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ORIGINAL PAPER

Exposure to ionising radiations arising from the operation of nuclear installations and cancer mortality

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Abstract World-wide controversy continues to surround the question of whether exposure to ionising radiations arising from nuclear power plants and radioactive fuel cycle facilities could increase the risk of cancer. The objective was to analyse cancer mortality in towns close to Spanish nuclear power plants and radioactive fuel cycle facilities by reference to their history of exposure to artificial radiation generated by such emissions. An ecological cancer mortality study was conducted to know the effect of artificial radiation, estimated taken into account the magnitude of emissions, in towns ≤30 km of any installation. A model of atmospheric and aquatic dispersion of radionuclides was used. As reference, towns within a 50–100 km radius were matched with exposed by socio-demographic characteristics. For analysis purposes, log-linear Poisson models were fitted. The cumulative effective dose was the measure of exposure. Mortality rates ratios were calculated for each tumour site. Natural radiation and socio-demographic matching variables were included in the models, with 'installation' as a random effects term. The estimated cumulative artificial radiation dose was below 350 µSv for all sites. For nuclear power plants overall, analysis showed no positive association with increases in the cumulative dose. In the joint analysis of radioactive fuel cycle facilities, however, mortality was observed to rise with increases in the estimated radiation dose in the case of lung, bone and colorectal cancer, and in breast cancer among women. These results would not appear to be due to exposure arising from the operation of the installations, since were not reproduced around installations of the same type.

Keywords Environmental pollution/prevention and control · Epidemiology · Industrial pollution · Nuclear power · Spatial epidemiology

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Introduction

For some years now, controversy has surrounded the question of whether exposure to ionising radiations stemming from effluent discharges during the operation of nuclear power plants (NPPs) could increase the incidence of cancer in the exposed population.

A number of reports on childhood leukaemias in England (Cook-Mozaffari et al. 1989) and Germany (Michaelis et al. 1992), along with other papers published recently (Hoffmann et al. 2007; Kaatsch et al. 2008) including a meta-analysis (Baker and Hoel 2007), have shown an increase in risk among the population residing near nuclear installations. The authors indicated that, according to current radiobiological theory, this excess risk is not to be expected, in view of the low levels of exposure to artificial radiation proceeding from the installations. Efforts have, since, been made to replicate these results in the UK

(Bithell et al. 2008), France (Laurier et al. 2008) and, more recently, in a cohort study in Switzerland (Spycher et al. 2011), without statistically significant excess risk being found. In this respect, it is estimated that exposure to radioactive effluents from facilities currently in service is several orders of magnitude below the limit values set by regulatory requirements (in Spain 0.1 mSv/year at NPPs and 0.3 mSv/year at all remaining nuclear installations).

Most of the studies cited used ‘distance to installation’ as the variable of exposure, without using estimates of the dose emanating from the effluent itself. This method of classifying individuals may entail misclassification bias, reducing study’s ability to detect possible risks associated with exposure to installations discharges. Despite the fact that efforts have been made to reconstruct the dosimetric history of populations living in the neighbourhood of these types of installations (National Research Council 1995), it is difficult to find epidemiological cancer studies in the literature which include dose estimates incorporating information on the effluents discharged by such installations. In Spain, few studies have been undertaken on population health in the vicinity of NPPs and radioactive fuel cycle facilities (NFFs) (López-Abente et al. 1999, 2001; Silva-Mato et al. 2003) and these also use distance from town of residence to installation as the measure of exposure.

This study aimed to analyse cancer mortality (1975–2003) in towns lying near Spanish NPPs and NFFs and its possible relationship with their history of exposure to artificial radiation generated by discharges arising from the operation of such installations, using other Spanish towns that displayed similar socio-demographic characteristics, but were not situated in the vicinity of these installations as reference for comparison purposes.

Materials and methods

Study design

Cancer mortality was studied in towns situated near seven NPPs and five NFFs that had been operational in the period 1975–2003. With the exception of El Cabril and Juzbado, the NFFs are uranium mills usually located in mining areas. El Cabril is a nuclear waste storage facility built on the site of an abandoned uranium mine and Juzbado is a factory of uranium oxide fuel. A map including site and year of start-up of NPPs and NFFs in Spain was provided by López-Abente et al. (2001).

This was an ecological retrospective cohort study, with a population base made up of the inhabitants of towns neighbouring the nuclear installations under review. The area falling within a 30-km radius of any such installation was the ‘exposed zone’, while selected towns lying within a 50–100-km radius were the ‘reference zone’. The area falling within a 30-km radius of these installations is radiologically monitored by the Nuclear Safety Council (NSC). Exposure to artificial radiation in the reference zone was assumed to be nil.

This paper presents the results on mortality due to stomach [International Classification of Diseases-9 (ICD) 151], colorectal (ICD 153–4, 159.0), lung (ICD 162), bone (ICD 170), connective tissue (ICD 171), breast (in women, ICD 174), brain cancer, and to other tumours of the central nervous system (CNS) (ICD 191–192), thyroid (ICD 193), bladder (ICD 188), kidney (ICD 189), ovary cancer (ICD 183), non-Hodgkin lymphomas (NHLs) (ICD 200, 202), myeloma (ICD 203), Hodgkin’s disease (ICD 201) and leukaemias (ICD 204–208), in towns situated adjacent to nuclear facilities. The induction period used was 10 years, with the exception of leukaemias which were 1 year (Parkin et al. 1996).

Follow-up covered the period 1st January 1975–31st December 2003 in the case of installations which had come into operation prior to 1st January 1975, and dated from the respective installations’ entry into service in all other cases. For the seven NPPs as a whole, 328 towns within a 30-km radius and 303 within a 50–100-km radius were included in the study, matched by number of inhabitants, percentage of illiteracy, farmers and unemployed, province according to the 1991 census, and income level (Ayuso-Orejana et al. 1993). The reference towns were selected at random from among all those that met the matching criteria. For the five NFFs as a whole, 177 and 174 towns in the exposed and reference zones, respectively, were included in the study, matched as above.

Data were supplied by the National Statistics Institute (INE). Individual mortality records were broken down by cause, sex, age group, year of death and town of residence. The populations breakdown by sex, age and year for towns included, was obtained from the population census (1981, 1991, 2001) and municipal rolls (1986, 1996) as furnished by the INE. Relying on a log-linear polynomial regression model, interpolation was used to estimate annual municipal population figures for the period, 1981–1991 (Aickin et al. 1991). Pre-1981 populations were extrapolated by a linear procedure, allocating more weight to the nearest census year. With the annual population estimates for each town, person-years for each age band (0–4,…, 65–74, 75+), sex and period (1975–1978, 1979–1983,…, 1999–2003) were then calculated.

Table 1 shows the general characteristics of the subjects included in the study, for each installation. According to the 1991 census, the total population included in the 0–30-km area was 644,064 persons. In the case of NPPs, the study’s population base across the follow-up period amounted to a total of 5 million person-years in the 0–30-km belt, and to

6 million in the reference zone; and in the case of NFFs, the calculations showed 6 and 8 million person-years in the exposure and reference zones, respectively.

Effective dose estimation

To estimate the effective dose received by the population due to artificial radiation, models applied in international dose calculation standards, as compiled by the International Atomic Energy Agency (IAEA 2001), were used. This estimation was computed by NSC technicians and a detailed report of the procedures has recently been published (Jiménez et al. 2011). Briefly, isotope-specific radioactivity was taken into account, using original data obtained through a historical review of the records kept by NSC and the respective installations from the time they entered into service. A Gaussian model of atmospheric dispersion, with negligible diffusion, total reflection in soil and constant conditions of turbulence in each period of integration was used. The aquatic dispersion model assumed instantaneous, complete mixing of waters downstream from the discharge point, except in the case of seaside sites where dilution of radionuclides was estimated to occur within a 370-m-wide strip along the coast.

Once the radionuclide concentrations in installations' physical environment had been ascertained, the processes whereby such radionuclides reached individuals in the population, whether through direct impact or via the trophic chain was then reproduced. These mechanisms constitute the 'exposure pathways', the properties of which are specific to each site. For effluents released into air, external exposure (both to the plume itself and to the deposits accumulated in the soil), and human-body intake through inhalation and ingestion of contaminated foods, whether vegetable or animal, were considered. Insofar as effluents released to the aquatic environment were concerned, the following were considered: external exposure to sediments on river banks or beaches, ingestion of drinking water and fish and shellfish, and other contaminated foods of vegetable or animal origin, as described above (García-Talavera et al. 2010).

The estimated effective doses for town populations are the best-estimate annual doses received by the average adult person, for each town studied. Using these estimates, a cumulative exposure dose was allocated to each town population age and year stratum, thus obtaining an estimation of the average cumulative dose received by each birth cohort in each exposure period.

Natural radiation dose estimation

To estimate the dose of naturally occurring radiation, the calculations followed the methodology described in García-Talavera et al. 2007. Since natural radiation was assumed to be constant in time, a single value was estimated for each town. The exposure pathways considered were: cosmic radiation, terrestrial gamma radiation, inhalation of radon and thoron, and internal exposure to the remaining natural isotopes through ingestion of water and food. Estimates were expressed as mean values of the effective dose received by the inhabitants of each town and were obtained using the best information available for each of these parameters. The experimental data were drawn from the natural gamma radiation map of Spain (Suárez et al. 2000), previous NSC-sponsored research projects and tailored measurement campaigns. For calculating the dose in the case of radon, a great proportion of the surrounding towns affected were directly sampled (Quindós Poncela et al. 2003, 2004). In the case of variables having a minor contribution and those for which no local data were available (e.g. exposure to thoron or radioactivity in foods), national or world averages, or parameterisations furnished by the UNSCEAR were used. With respect to dose conversion factors, values proposed by the International Commission on Radiological Protection (ICRP) and stipulated in national legislation (RPSRI, 2001) transposing EU Directive 96/29 were used with the exception of factors corresponding to doses arising from external exposure to deposits in soil, in which case other sources had to be used (EPA 2002).

Statistical analysis

To analyse the association between cancer mortality and exposure to artificial radiation, cumulative doses were categorised into four levels, applying an algorithm designed to maximise heterogeneity among categories, as follows: (1) recorded doses are ranked in ascending order, (2) accumulated person-years per dose are calculated, (3) cut-off points that establish the quartiles of person-years are calculated, (4) a margin of variation is allocated to either side of each cut-off point, the largest dosimetric 'jump' within this range is sought, and this point is then chosen. This margin is calculated in such a way that, at minimum, each category will have a given proportion (85 %) of the population which is similar to what it would have if the cut-off points were population quartiles.

For analysis purposes, log-linear models were fitted on the assumption that the number of deaths per stratum followed a Poisson distribution. The study's main exposure variable was the effective dose for each year and town. The measure of exposure used was the cumulative effective dose: this involved taking individual age strata and birth cohorts for each town and considering the estimated doses in each year of exposure relevant for the stratum in question. The cumulative effective dose was the main explanatory covariate in the models. The dependent variable was

Table 1 General characteristics of the study population in areas adjacent to installations

	Population[a]	Subjects aged under 25 years[a]	Person-years (in thousands)[b]	Person-years (in thousands)[c]	% Illiteracy	% Unemployment	% Population engaged in farming	Income	Mean population 1991	Mean population 2001
Nuclear power plants[d]										
José Cabrera (1968–2006)										
0–30 km	25,816	7,305	807.1	684.0	5.6	10.4	22.7	6.2	461.0	481.4
50–100 km	29,914	9,293	943.7	825.8	4.5	10.9	18.8	6.5	564.4	819.7
Garoña (1971–)										
0–30 km	57,625	20,236	1,977.8	1,549.8	1.3	13.4	12.7	6.7	992.3	974.3
50–100 km	50,060	15,475	1,477.3	1,159.8	1.1	14.7	23.4	7.0	725.7	702.6
Vandellós (1972–)										
0–30 km	73,594	26,161	2,705.7	1,901.3	3.1	13.5	16.8	6.2	2,628.4	3,177.6
50–100 km	43,373	14,675	2,814.4	2,046.5	2.6	12.9	11.3	6.6	1,606.4	1,788.7
Almaraz (1981–)										
0–30 km	47,637	17,672	1,051.4	624.5	5.4	30.3	32.7	5.6	1,488.7	1,527.2
50–100 km	45,946	16,390	1,019.3	597.3	5.2	27.5	31.0	5.8	1,584.3	1,571.8
Ascó (1983–)										
0–30 km	49,049	13,410	967.4	468.0	1.9	10.7	27.1	6.5	876.7	817.9
50–100 km	61,594	19,275	1,322.6	719.3	2.1	9.7	23.5	6.6	1,162.2	1,455.1
Cofrentes (1984–)										
0–30 km	35,881	11,733	351.8	161.2	4.0	17.8	16.8	6.8	1,888.5	980.5
50–100 km	71,975	27,159	1,424.9	701.0	4.0	19.0	10.6	6.1	4,498.4	5,061.9
Trillo (1988–)										
0–30 km	13,259	3,312	195.6	61.8	3.2	11.2	25.5	5.4	232.6	214.1
50–100 km	12,976	3,392	188.3	59.9	2.4	11.4	26.2	5.7	231.7	212.2
Total										
0–30 km	302,861	100,075	8,056.8	5,450.6						
50–100 km	315,838	105,702	9,190.5	6,109.6						
Fuel cycle facilities										
Andújar (1959–1986)										
0–30 km	126,063	50,411	3,660.5	3,660.5	8.4	22.4	30.7	5.1	6,003.0	6,038.3
50–100 km	152,673	58,224	4,472.5	4,472.5	8.8	21.6	31.8	5.3	7,270.1	7,410.5
El Cabril (1961, 1993–)[e]										
0–30 km	38,781	13,545	441.9		9.7	34.8	25.2	5.1	4,309.0	4,291.9
50–100 km	44,373	18,114	405.1		10.2	35.6	39.0	4.5	5,546.6	5,637.1
La Haba (1977–1990)										
0–30 km	111,456	41,790	2,947.2	1,913.1	6.2	27.5	26.5	5.5	4,458.2	4,426.6
50–100 km	151,289	59,682	3,952.3	2,624.3	6.0	26.5	21.0	5.6	6,051.6	6,146.5
Saelices El Chico (Pl.Elefante 1978–2004)										
0–30 km	32,276	9,393	780.5	460.1	2.7	18.7	24.2	5.8	733.6	641.4
50–100 km	35,848	10,556	853.4	508.5	2.1	19.9	19.8	5.7	833.7	718.3

Table 1 continued

	Population[a]	Subjects aged under 25 years[a]	Person-years (in thousands)[b]	Person-years (in thousands)[c]	% Illiteracy	% Unemployment	% Population engaged in farming	Income	Mean population 1991	Mean population 2001
Juzbado (1985–)										
0–30 km	32,627	11,151	650.3	325.5	0.8	16.2	26.9	5.6	429.2	614.8
50–100 km	36,713	10,832	637.5	265.4	1.2	16.6	30.1	5.8	476.8	415.1
Total										
0–30 km	341,203	126,290	8,480.4	6,359.3						
50–100 km	420,896	157,408	10,320.8	7,870.7						

Income is a summary indicator ranging from 1 to 10

Nuclear power plants: the study covered 328 towns within 0–30 km and 303 within 50–100 km

Nuclear fuel facilities: 177 towns at a distance of 0–30 km and 174 at a distance of 50–100 km

[a] 1991 census

[b] Person-years based on 1-year induction period

[c] Person-years based on 10-year induction period

[d] Year of entry into service and closure

[e] As from 1961, radioactive waste produced by the then Nuclear Energy Board began to be stored in El Cabril. The current installations entered into service in 1993, and the dosimetric data furnished date from that time

the mortality rate (with person-years included as offset in the models). The regression coefficient of the exposure term gave the logarithm of the mortality rates ratios (RRs) for each malignant tumour.

In these Poisson regression models, the following variables were included as covariates: age group, period, naturally occurring radiation, and socio-demographic matching variables (percentage of illiteracy, farmers and unemployment and income level). In the joint analysis of the installations, the variable ‘installation’ was included as a random effects term (Gelman and Hill 2007). Moreover, specific analyses on individual installations were run.

Exposure was analysed as a continuous variable, and in another model, as a categorical variable; in the former case, a linear relationship with dose was assumed, and the RR and its confidence interval were estimated for an increase of 10 μSv in the cumulative effective dose; in the latter case, the RR and its confidence interval were estimated for the respective exposure levels, which enabled the ‘shape’ of the relationship between dose and mortality to be ascertained. The existence of a dose–response gradient is estimated by considering the statistical significance of the inclusion of the exposure variable categorised in the model as a continuous variable. In the second analysis, the median dose in each exposure category was used (Thakur 1985; Thomas 2009). Model results were checked and corrected for overdispersion problems (Breslow 1984) using robust methods (Zellels 2006).

Results and discussion

Table 2 shows the ranges of exposure estimations due to artificial radiation expressed as cumulative effective dose in microSievert, and to annual natural radiation in towns in these installations’ respective vicinities. The magnitude of the estimated levels of artificial radiation, to which populations in the proximity of installations are exposed, is very low. The highest cumulative exposure levels for NPP, 303 μSv, were registered in the Garoña area, where annual natural radiation exposure ranges from 1.67 to 2.28 mSv (2,280 μSv). Doses due to the operation of Spanish nuclear facilities represent at most 0.15 % of the total (natural plus artificial) radiation doses which is consistent with the average figure of 0.03 % cited by BEIR V (National Research Council’s Committee on Biological Effects of Ionizing Radiations 1990).

Joint analyses of all nuclear power plants and nuclear fuel facilities

Table 3 sets out the results of the joint analysis of the NPPs and NFFs for both sexes, with the different types of cancer-

Table 2 Range of annual cumulative artificial and natural radiation doses in towns lying in the vicinity of installations

	Number of towns 0–30 km	Cumulative artificial radiation dose range µSv	Annual natural radiation dose range µSv 0–30 km	Annual natural radiation dose range µSv 50–100 km
Nuclear power plants				
José Cabrera	60	0.1015–267.5055	2,031–2,837	2,270–4,250
Santa M[a] de Garoña	68	6.5186–303.6069	1,770–2,280	1,760–3,230
Vandellós (I and II)	46	0.0711–203.0569	1,928–2,627	2,020–2,850
Almaraz	33	0.0188–27.5820	2,340–5,840	2,360–4,420
Ascó (I and II)	65	0.0302–5.6996	1,819–2,786	1,780–2,420
Cofrentes	19	0.0284–2.6245	1,695–3,730	1,480–2,310
Trillo	62	0.0458–10.6320	1,752–2,040	2,110–3,620
Total	328[a]	0.0188–303.6069	1,695–5,840	1,480–4,420
Nuclear fuel facilities				
Andújar	22	2.9096–348.4730	1,917–2,470	1,480–3,840
El Cabril	9	0.0004–0.0030	2,705–4,198	1,600–4,170
La Haba	26	8.1387–138.1390	2,577–20,103	1,830–2,490
Saelices El Chico	44	19.8833–289.1230	3,431–15,413	25,70–6,570
Juzbado	76	0.000015–0.0579	2,416–5,112	1,740–5,400
Total	177	0.000015–348.4730	1,917–20,103	1,480–5,400

[a] Vandellós and Ascó share 25 municipalities located at a distance of less than 30 km from the two facilities. For this reason, the total number of municipalities included (328) does not correspond to the sum of the municipalities in the vicinity of the nuclear power plants (353)

related mortality shown against the estimated doses of cumulative artificial radiation. For NPPs, no increase in RRs was seen with dose in the analysis using dose categories or in the analysis of dose as a continuous variable, since all the confidence intervals included unity. None of the point estimators for the respective levels of exposure proved to be statistically significant. The table indicates that there was heterogeneity among installations in the case of lung and stomach cancer. All estimates were adjusted for age, period, natural radiation, and socio-demographic variables.

The results for NFFs show mortality increasing with the estimated dose of radiation for lung, bone and colorectal cancer, and for breast cancer in women. Moreover, in the first three cases, analysis of exposure as a continuous variable was also statistically significant. In these tumours, the RRs for all dose categories were >1. The heterogeneity test showed that, as between installations, there were differences in risk for breast cancer and lung cancer, though in the latter case these failed to attain statistical significance. When separate analyses were conducted for men and women, the statistical association between dose and mortality in the case of lung cancer was observed among men, while in the case of bone cancer, colorectal cancer, and leukaemias this association only acquired statistical significance among women.

Results for specific nuclear power plants

For NPPs, in general, the results by installation again failed to display any systematic increase in mortality RRs with dose. There are, however, some results of interest (Table 4).

In the José Cabrera area, no association of statistical significance was detected, though in the case of multiple myeloma, all RRs were above unity and statistically significant excess mortality was observable in the third category (RR 3.260; 95 % CI 1.115–9.535). No clear dose–response relationship was in evidence. The area surrounding the José Cabrera facility registered higher multiple myeloma mortality in both sexes, a result already reported (López-Abente et al. 1999). Yet, this result would not seem to be associated with the dose of artificial radiation, since the RR in the highest exposure category was lower than that observed for the lowest exposure category. Though the aetiology of multiple myeloma is poorly understood, ionising radiation is still considered a possible risk factor for this cancer. The results, however, do not seem to support a causal relationship.

The Garoña area did not register statistically significant excess cancer mortality with increasing dose, with the sole exception of kidney cancer, when dose was analysed as a continuous variable (RR 1.045; 95 %CI 1.003–1.088). When exposure categories were examined, however, the

RRs were not coherent with a possible increase in risk with cumulative dose, since the RRs corresponding to the first three levels of exposure were <1. In the analysis by sex, a positive relationship was seen only for women. Renal tissue, though apparently not overly radiosensitive (IARC 2000), is the target organ for the toxic effects of uranium (Taylor and Taylor 1997). Nevertheless, this result was not replicated at other NPPs and NFFs. Leukaemia-related mortality was higher among exposed groups, but the RRs displayed no clear upward trend with dose of artificial radiation.

The results around the Vandellós facility showed a dose–response relationship for lung cancer mortality when exposure was analysed as a continuous variable. Even so, neither the joint analysis nor the analysis by sex depicted any clear increase in RRs by category.

In the Almaraz area, the single most notable finding was arguably that for mortality due to connective tissue tumours because, while only one death was registered in the reference zone, ten were recorded in towns lying at distances of less than 30 km. Although this difference gave rise to very high point estimators by the exposure category, their accuracy was very low, due to the small number of deaths. Ovarian cancer displayed excess risk in the highest exposure interval as well as a statistically significant dose–response relationship.

Other tumours with a positive result were NHLs in the proximity of the Ascó NPP, around which these tumours registered an excess mortality of over 15 % vis-à-vis the reference zone for all exposure categories, in men and women alike, though the dose–response test for trend failed to reach statistical significance.

Finally, in the Cofrentes and Trillo areas, there was no result warranting detailed comment.

As noted above, there is still a controversy as to whether exposure to ionising radiations arising from effluent discharges during routine NPP operation could increase the risk of incidence of cancer in the exposed population. Most of the studies mentioned in "Introduction" were conducted using distance to installation as the exposure variable, with it proving difficult to locate the papers that used an approach similar to the applied here.

The examples of dose reconstruction described in the National Research Council's monograph are radically different to this case, since they involve nuclear weapons test sites and reactor accidents (National Research Council 1995). In 2006, however, a paper was published on leukaemia incidence in subjects under 15 years of age residing in the vicinity of 23 nuclear installations in France (Evrard et al. 2006). The exposure considered was the estimated dose received by the red bone marrow arising from emissions to air. Exposure was assessed by the Institute for Radiation Protection and Nuclear Safety using emission and climatological data and a mathematical model of radionuclide transfer to the environment. The estimated doses ranged from 0.06 to 1.33 μSv/year, with an average of 0.17 μSv/year. Standardised incidence ratios were used as the effect measure, and doses categorised into five levels were studied without taking cumulative doses into account. The data corresponded to emissions for the period 1996–2000 and incidence of leukaemias from 1990 to 2001. The designated study area was 40 km^2 around each installation, corresponding to a radius of 3.6 km. The paper concludes by stating that no excess or dose–response trend was found in leukaemia incidence among teenagers and young adults, associated with the dose of artificial radiation in the proximity of the 23 French nuclear installations studied.

This study adds no new information about a possible excess of childhood leukaemias in the vicinity of installations, due to the non-existence of cancer incidence records in most of the areas studied and to the fact that mortality data are insufficient to study these types of tumours. Childhood leukaemia mortality in Spain began to decline in the late 1970s as result of therapeutic improvements introduced in this decade (Pollán et al. 1995). Among childhood tumours, leukaemias display the best survival, i.e. from 1980 to 1985, survival stood at 54 %, and by the 1990s haematological tumour survival exceeded 70 % (Peris-Bonet et al. 2010). The same can be said of some of the other above-mentioned tumours having high survival rates, such as Hodgkin's lymphomas, testicular cancer and breast cancer.

Results for specific nuclear fuel facilities

The results of the joint analysis of the NFFs showing a dose–response pattern for lung, bone and colorectal cancer mortality in both sexes and for breast cancer in females, appeared to be determined by the results obtained around the Andújar Uranium Plant (Table 5). This installation accounts for 43 % of the total person-years for NFFs. In the environs of this plant, excess mortality was observed for lung cancer, bone cancer, colorectal cancer and female breast cancer. Lung cancer mortality RRs for men were significantly higher at all levels of exposure than in the reference zone, and above 1.25 for all exposure categories of cumulative artificial radiation dose, with a statistically significant trend. In Andújar, an earlier cohort study highlighted higher lung cancer mortality associated with occupational exposure to radiations among Nuclear Energy Board employees engaged in uranium processing (Rodríguez Artalejo et al. 1997). In this study, lung cancer mortality rates in men and women were higher than those in the reference zones, with a significant dose–response association in men, yet the nature of the study meant that the most important confounding factor for this tumour,

Table 3 Joint analysis of all nuclear power plants (a) and nuclear fuel cycle facilities (b). Both sexes

	Deaths[a]					RR[b] d1	RR d2	RR d3	RR d4	Trend p value	RR[c] dose	95 % CI		Homog p value
Dose category μSv	d0 reference	d1	d2	d3	d4	(0.0001–	6.3649–	28.2267–	70.255–)					
(a) Nuclear power plants														
Lung cancer	2,022	572	498	457	421	0.938	0.873[d]	0.811[d]	0.997	0.425	1.001	0.995	1.008	0.007
Bone cancer	56	18	12	9	19	1.250	0.708	0.471	1.316	0.273	1.012	0.979	1.046	0.058
Cancer of the CNS	306	64	99	74	65	0.730[d]	1.125	0.795	0.870	0.492	0.993	0.978	1.009	0.243
Thyroid cancer	36	4	8	6	6	0.376	0.762	0.734	0.925	0.795	1.003	0.954	1.055	0.079
NHL	217	63	64	43	50	1.012	1.004	0.682	1.144	0.297	1.011	0.993	1.029	0.058
Hodgkin	27	5	13	5	9	0.614	1.482	0.644	1.065	0.849	0.997	0.952	1.045	0.364
Myeloma	150	44	49	26	39	0.987	1.112	0.601[d]	1.229	0.270	1.004	0.983	1.025	0.684
Bladder cancer	485	142	148	141	109	1.082	0.980	0.872	0.944	0.872	1.000	0.988	1.012	0.067
Connective tissue	39	14	18	8	7	1.335	1.617	0.704	0.784	0.348	0.973	0.927	1.021	0.822
Kidney cancer	203	60	51	67	47	1.008	0.868	1.248	1.170	0.308	1.013	0.996	1.031	0.090
Stomach cancer	1,092	262	273	414	197	0.843[d]	0.875	1.109	0.890	0.494	0.999	0.990	1.008	0.009
Colorectal cancer	1,369	432	430	334	271	1.038	1.046	0.967	0.918	0.182	0.995	0.987	1.003	0.353
Breast cancer (women)	690	177	219	188	174	0.932	1.070	1.029	1.107	0.411	1.006	0.996	1.016	0.376
Ovarian cancer	166	61	60	36	33	1.250	1.274	0.864	0.873	0.364	0.984	0.963	1.006	0.412
Testicular cancer	7	1	1	0	1	0.405	0.511	–	0.764	0.996	1.004	0.890	1.134	0.632
Dose category μSv						(0.00041–	0.11239–	1.61190–	43.97026–)					
Leukaemias[e]	502	121	159	78	132	0.953	0.975	0.924	0.977	0.966	1.002	0.988	1.016	0.199
(b) Fuel cycle facilities														
Dose category μSv						(0.00001–	6.3649–	28.2267–	70.255–)					
Lung cancer	2,812	486	760	516	750	1.097	1.175[d]	1.209[d]	1.303[d]	<.001	1.008	1.003	1.013	0.086
Bone cancer	81	23	17	18	26	1.536	1.125	1.551	1.770[d]	0.046	1.031	1.005	1.058	0.507
Cancer of the CNS	312	43	86	56	71	0.696[d]	1.378[d]	1.119	1.207	0.136	1.004	0.988	1.019	0.070
Thyroid cancer	34	5	12	11	5	0.762	1.659	2.289	0.862	0.778	1.002	0.953	1.055	0.209
LNH	232	47	63	31	47	1.129	1.156	0.772	0.966	0.430	0.992	0.974	1.011	0.896
Hodgkin	61	7	14	12	11	0.467	1.072	0.953	0.966	0.785	1.023	0.988	1.059	0.401
Myeloma	181	43	41	25	41	1.376	0.811	0.844	0.961	0.577	0.998	0.979	1.018	0.346
Bladder cancer	633	98	150	91	130	0.926	1.156	1.068	0.990	0.977	1.000	0.989	1.010	0.438
Connective tissue	64	7	18	7	10	0.787	1.253	0.655	0.724	0.267	0.980	0.942	1.019	0.327
Kidney cancer	263	62	74	52	57	1.365	1.129	1.165	1.055	0.990	0.994	0.977	1.011	0.512
Stomach cancer	1,427	309	266	211	274	0.838[d]	0.728[d]	0.774[d]	0.945	0.510	1.001	0.993	1.009	0.217
Colorectal cancer	1,568	300	444	280	394	1.011	1.146[d]	1.079	1.153[d]	0.037	1.007	1.001	1.013	0.384
Breast cancer (women)	887	158	208	143	211	1.036	1.062	1.039	1.196[d]	0.022	1.003	0.993	1.012	0.044
Ovarian cancer	203	40	63	35	49	1.271	1.473[d]	1.176	1.025	0.737	0.994	0.978	1.011	0.123

Table 3 continued

	Deaths[a]													
Dose category µSv	d0 reference	d1	d2	d3	d4	RR[b] d1	RR d2	RR d3	RR d4	Trend *p* value	RR[c] dose	95 % CI		Homog *p* value
						(0.0001–	6.3649–	28.2267–	70.255–)					
Testicular cancer	9	0	7	3	1	0.000	2.188	1.600	0.314	0.460	0.980	0.903	1.063	0.992
Dose category µSv						(0.000003–	2.2852–	18.45577–	59.512–)					
Leukaemias[e]	636	105	156	116	155	0.956	1.015	1.170	1.109	0.173	1.010	1.000	1.019	0.199

Estimates were obtained from a mixed regression model that included power plants as a random effects term, and were adjusted for natural radiation, age and socio-demographic variables. The analysis was restricted to the operational period

[a] Number of deaths by exposure category (estimated cumulative artificial radiation dose)

[b] Rates ratios (RRs) by category of cumulative artificial radiation dose compared to the reference zone and test for trend *p* value

[c] RRs for the cumulative dose (per 10 µSv) taken as continuous variable, 95 % confidence interval. 10-year induction and 5-year latency period (exposure lag)

[d] The confidence interval does not include unity

[e] The dose categories for leukaemias are different for the 1-year induction and latency period

namely, tobacco use, could not be controlled for. Excess mortality was also observed for colorectal cancer in both sexes, and for breast cancer and leukaemias among women.

Of the remaining NFF, the only one warranting special mention is Saelices El Chico, where higher central nervous system (CNS) cancer mortality rates were observed in the highest exposure categories. Thus, of the 24 deaths registered in the 0–30-km zone, 11 occurred in the highest exposure category, with this pattern being applicable to men and women alike. Ionising radiation can induce tumours of the CNS, though the relationship is not as strong as for several other tumours (UNSCEAR 2008).

The nuclear fuel cycle generates discharges of artificial radionuclides, and isotopes of plutonium, americium, cesium, strontium, iodine, polonium, uranium and thorium in particular. In some countries, this has led to the study of radio-analytical data on autopsy, foetal, urine and dental material in the general population (Hodgson et al. 2004; Mangano et al. 2003). These studies show that all such discharges leave biological traces in exposed populations, which can be detected through isotopes that are not present in nature. For radioactive elements with a very long half life, chemical toxicity far outweighs radiological toxicity (e.g. rubidium versus natural uranium). Uranium's chemical toxicity is more important than its radiological toxicity and has led the French authorities to regulate the limits of ingestion and inhalation of uranium compounds to 150 and 2.5 mg, respectively, without considering the isotopic composition of the element (CEA 2003).

In epidemiological terms, the problem of the chemical toxicity of these artificial elements is very little studied in human populations and might be an avenue to be considered in the explanation of phenomena that do not fit into current radiobiological knowledge (Hodgson et al. 2004).

One aspect to be borne in mind when assessing the results is the presence of other types of polluting industries in the vicinity of nuclear installations. There are 11 polluting industries located near the Andújar Uranium Plant, namely, eight ceramic manufacture plants, two waste storage sites and a paper mill. The ceramic industry is characterised by its heavy discharges of SO_2, fluoride and PM_{10}. While these types of discharges could theoretically contribute to the excess lung cancer observed, they would not account for the results obtained for bone cancer and leukaemias. Furthermore, excess lung cancer mortality was not observed among women, something that could point to either an occupationally related effect, or alternatively, to differential lifestyle habits. Excess bone cancer mortality was only observed among women, with an RR of over 1.70 in all the exposure intervals. Some radionuclides (barium, strontium, radium and transuranic elements) are osteotrophic (CEA 2003).

Table 4 Analysis by nuclear power plant

	Deaths[a]												
	d0 reference	d1	d2	d3	d4	RR1[b]	RR2	RR3	RR4	Trend p value	RR[c] dose	95 % CI	
Jose Cabrera (doses in µSv)						(0.016–	0.154–	0.395–	2.357–)				
Myeloma (both sexes)	21	8	8	12	6	2.164	2.197	3.260[d]	1.624	0.590	0.999	0.961	1.038
Myeloma men	12	2	6	8	3	1.068	1.704	2.691	1.211	0.630	1.000	0.942	1.062
Myeloma women	9	6	2	4	3	2.998	2.212	3.987	2.489	0.839	1.007	0.957	1.060
Garoña (doses in µSv)						(0.021-	10.541-	42.484-	45.913-)				
Kidney cancer (both sexes)	45	8	14	17	37	0.481	0.828	0.484	1.146	0.026	1.045	1.003	1.088
Kidney cancer men	34	4	7	11	24	0.367	0.493	0.383	1.028	0.022	1.026	0.977	1.076
Kidney cancer women	11	4	7	6	13	0.593	1.825	0.891	1.584	0.279	1.078	1.002	1.160
Ovarian cancer	43	9	11	9	11	0.604	0.445[d]	0.285	0.179[d]	0.012	0.781	0.587	1.039
Leukemias (both sexes)	73	9	32	21	32	1.032	1.103	1.459	1.131	0.947	1.016	0.974	1.061
Leukemias men	44	6	16	13	20	1.417	0.879	1.876	1.448	0.580	1.049	1.003	1.097
Leukemias women	29	3	16	8	12	0.612	1.307	0.972	0.759	0.557	0.918	0.842	1.002
Vandellós (doses in µSv)						(0.021–	0.321–	130.588–	174.585–)				
Lung cancer (both sexes)	779	126	152	132	219	0.930	0.843	0.990	1.159	0.703	1.001	1.000	1.002
Lung cancer men	687	114	138	120	198	0.951	0.859	0.984	1.166	0.801	1.001	1.000	1.002
Lung cancer women	92	12	14	12	21	0.836	0.747	1.001	1.061	0.795	1.001	0.998	1.004
Almaraz (doses in µSv)						(0.011–	0.087–	0.107–	0.155–)				
Connective tissue (both sexes)	1	3	4	2	1	14.988[d]	58.541[d]	87.120[d]	3.531	0.920	1.189	0.424	3.332
Connective tissue men	0	2	4	2	1								
Connective tissue women	1	1	0	0	0								
Ovarian cancer	18	5	4	7	13	0.776	2.267	2.131	3.507[d]	0.001	1.009	0.443	2.295
Ascó (doses in µSv)						(0.020–	0.046–	0.118–	1.842–)				
NHL (both sexes)	38	9	9	9	15	1.376	1.252	1.166	1.799	0.148	10.039	0.596	169.080
NHL men	21	5	5	1	8	1.461	1.460	0.228	1.607	0.326	9.529	0.193	469.343
NHL women	17	4	4	8	7	1.344	1.109	2.313	2.068	0.252	12.057	0.269	540.45

[a] Number of deaths by exposure category (estimated cumulative artificial radiation dose)

[b] Rates ratios (RRs) by category of cumulative artificial radiation dose compared to the reference zone and test for trend p value

[c] RRs for the cumulative dose (per 10 µSv) taken as continuous variable, 95 % confidence interval. 10-year induction and 5-year latency period (exposure lag)

[d] The confidence interval does not include unity

Table 5 Results of the analysis in the area adjacent to the Andújar Uranium Plant

	Deaths[a]												
	d0 reference	d1	d2	d3	d4	RR1[b]	RR2	RR3	RR4	Trend p value	RR[c] dose	95 %	CI
Dose category μSv						(0.036–	7.438–	52.266–	97.282–)				
Lung cancer (both sexes)	1,239	275	295	195	428	1.276[d]	1.248[d]	1.299[d]	1.255[d]	0.040	1.004	0.997	1.012
Lung cancer men	1,111	245	277	176	393	1.307[d]	1.280[d]	1.341[d]	1.253[d]	0.038	1.003	0.996	1.011
Lung cancer women	128	30	18	19	35	1.103	0.876	1.083	1.332	0.310	1.020	1.001	1.039
Bone cancer	53	16	11	12	14	1.290	1.414	1.198	1.459	0.450	1.031	0.998	1.065
Bone cancer men	40	9	7	8	7	0.884	1.212	1.049	0.980	0.957	1.007	0.966	1.050
Bone cancer women	13	7	4	4	7	2.754[d]	2.063	1.721	2.973	0.216	1.062	1.014	1.112
Breast cancer women	393	84	76	62	117	1.149	1.114	1.271	1.376[d]	0.018	1.003	0.993	1.013
Stomach cancer	710	163	92	121	135	0.907	0.854	1.035	1.073	0.354	1.010	1.001	1.018
Stomach cancer men	434	100	59	80	85	0.881	0.860	1.192	1.054	0.258	1.011	1.001	1.021
Stomach cancer women	276	63	33	41	50	0.949	0.840	0.823	1.119	0.889	1.008	0.991	1.025
Colorectal cancer	701	144	165	101	222	1.078	1.237[d]	1.398[d]	1.199	0.030	1.008	1.001	1.015
Colorectal cancer men	363	75	88	49	117	1.126	1.219	1.416	1.126	0.273	1.006	0.996	1.016
Colorectal cancer women	338	69	77	52	105	1.027	1.253	1.388	1.294	0.039	1.011	1.001	1.021
Dose category μSv						(0.015–	1.247–	26.775–	70.885–)				
Leukaemias	244	52	58	63	62	1.248	1.300	1.122	1.490	0.141	1.010	0.995	1.026
Leukaemias men	131	24	37	30	37	0.968	1.457	0.986	1.584	0.274	1.013	0.992	1.034
Leukaemias women	113	28	21	33	25	1.643	1.104	1.286	1.401	0.272	1.007	0.988	1.030

[a] Number of deaths by exposure category (estimated cumulative artificial radiation dose)

[b] Rates ratios (RRs) by category of cumulative artificial radiation dose compared to the reference zone and test for trend p value

[c] RRs for the cumulative dose (per 10 μSv) taken as continuous variable, 95 % confidence interval

[d] The confidence interval does not include unity

Radiosensitivity of different tissues

When it comes to interpreting the results, it is advisable to bear in mind that the radiosensitivity of human tissue to induction of cancer is variable (UNSCEAR 2000, 2008). The types of cancer that tend to be more consistently associated with exposure to ionising radiations are leukaemias, cancer involving breast tissue, and thyroid cancer among teenagers and young adults. Although comparatively less susceptible, it also accepted that tumours of the salivary glands, oesophagus, stomach, colon, liver, lung and CNS are associated with exposure to ionising radiations. Those malignancies which have never shown or only sporadically shown an association with this exposure are chronic lymphatic leukaemia, pancreatic cancer, Hodgkin's lymphoma, and tumours of prostate, testicle and cervix (UNSCEAR 2000, 2008). Sites of all the above categories were included in this study. Even so, the statistical associations found were not observed for the most radiosensitive tumours. When it comes to assessing this lack of association, it should be borne in mind that some of the tumours which affect especially radiosensitive organs register high survival rates, as is the case of breast cancer (81 % at 5 years) and thyroid cancer (87 %) (Sant et al. 2009).

Strengths and limitations of the study

One limitation of this study is its use of mortality rather than incidence data. Currently there is not a national cancer incidence registry in Spain, which would allow for this type of approach using incidence data. With the exception of Tarragona, none of the regions included have a population-based cancer registry. However, the validity of death-certificate diagnoses for investigating cancer in Spain (Pérez-Gómez et al. 2006) and in other western countries is generally accepted (Laplanche 1998; Reynolds et al. 1991).

The study is ecological in the sense that the main exposure variables refer to population groups. Although the matching used to select reference towns was intended to ensure that these would be as similar as possible, to reduce possible confounding effects, the study took no account of the possible influence of other individual exposures of the populations compared (local occupational or environmental exposures). The way of controlling for possible confounding factors is closely limited by the availability of information. The most evident example is tobacco use. The results yielded by women for smoking-related tumours are of special interest, since the prevalence of female smokers in generations

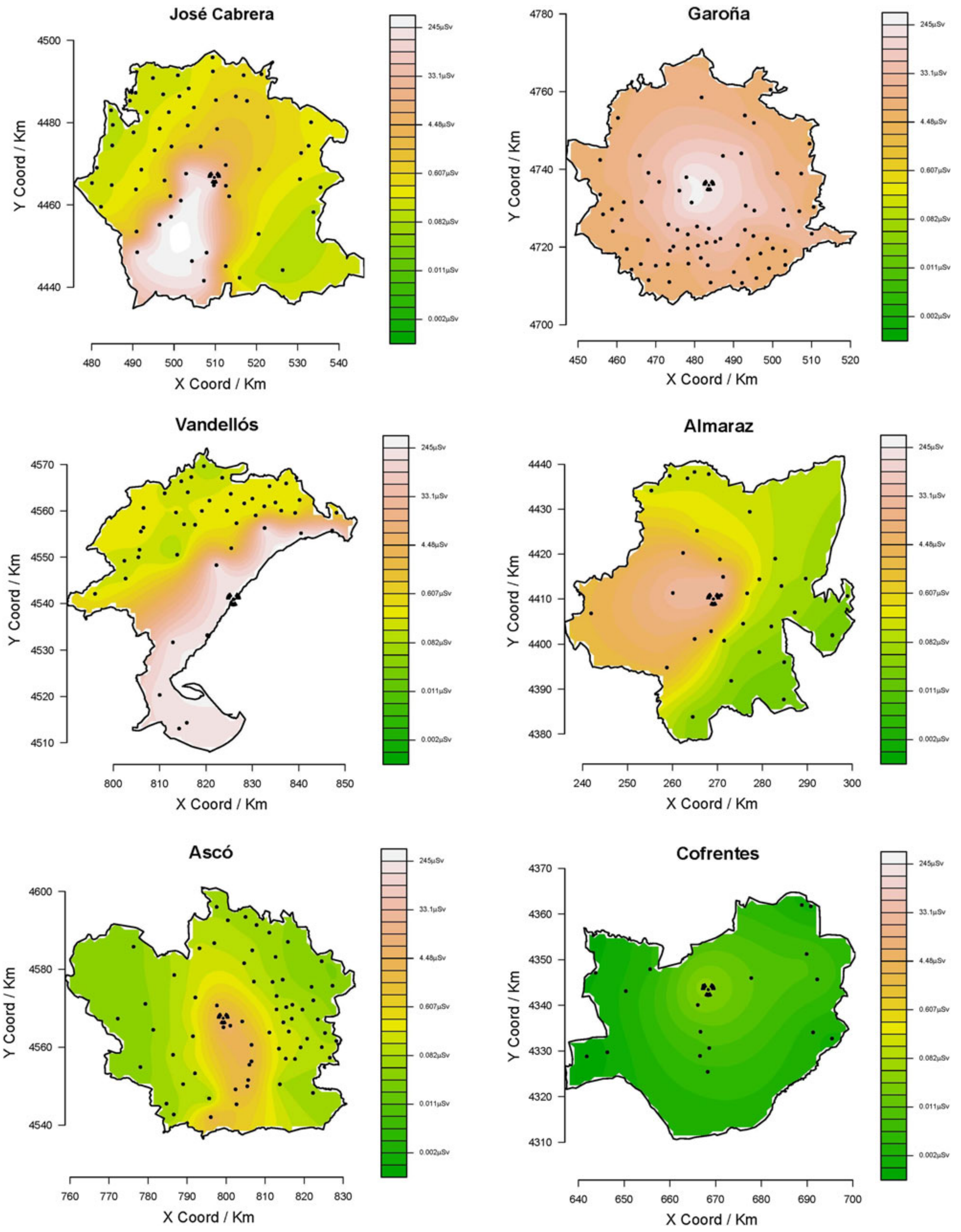

Fig. 1 Distribution of cumulative effective doses arising from effluents discharged by nuclear power plants, depicted on a single scale. Only the towns in the 30-km areas are mapped. Isodose lines were estimated using kriging

born before 1940 was very low in Spain (López-Abente et al. 1995). With respect to other confounding factors, one strength of this study is the inclusion of the estimated dose of natural radiation in each town. Other sources of exposure to ionising radiations (such as medical or occupational exposures) could not be taken into account. Nonetheless, there is no reason to believe that in this exposure there are differential values which might be associated with artificial radiation.

The effective dose was selected as exposure indicator, since this parameter provides clear benefits in the case of wide-ranging, broad-spectrum studies. This approach has been endorsed by the ICRP in response to a query from the NSC. To estimate effective doses, conservative values were used when best estimates of site-specific parameters were unavailable. While the magnitude of effective doses due to effluents ranged from 3.05e7 μSv to 73.4 μSv per year, the magnitude of doses due to natural radiation ranged from 1,670 to 20,100 μSv per year, though this latter value was obtained in a single town. On average, effective dose due to exposure to natural radiation is 300 times higher than that due to exposure from installations' effluent discharges. One limitation is the impossibility of finding ways of validating the estimated doses by means of environmental or biological measurements drawn from the study area. Although radiological surveillance of such installations and their surrounding areas includes these types of measurements, the values recorded are generally below the detection limits.

The spatial distribution of data classified by the dose category differs from the radial pattern produced by the distances used in previous studies, owing to the fact that the specific characteristics of each site and of land and water use in the zone were considered. The dose arising from effluent discharges depends most on the exposure to liquid effluents (if any) and, to a lesser degree, on atmospheric dispersion, which is determined by the local wind patterns, release height and relief of terrain. The distribution of the cumulative dose by town is depicted in Fig. 1 for some of the NPPs. Although distance might be a good approximation in certain installations (e.g. Garoña), the spatial distribution of the estimated dose is generally anisotropic. Hence, in the environs of Almaraz, 66 % of the towns classified by distance would change the level if dosimetric categorisation was applied.

Nuclear safety

The results of this and earlier studies, coupled with the nonexistence of mortality patterns pointing to an excess risk of cancer in the proximity of these installations, lead to the conclusion that population exposure to radiation arising from their emissions from normal operation of the facilities is very low. The real problem that originated this study lies in the existing deep social concern. This study was undertaken between 2006 and 2009, prior to the nuclear accident caused by the tsunami in Japan (11th March 2011), which marked a 'before and after' in the assessment of the sustainability of nuclear energy and its impact on human and natural ecosystems. Nevertheless, in the light of the existing store of knowledge about the carcinogenic nature of exposure to ionising radiations and the experience gained in nuclear energy production world-wide, it is essential (1) to ensure that the existent NPPs and NFFs are safe against natural disasters or caused accidents, and (2) to seek a reasonable and safe solution for the proper management of the waste generated by such installations. From a public health standpoint, these last two matters—rather than emissions from standard, routine operation of facilities—that are the crux of the problem now confronting nuclear energy, and they are important enough to question the sustainability of this form energy production in the long term.

Conclusion

In conclusion, this study shows that the cumulative doses of artificial radiation, which the population would have received as a consequence of the operation of the installations across the study period, are very small. This study has detected no results that would consistently indicate a systematic increase in mortality due to any type of cancer associated with the dose of artificial radiation incurred.

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