the approximations behind Table 6.) The random effects model with additional controls implies that the fallout range comprising between 2 and 10 kBq/m² is associated with an ERR equal to 0.33% (95% confidence interval is {0.02,0.64}). Since the ERR estimated by the INWORKS study is equal to 0.07% (95% confidence interval is {0.03,0.11}), assuming comparability between the 2 outcomes, our point estimates are therefore 5 times larger, although the confidence intervals overlap.

In the case of the fallout range of between 10 and 40 kBq/m², our estimated ERR is equal to 0.40%, whereas the INWORKS estimated effect on ERR is equal to 0.34%. Considering the standard errors, the difference between the 2 estimates is not statistically different from 0.

Finally, for what concerns the fallout range of between 40 and 185 kBq/m², our estimated ERR is 0.91%, whereas the INWORKS ERR is

Table 6. Comparison of Our Findings With the INWORKS Study

Fallout Dummy	(1) Estimated mSv in 20 Years (mSv)	(2) Excess Relative Risk (p.p) INWORKS	(3)	(4)
			Excess Relative Risk (p.p) Random Effects Baseline Controls	Excess Relative Risk (p.p) Random Effects Additional Controls
D _{F1} (2<D _{F1} <10 kBq/m ²)	1.35	0.07 (0.02)	0.54 (0.14)	0.33 (0.16)
D _{F2} (10<D _{F2} <40 kBq/m ²)	6.75	0.34 (0.12)	0.63 (0.12)	0.40 (0.17)
D _{F3} (40<D _{F3} <185 kBq/m ²)	29.73	1.48 (0.53)	1.26 (0.21)	0.91 (0.25)

Column 1 indicates the approximate mSv dose for each fallout category for 20 years of exposure assuming shielding. Column 2 indicates the excess relative risk implied by the INWORKS study.⁴ Columns 3 and 4 display the approximate excess relative risk calculated using the hospital discharges for neoplasms in excess resulting from the estimates of the Random Effects models of column 2 in Tables 1 and 2, respectively, adjusted by the average number of per capita hospital discharges in zero fallout areas, equal to 1.08. Standard errors in parentheses.

equal to 1.48%, again with overlapping confidence intervals. When we consider the model without additional controls, the confidence intervals overlap only for the 2 most intense fallout categories.

Overall, our findings are comparable with those of Richardson et al., with our models’ point estimates predicting larger effects for low doses of external radiation and comparable effects for higher doses. The differences are probably related to the nature of the examined outcomes, ie, discharges versus deaths, and to the different functional form of the association between radiation exposure and the outcome inferred by the 2 studies, ie, linear in the INWORKS study and nonlinear in ours. Notably, Mathews et al. find a nonlinear relationship as well, using data on CT scans in childhood or adolescence in Australia.⁵²

Still, the findings of the 2 studies should be compared with care, considering that the calculations are based on rough approximations, given the different nature of the outcome variables, and considering the different forms of exposure to radioactivity: external, internal (through ingestion or inhalation of radioactive substances), or contact.

In addition, our analysis is based on a different methodology and slightly different time span.

Our estimated effects are also comparable to the crude neoplasm-incidence ratios found by Tondel et al., Tondel et al. and Alinaghizadeh et al.^{8,20,21}

Deaths by Neoplasm

We also checked whether we detect an association between the fallout and the standardized number of deaths by neoplasm. Our empirical findings should be interpreted with more care in this case, first, because of the longer latency periods needed to detect actual effects on deaths, and second, because the effect on deaths may be confounded by the general efficacy of the health care system in the different regions. This is especially problematic in a multi-country study like ours. Indeed, several studies have highlighted a positive trend in 1-, 5-, and 10-year survival rates after a neoplasm diagnosis in Europe.^{53,54} Such increasing survival rates from neoplasms may be heterogeneous across regions, and whether or not a disease leads to a death event may be affected by how early the disease is diagnosed and how well it is treated. As a result, confounders may play a more important role in these estimates than in those analyzing hospital discharges.

We estimated our models using standardized deaths as outcome variable. Table 7 presents the estimated effect on deaths by neoplasms over 100,000 inhabitants. Our model cannot find any robust and significant effect of the fallout on deaths by neoplasms, either in the case of total neoplasms (columns 3 and 4) or in the case of malignant neoplasms only (columns 5 and 6). However, we checked the correlation between deaths and hospital discharges by neoplasms over the 2000-2010 time span, finding a positive correlation that tends to increase as the time lag between the 2 measures grows (Supplementary Table S.12). Deaths are generally positively correlated with hospital discharges. The correlation is equal to 0.19 when comparing contemporaneous measures of deaths and discharges, while it amounts to 0.27 when comparing measures observed 8 years apart, indicating that death patterns tend to be more correlated to past levels than to contemporaneous levels of hospitalization. However, this is only suggestive that an increase in discharges today may evolve to an increase in deaths years later.

Table 7. *Continued*

Dependent Variable:	Hospital Discharges by Neoplasms Over 100 Inhabitants		Deaths by Neoplasms Over 100,000 Inhabitants		Deaths by Malignant Neoplasms Over 100,000 Inhabitants	
	(1) RE	(2) T.A. OLS	(3) RE	(4) T.A. OLS	(5) RE	(6) T.A. OLS
ICD10 Code:		C00-D48		C00-D48		C00-C97
Medical obs.	0.0137 (0.459)	0.107 (0.399)	-5.139 (8.725)	84.35*** (13.24)	-0.176 (8.391)	84.17*** (13.55)
Doctors	0.917*** (0.342)	1.019 (1.010)	-12.74 (9.684)	-47.63 (59.06)	-13.03 (9.842)	-42.15 (60.00)
Non-curative beds	0.943*** (0.253)	0.718 (0.534)	56.32*** (12.69)	51.39*** (24.28)	48.49*** (12.26)	41.51* (23.64)
Observations	1,021	80	811	80	811	80
R ²	0.600	0.739	0.635	0.721	0.634	0.704
Number of id	80		80		80	

Robust standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Baseline fallout dummy specification: F1 Fallout > 2 kBq/m² and < 10 kBq/m², F2 Fallout > 10 kBq/m² and < 40 kBq/m², F3 Fallout > 40 kBq/m², F4 Fallout > 40 kBq/m² (more than 50%). ICD10 illness code reported, 10th revision of the *International Statistical Classification of Diseases and Related Health Problems* (ICD10). Results from Random Effects model (RE) including year fixed effects, and OLS-averages estimations (T.A. OLS) and baseline controls: GDP per capita, population density, proportion of population aged over 60, and per capita number of hospital discharges by medical observation and evaluation for suspected diseases and conditions, number of doctors in the area, and number of available non-curative-care beds in the area, all standardized for 100 inhabitants. Data on causes of deaths refer to the time span 2000-2010. For more information on data used see Supplementary Table S.2.

Estimating the Probability of Radioactive Fallout

The International Atomic Energy Agency (IAEA) report argues that the main drivers of the fallout dispersion pattern over Europe were the transit of the radioactive cloud and the contextual presence of rainfall.¹⁰ The random nature of the fallout deposition over European regions is the product of these mechanisms. Almond et al. provide some supporting evidence by checking if these phenomena alone can explain the final location of the fallout deposition.²⁵ Their county-level information on precipitation intensity data in Sweden grants a fine match between the fallout and local precipitation over a homogeneous area that absorbed around 5% of the accident's cesium fallout. They find that the rainfall in the 10 days following the accident is a strong predictor of the ¹³⁷Cs soil deposition in Sweden after the disaster.

The aim of this section is to provide similar supporting evidence for our sample of countries. To perform our analysis, we used historical weather data provided by Menne et al. and the French Radioprotection and Nuclear Safety Institute (IRSN).⁵⁵⁻⁵⁷ However, no precise match between local precipitation and hospitalization is possible with our data, since we cover a number of European countries with very different exposure to the radioactive cloud.⁵⁸ For example, whole regions in Spain and Portugal reported rain just after the accident. However, they were never reached by the nuclear plume, resulting in no fallout deposition. In addition, we observe incomplete information on atmospheric conditions at the time of the disaster over a large extension of countries. The data are not available for all regions, and in some cases the available information does not cover the whole 10 days following the accident.

As a result, we can provide only suggestive evidence on the random nature of the fallout that is nevertheless in line with what was previously suggested in the literature. We first estimate a simple model in which the deposition of nuclear materials across European regions is a function of the number of days the plume was present over each region, the number of rainy days, and a nonlinear interaction between the two. Results in Supplementary Table S.13 show that the passage of the radioactive cloud alone is a significant predictor of the fallout deposition, with an R^2 of 0.54. Not surprisingly, precipitation alone shows no predictive power, since some regions that were subject to rain in those days were never reached by the radioactive cloud. When we include all terms

mentioned here and their squared terms, the model's explanatory power improves significantly, with an R^2 of 0.65. Not surprisingly, an important explanatory factor is the interaction term between the presence of the radioactive cloud and local precipitation.

These findings are confirmed by simple inspection of the mean values of the fallout dummy used in Supplementary Table S.13 by each combination of radioactive-cloud passage days and rain days in the sample, as reported by Supplementary Table S.14. Almost all of the regions with no fallout experienced no passage of the cloud, and the fallout deposition is mainly concentrated in regions characterized by a longer interplay of the nuclear plume with rainfall. The average number of days of contextual passage of the cloud and rain is larger in the fallout areas (average interaction days equal to 2.7) compared to the no-fallout areas (average interaction days equal to 0.9), with the difference being highly statistically significant (Supplementary Table S.15).

Taken together, the empirical evidence suggests that the most important variable predicting the final radionuclide's soil deposition is the presence of the cloud while it was raining on the area, in the 10 days following the disaster, endorsing the process of wet deposition described by the IAEA and confirming the random nature of the geographical dispersion of the fallout.

Economic Implications of the Chernobyl Nuclear Disaster

Finally, we provide a back-of-the-envelope estimate of the amount of annual health care expenditure implied by the excess hospital discharges associated with the fallout, under the hypothesis that the estimated association is causal. These numbers should be considered a very rough approximation, since they are based on a number of strong assumptions, including homogeneous inpatient curative-care costs across medical conditions in each country. Table 8 indicates the health care expenditure implied by our regressions, with and without additional controls.

Using Eurostat data on health expenditure by country,³² we calculate what share of the 2000-2013 annual curative-care expenditure may be associated with the fallout. (See the online Appendix for the detailed procedure.) Table 8 suggests that, taken at face value, our estimates imply a substantial increase in curative expenditure.

Table 8. Hospitalization Costs, Expenditure Share Attributable to Chernobyl

	(1) Total Expenditure in Inpatient Curative Care	(2) Amount due to Chernobyl Using Average Hospitalization Cost by Neoplasm	(3) Additional Controls
AT	€8,466.89	€334.38 (3.95%)	€233.00 (2.75%)
CZ	€25,337.10	€1,265.69 (5.00%)	€776.52 (3.06%)
DE	€63,094.33	€2,261.76 (3.58%)	€1,550.90 (2.46%)
DK			
EE	€249.14	€14.93 (5.99%)	€8.50 (3.41%)
FR	€54,641.06	€875.19 (1.60%)	€691.04 (1.26%)
IE			
LT	€921.47	€25.11 (2.73%)	€20.35 (2.21%)
LU	€533.47	€19.67 (3.69%)	€15.94 (2.99%)
LV	€378.97	€11.59 (3.06%)	€9.39 (2.48%)
NL	€16,754.10	€1,091.58 (6.52%)	€884.64 (5.28%)
PT			

Abbreviations: AT, Austria; CZ, Czech Republic; DE, Germany; DK, Denmark; EE, Estonia; FR, France; IE, Ireland; LT, Lithuania; LV, Latvia; LU, Luxembourg; NL, Netherlands; PT, Portugal.

Column 1 presents the average total inpatient curative-care expenditure by country (in millions of euros) from Eurostat.³² Columns 2 and 3 present the amount of curative-care expenditure of the country due to the excess hospital discharges predicted by the corresponding model (baseline and with additional controls, in Tables 1 and 2, respectively) and in parentheses the share of total curative-care expenditure due to Chernobyl-related excess hospital discharges calculated using the figures estimated. All figures are intended as annual averages for the period 2000-2013.

Considering our more conservative estimates, around 2.8% of the average curative-care expenditure in Austria could be imputed to the consequences of the fallout, conditional on the causal validity of our findings. That share is 3.1% for the Czech Republic.

Germany and France, may have spent, respectively, 2.5% and 1.3% of their total curative-care expenditure because of the excess number of hospitalizations due to the fallout.

Conclusions

This study provides one of the first attempts at investigating the long-term health consequences of the Chernobyl nuclear disaster in the European regions that were not immediately adjacent to Chernobyl. Our research design exploits the random nature of the soil deposition of ^{137}Cs to investigate the association with hospitalizations due to neoplasms almost 30 years later, using longitudinal data from 2000 to 2013, controlling for a number of observed time-varying regional characteristics and modeling the regional unobservable characteristics through a random effects specification.

Our findings indicate that the radioactive fallout from the Chernobyl accident is positively associated with the neoplasm-related hospitalization rate, with point estimates that increase with the intensity of the radioactive fallout. This association does not depend on the characteristics of the regions in our sample, such as GDP per capita, population age and density, the amount of wooded areas in the region, the distance from the epicenter of the nuclear disaster, life expectancy before the explosion, the diffusion of doctors and hospitals in the area, or health care policies at the national level. In addition, it is not driven by any specific country in the sample or by unobserved regional characteristics modeled using random effects. Our placebo regressions show that our findings are unlikely to be determined by chance, and we do not detect similar patterns when we consider the incidence of other health conditions that in principle should not be related to radiation exposure. Finally, we show that the estimated larger incidence of hospital discharges for neoplasms implies a substantial increase in curative-care expenditure in affected countries.

Our empirical findings are in line with the findings of the largest study of the effects of occupational exposure to ionizing radiation among

workers in the nuclear industry in France, the United Kingdom, and the United States.⁴ Our point estimates tend to be larger for the lowest level of radioactive fallout, but comparable for the other fallout categories. Our findings are also in line with other studies in the literature that focus on national-level data,^{8,20,21} but are at odds with Auvinen et al., who find a much more limited effect of the Chernobyl fallout, confined on colon cancer among females, only.⁷

Our evidence calls for further research to replicate and validate our findings on the implications of the Chernobyl radioactive fallout in the regions that were not immediately adjacent to the disaster area. One possible direction for future research would require the collection of homogeneous data on the per capita incidence of neoplasms across Europe, before and after 1986, to test the effect of the radioactive fallout in a difference-in-differences framework. Indeed, while we control for a number of potential confounding factors and we provide an extensive set of robustness checks, we still cannot be certain that all confounding factors are accounted for. As a result, we need to be cautious about a causal interpretation of our findings. Considering the long latency periods required to detect the effects of radioactivity on health, future research should also monitor health outcomes over time.

Our study also provides several indications for European health care policymakers. First, in presence of relevant health consequences of the Chernobyl fallout, health care expenditure should be targeted on the basis of the geographical dispersion of the fallout in order to attenuate its possible effect on neoplasm incidence. Second, health care policies should provide effective screening and prevention strategies with a specific focus on the regions that were hit more severely by the fallout. Third, neoplasm diagnosis and medical care should be designed taking into account the possible role of long-term low-dose radiation exposure. Fourth, policymakers should invest more on researching the long-term health effects of low ionizing radiation exposure, as we are still far from reaching a consensus on a topic that is of enormous importance for public health and safety. Public policies such as those limiting the import of contaminated food from areas hit by a radioactive disaster or those regulating the resident population's access to such areas should follow a precautionary approach and be rigorously informed by the current and future evidence produced by the ongoing scientific debate.

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Funding/Support: Financial support from the Italian Ministry of Education, University and Research is gratefully acknowledged.

Acknowledgments: We wish to thank Amy Berrington, Mariacristina De Nardi, Lorenzo Rocco and seminar participants of the Health Econometrics Satellite Workshop 2014 at the University of Padua and at the University of Venice and the University of Alicante for comments and suggestions.

Address correspondence to: Luca Nunziata, Department of Economics, University of Padua, Via del Santo 33, 35121, Padua, Italy (email: luca.nunziata@unipd.it).

Supplementary Material

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Online Appendix

Table S.1 Fallout dummy specification

Table S.2 Description of main variables

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