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Cancer Incidence among Australian Nuclear Industry Workers

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Abstract: Cancer Incidence among Australian Nuclear Industry Workers: Rima R. HABIB, *et al*. Faculty of Health Sciences, American University of Beirut, Lebanon—To assess whether workers at Lucas Heights Science and Technology Centre (LHSTC) had different levels of cancer incidence from the New South Wales (NSW) population in Australia. A retrospective cohort study was undertaken at LHSTC. Data on 7,076 workers employed between 1957–98 were abstracted from personnel, dosimetry, and medical files. An inception cohort was defined which included 4,523 workers in employment between 1972–96 to examine cancer incidence. Cancer registrations in the inception cohort were identified to 1996 through electronic linkage of records with the NSW and the Australian national registers of cancer incidence. All-cancer incidence in workers at LHSTC was 15% below the NSW rates [SIR=0.85; 95% CI=(0.75, 0.95)]. Of 37 specific cancers and groups of cancers examined, statistically significant excesses relative to NSW rates were observed only for pleural cancer incidence [SIR=17.71; 95%=(7.96, 39.43)], and for incidence of cancer of the small intestine [SIR=4.34; 95% CI=(1.40, 13.46)]. This study gives little evidence of an increased risk of cancers associated with radiation exposure in a cohort of nuclear workers in Australia. The observed increase in the risk of cancer of the pleura was probably due to unmeasured exposures, given the lack of an established association with radiation exposure, and the strong link to asbestos exposure. Findings for cancers of the small intestine were based on small numbers and were likely to be due to chance.
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Key words: Cohort, Ionising radiation, Cancer incidence, Nuclear industry

Studies of workers in the nuclear industry have burgeoned over the last three decades in an effort to understand the long term health effects of low protracted doses of ionising radiation[1–10]. Mortality, and specifically cancer mortality, has been the main focus of these studies. Mortality data, however, are inherently limited as a means of assessing cancer causation, as they are influenced by trends and patterns in treatment. In addition, cancer sites with relatively high survival rates result in fewer death than incidence counts. Consequently, cancer incidence analyses are more accurate than mortality analyses in cancer risk estimation. It was not until recently, though, that such morbidity studies became feasible and the establishment of cancer registries has greatly facilitated the follow-up of cohorts in cancer incidence studies[4, 11–15] by providing reliable passive mechanisms through electronic linkage of records.

Lucas Heights Science and Technology Centre (LHSTC) houses Australia's only nuclear reactor which has been in operation since 1959 in New South Wales (NSW). The health of workers at LHSTC was the subject of an earlier study[16], which found no evidence of an association between radiation and cancer. However, the cross-sectional nature of that study was not suitable for exploring diseases with long latency such as malignancies[16, 17].

In order to provide better information on the health of the workforce at LHSTC, the authors carried out a retrospective cohort study to assess cancer risks among these workers. Results on cancer mortality among workers at LHSTC were previously reported[18].

The main focus of this paper was to compare the cancer incidence rates of workers at LHSTC with those of the general NSW population of approximately 6.5 million people (around one-third of the total Australian population)[19], and by inference to provide an indication of cancer risks to these workers. Of particular interest were radiosensitive cancer sites known *a priori* to be associated with ionising radiation.

This study is also part of a larger international collaborative effort coordinated by the International Agency for Research on Cancer (IARC)[20], to estimate cancer risk from low-level ionising radiation through

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analyzing pooled data on more than 400,000 nuclear industry workers from 15 countries.

Methods

Study population and inception cohort

The design and methods of data collection, methods used to determine the vital status, and ethical considerations have been described previously[18]. We summarize here some of these aspects and we give additional information relevant to the inclusion of data on cancer registration.

A cohort of 7,076 workers, employed at LHSTC between 1 January 1957 and 31 December 1998, was compiled using LHSTC records. Workers with potential exposure to ionising radiation were monitored for such exposure through the Personnel Dosimetry Service at LHSTC. They were issued individual dosimetry files on which radiation doses were documented. These files were all archived by the Personnel Dosimetry Service. Workers not monitored for ionising radiation exposure were considered by default not to have been exposed. Such workers were employed mainly in administrative jobs.

The period of follow-up for cancer incidence was dictated by the establishment of state and national cancer registries in Australia. Cancer incidence data were available from 1972 to 1996 at the New South Wales Central Cancer Registry (NSW CCR), which compiles data on incidence and cancer mortality in NSW. An inception cohort was therefore defined for the purpose of the risk analysis, on the basis of period of employment. A worker's membership in this inception cohort is defined as being recorded as employed at LHSTC on or after the specific time when the NSW CCR began recording cancer cases, that is 1 January 1972, until 31 December 1996. Prior to January 1972, there is no basis for recording events of interest, or loss to follow-up through death from other causes. Hence, this cohort [72–96] included workers in employment between 1972 and 1996, reflecting the coverage period of the registry.

Source of external and internal radiation exposure at LHSTC

The main sources of external exposure to ionising radiation for LHSTC workers were the HIFAR reactor, two accelerators, the National Medical Cyclotron, analytical X-ray units, radioisotope production laboratories, and, in the past the Moata reactor[21].

External radiation exposure to LHSTC workers was mainly by gamma rays and both fast and slow neutrons; and to a lesser extent, by beta particles, X-rays and positrons. The main sources of neutrons are the reactors and accelerators. The predominant photon (X and gamma rays) energies resulting from LHSTC's activities were between 100 and 1,500 keV.

Personal dosimeters (film badges) were used to measure external radiation exposure at LHSTC. Workers exposed to ionising radiation were assigned a film badge which was worn on the waist. The film badges were read on a monthly basis and exposure readings, which were adjusted for background radiation exposure, were documented on workers' individual dosimetry files.

In addition, workers at risk for internal contamination from handling radioactive substances, such as uranium and thorium nuclides, fission and activation products, and transuranic elements, were subjected to periodic bioassays and whole body monitoring. The results were also documented on workers' individual dosimetry files.

Linkage and follow-up

Cancer incidence among LHSTC workers was primarily ascertained by matching the cohort names, sex and date of birth to the computerised National Cancer Statistics Clearing House (NCSCH) at the Australian Institute of Health and Welfare covering cancer incidence in Australia since 1982. The NCSCH data are obtained from individual Australian State and Territories cancer registries, and include the dates of diagnoses and cancer sites which were coded according to the 9th revision of the International Classification of Diseases (ICD9)[22]. Due to confidentiality legislation, identifiable cancer incidence data from South Australia were excluded from the NCSCH in 1998. Hence, the linkage with the NCSCH covered incident cancer cases among LHSTC workers occurring in all Australians states and territories except South Australia.

Since the data obtained from NCSCH covered only the period between 1982 and 1996, cancer incidence in NSW was also ascertained from the NSW Central Cancer Registry (NSW CCR) records, to complement the information supplied by the Australian Institute of Health and Welfare. The NSW CCR has recorded cancers incident in NSW, since January 1972. The quality of the data obtained from this register is revealed by indices such as the percentage of cases for which death certificates were the only source of notification (DCO) and the mortality to incidence (MI) ratio. The DCO % in the NSW CCR has varied between 0.3% in 1991 to a peak of 3.3% in 1987[23]. For most of the study follow-up period, the DCO was below 1%, that is, from 1976 to 1982 and from 1991 to 1996[23]. Since 1972, there has been a significant decline in the mortality to incidence ratio in men by 1% per year and in women by 0.5% per year for all cancers; it reached 39% in men and 38% in women in 2003[23].

Incident cases occurring in states other than NSW between 1980 and 1981 were not recorded. The period 1972–1979 had a recording of cancer incidence in NSW only. Consequently, our results missed incident cases that may have been diagnosed and registered in Australian states and territories other than NSW between 1972 and

Table 1. Inception cohort used in the analyses. Also included are the groups of people excluded from the analyses

	Inception Cohort		Excluded Workers				Total Study Cohort	
	[72–96]	(%)	Left [57–71]	(%)	Hired [97–98]	(%)	[57–98]	(%)
Number of workers	4,523	(100.0)	2,306	(100.0)	194	(100.0)	7,023	(100.0)
Men	3,269	(72.3)	1,810	(78.5)	133	(68.6)	5,212	(74.2)
Women	1,254	(27.7)	496	(21.5)	61	(31.4)	1,811	(25.8)
SES Job Classification								
Unknown	18	(0.4)	18	(0.8)	24	(12.4)	60	(0.9)
Management & Professional	1,066	(23.6)	251	(10.9)	50	(25.8)	1,367	(19.5)
Technical	1,389	(30.7)	766	(33.2)	40	(20.6)	2,195	(31.3)
Administration	803	(17.8)	458	(19.9)	12	(6.2)	1,273	(18.1)
Craftsperson	1,247	(27.6)	813	(35.3)	68	(35.1)	2,128	(30.3)
Period of first employment								
Pre–1960	276	(6.1)	495	(21.5)	–	–	771	(11.0)
1960's	753	(16.7)	1,671	(72.5)	–	–	2,424	(34.5)
1970's	1,459	(32.3)	140	(6.1)	–	–	1,599	(22.8)
1980's	1,232	(27.2)	–	–	–	–	1,232	(17.5)
1990's	803	(17.8)	–	–	194	(100.0)	997	(14.2)
Non-monitored	2,010	(44.4)	1,158	(50.2)	103	(53.1)	3,271	(46.6)
Monitored	2,513	(55.6)	1,148	(49.6)	91	(46.9)	3,752	(53.4)
Person-years	73,413		–		–		–	
Non-monitored	30,937							
Monitored	42,476							
Age at risk								
<65 yr	67,595							
65–75 yr	4,806							
≥75 yr	1,014							
Average duration of follow-up (yr)	16.23		–		–		–	

1981. People who were not caught in the electronic matching were assumed not to have cancer.

The period between 1957 and 1972 was not accounted for in the follow-up of LHSTC workers. Vital status was established primarily through probability linkage with the computerised National Death Index at the Australian Institute of Health and Welfare covering deaths in Australia since 1980. Cancer deaths in the period 1972–79 were ascertained through electronic linkage with the NSW CCR of cancer mortality in NSW between 1972 and 1996[18].

Statistical analysis

Analyses were carried out by computing standardised incidence ratios (SIRs), based on age-, sex-, and calendar year-specific rates for NSW.

For each worker, person-years at risk were accumulated over time from the date of entry in the study, defined as the later of '*date of start of employment*' and '*date of start of follow-up*', to date of exit from the study defined as the earliest of '*date of cancer diagnosis*', '*date of death*' and '*date of end of follow-up*'.

Workers were classified as, non-monitored or monitored for radiation exposure. Person-years at risk and events (cancer incidences) were stratified by sex, 5-yr age groups (15–19, 20–24, and ≥85 yr) and calendar year in single years, for comparison with rates for NSW.

The SIRs were computed by dividing the number of observed incident cases by the expected number of cases by monitoring status (monitored, non-monitored). The 95% confidence intervals for the SIRs were calculated using the quadratic approximation to the Poisson log likelihood for the log SIR parameter[24].

Radiosensitive solid cancers were analysed as one category in an effort to increase statistical power.

Results

Due to missing data, 53 workers were excluded from the study, and were not monitored for radiation. The majority of the remaining 7,023 workers was men (74.2%) and was distributed almost equally among non-monitored (46.6%) and monitored (53.4%) groups (Table 1). Men (64.4%) formed the majority of the monitored group, while women (78.2%) formed the majority of the non-monitored group.

Inception cohort [72–96], used in the analysis to examine cancer incidence, consisted of 4,523 workers. The characteristics of this cohort are summarized in Table 1. The average duration of follow-up was 16.2 yr. The average individual cumulative external dose from photons in the monitored workers was 15.04 mSv which was below the average individual cumulative dose (19.4 mSv) in the International IARC study which pooled data on 407,931 workers[20, 25].

The two groups of workers excluded from the inception cohort were those who left employment between 1957 and 1971, and those workers whose date of hire was between 1997 and 1998 (Table 1). The former group consisted of 2,306 workers divided equally between monitored (49.6%) and non-monitored (50.2%) workers; the distribution among the categories of socioeconomic status for this excluded group was also comparable to that of the inception cohort [72–96]. The latter group consisted of 194 (68.6% men and 31.4% women) workers with a distribution of monitored (46.9%) to non-monitored (53.1%) workers also in line with that of the inception cohort [72–96].

The majority of the 1,066 workers in the "Management and Professional" job category were monitored for radiation exposure (68%), while only 15% of the 803 workers in the "Administration" job category were monitored for radiation exposure.

A total of 263 cancer registrations were recorded for the 4,523 workers in cohort [72–96] (Table 2). The overlap in the follow-up period among the cancer and death registers served as a validation tool to identify inconsistencies in the data. Cross-checks between the file resulting from the linkage with the NDI and that from the linkage with the NSW CCR database identified four additional cancer incidence cases that were missed by the linkage with the NSW CCR database. These four cases were in fact reported on the NSW CCR database but were missed by the linkage process. Assessment of the methodology of linkage results were also carried out by checking cancer incidence in workers at LHSTC from other sources such as information available on personnel, medical or dosimetry files archived at LHSTC.

All-cancer incidence in workers at LHSTC was 15% below the NSW rates [SIR=0.85; 95% CI=(0.75, 0.95)] (Table 2). Men and women workers were 17% [SIR=0.83; 95% CI=(0.72, 0.94)] and 6% [SIR=0.94; 95% CI=(0.71, 1.25)] below the NSW rate, respectively. The SIRs were generally in deficit.

Registration of cancer of the pleura and other thoracic organs was significantly in excess compared to the NSW rates [SIR=17.71; 95% CI=(7.96, 39.43)] (Table 2). This significant excess was also apparent in both non-monitored [SIR=19.21; 95% CI=(4.80, 76.81)] and monitored workers [SIR=17.05; 95% CI=(6.40, 45.42)] (Table 2).

A significant deficit was seen in the registration of lung cancers in monitored workers [SIR=0.46; 95% CI=(0.28, 0.76)] and all workers combined [SIR=0.57; 95% CI=(0.39, 0.85)] compared to the NSW rates (Table 2).

A significant deficit was found for buccal and pharynx cancer incidence in both monitored [SIR=0.36; 95% CI=(0.14, 0.97)] and all workers combined [SIR=0.42; 95% CI=(0.19, 0.93)] (Table 2).

The SIR for radiosensitive solid cancers was identical for the monitored and non-monitored groups (SIR=0.85 without reaching statistical significance for both groups).

Cancer registration for the group of smoking related cancers was significantly in deficit compared to the NSW rates, for both monitored workers [SIR=0.55; 95% CI=(0.40, 0.74)] and all workers combined [SIR=0.62; 95% CI=(0.48, 0.80)] (Table 3).

Compared to the NSW rates, registration of cancers of the small intestine was significantly elevated in monitored workers [SIR=6.12; 95% CI=(1.98, 18.99)] and all workers combined [SIR=4.34; 95% CI=(1.40, 13.46)] (Table 2).

Discussion

This paper focused on comparing cancer incidence rates in nuclear industry workers with those in the general population. More precise estimates on cancer risk from low doses of ionising radiation are available from the international collaborative study coordinated by the International Agency for Research on Cancer[25]. Data provided on cancer incidence in the LHSTC cohort was not available for most cohorts in the international study.

The SIRs reported in this paper were generally in deficit and mostly replicated the results from the cancer mortality analyses reported by the authors in previous analyses of 4,717 workers in employment between 1972 and 1998[18]. Mortality of LHSTC workers from all cancers combined was 19% below that of the NSW population [SMR=0.81; 95% CI=(0.69, 0.96)]. However, most cancer sites with relatively high survival rates had more incidence than mortality counts, and hence a few additional significant results were revealed in the cancer incidence analyses. The total number of incident cancers [263] reported here is almost twice the number of cancer deaths [135] reported in the previous mortality analyses[18].

As expected, for cancer sites with high fatality rates, the findings for cancer incidence largely replicated those of cancer mortality analyses. In particular, results for incidence of cancer of the pleura and other thoracic organs, lung cancer, and smoking related cancers, were similar to those in the mortality analyses[18].

Due to the small number of events, analyses by specific sites were not conclusive for most cancer types. The results did not reveal any significant excess in cancer incidence except for cancers of the pleura and the small intestine. The observed excess of cancer of the pleura in both monitored and non-monitored workers was, we

Table 2. Cancer incidence by monitoring status (SIRs). Observed and expected numbers of cancer incidence, and SIRs, for specific cancer sites among non-monitored and monitored workers

Inception cohort [72–96]	Non-monitored workers				Monitored workers				All workers			
Cancer Incidence Cancer site (ICD9 codes)	Observed	Expected NSW	SIR NSW	(95% CI)	Observed	Expected NSW	SIR NSW	(95% CI)	Observed	Expected NSW	SIR NSW	(95% CI)
Buccal and pharynx (140–149)	2	3.43	0.58	(0.15, 2.33)	4	11.00	**0.36**	**(0.14, 0.97)**	6	14.43	**0.42**	**(0.19, 0.93)**
Oesophagus (150)	0	0.87	0.00	–	2	2.99	0.67	(0.17, 2.67)	2	3.87	0.52	(0.13, 2.07)
Stomach (151)	1	2.23	0.45	(0.06, 3.19)	7	7.26	0.96	(0.46, 2.02)	8	9.48	0.84	(0.42, 1.69)
Small intestine (152)	0	0.20	0.00	–	3	0.49	**6.12**	**(1.98, 18.99)**	3	0.69	**4.34**	**(1.40, 13.46)**
Colon (153)	5	7.10	0.70	(0.29, 1.70)	23	18.72	1.23	(0.82, 1.85)	28	25.82	1.08	(0.75, 1.57)
Rectum (154)	3	4.14	0.73	(0.23, 2.25)	12	12.21	0.98	(0.56, 1.73)	15	16.35	0.92	(0.55, 1.52)
Liver (155)	0	0.49	0.00	–	2	1.69	1.19	(0.30, 4.74)	2	2.18	0.92	(0.23, 3.67)
Gall bladder (156)	2	0.54	3.74	(0.93, 14.94)	0	1.29	0.00	–	2	1.83	1.09	(0.27, 4.38)
Pancreas (157)	1	1.63	0.61	(0.09, 4.36)	2	4.77	0.42	(0.10, 1.67)	3	6.40	0.47	(0.15, 1.45)
Nasal cavity and sinuses (160)	0	0.17	0.00	–	0	0.50	0.00	–	0	0.67	0.00	–
Larynx (161)	0	0.92	0.00	–	1	4.12	0.24	(0.03, 1.72)	1	5.04	0.20	(0.03, 1.41)
Lung (162)	9	9.22	0.98	(0.51, 1.88)	16	34.50	**0.46**	**(0.28, 0.76)**	25	43.72	**0.57**	**(0.39, 0.85)**
Pleura & other thoracic organs (163–164)	2	0.10	**19.21**	**(4.80, 76.81)**	4	0.23	**17.05**	**(6.40, 45.42)**	6	0.34	**17.71**	**(7.96, 39.43)**
Bone (170)	1	0.24	4.22	(0.60, 30.00)	1	0.40	2.51	(0.35, 17.81)	2	0.64	3.15	(0.79, 12.59)
Connective tissue (171)	1	0.65	1.53	(0.22, 10.84)	2	1.40	1.43	(0.36, 5.73)	3	2.05	1.46	(0.47, 4.54)
Melanoma of the skin (172)	14	11.39	1.23	(0.73, 2.08)	22	21.46	1.03	(0.68, 1.56)	36	32.85	1.10	(0.79, 1.52)
Breast (174) [w]	13	13.76	0.95	(0.55, 1.63)	4	2.61	1.53	(0.58, 4.08)	17	16.37	1.04	(0.65, 1.67)
Cervix uteri (180)[w]	2	2.46	0.81	(0.20, 3.26)	0	0.53	0.00	–	2	2.98	0.67	(0.17, 2.68)
Body of uterus (182)[w]	0	1.56	0.00	–	0	0.26	0.00	–	0	1.82	0.00	–
Ovary (183)[w]	0	1.59	0.00	–	0	0.29	0.00	–	0	1.88	0.00	–
Prostate (185)[m]	6	7.34	0.82	(0.37, 1.82)	34	35.53	0.96	(0.68, 1.34)	40	42.88	0.93	(0.68, 1.27)
Testis (186)[m]	2	1.27	1.58	(0.40, 6.30)	0	2.24	0.00	–	2	3.51	0.57	(0.14, 2.28)
Bladder (188)	3	2.62	1.14	(0.37, 3.55)	9	9.55	0.94	(0.49, 1.81)	12	12.17	0.99	(0.56, 1.74)
Kidney (189)	3	2.24	1.34	(0.43, 4.15)	6	6.23	0.96	(0.43, 2.14)	9	8.47	1.06	(0.55, 2.04)
Eye (190)	0	0.29	0.00	–	1	0.65	1.53	(0.22, 10.88)	1	0.94	1.06	(0.15, 7.56)
Brain and CNS (191–192)	0	1.84	0.00	–	5	4.12	1.21	(0.51, 2.92)	5	5.96	0.84	(0.35, 2.01)
Thyroid (193)	0	1.41	0.00	–	2	1.25	1.60	(0.40, 6.41)	2	2.66	0.75	(0.19, 3.01)
Ill-defined & unspecified (159, 165, 195, 199)	1	3.45	0.29	(0.04, 2.06)	8	9.72	0.82	(0.41, 1.65)	9	13.17	0.68	(0.36, 1.31)
Non-Hodgkin lymphoma (200, 202)	4	3.50	1.14	(0.43, 3.04)	4	7.92	0.51	(0.19, 1.35)	8	11.42	0.70	(0.35, 1.40)
Hodgkin's disease (201)	1	0.74	1.34	(0.19, 9.55)	2	1.23	1.62	(0.41, 6.48)	3	1.98	1.52	(0.49, 4.70)
Multiple myeloma (203)	0	0.91	0.00	–	0	2.62	0.00	–	0	3.52	0.00	–
All leukemia's (204–208)	0	2.25	0.00	–	8	5.78	1.38	(0.69, 2.77)	8	8.03	1.00	(0.50, 1.99)
All cancers except leukemia (140–203)	76	90.40	0.84	(0.67, 1.05)	179	212.73	**0.84**	**(0.73, 0.97)**	255	303.13	**0.84**	**(0.74, 0.95)**
All cancers (140–208)[a]	76	92.65	0.82	(0.66, 1.03)	187	218.53	**0.86**	**(0.74, 0.99)**	263	311.19	**0.85**	**(0.75, 0.95)**

[a] For specific cancers, the exit date is the minimum (diagnosis date, death date, end of study). The exit date for "all cancers" is the minimum (death date, end of study) to allow for multiple cancers. There are 15 cases of double cancers in this inception cohort. [m]Men only. [w]Women only.

Table 3. Incidence from cancer groups (SIRs). Observed and expected numbers of cancer incidence, and SIRs, for groups of cancer sites among non-monitored and monitored workers

Inception cohort [72–96]	Non-monitored workers				Monitored workers				All workers			
Cancer Incidence Cancer site (ICD9 codes)	Observed	Expected NSW	SIR NSW	(95% CI)	Observed	Expected NSW	SIR NSW	(95% CI)	Observed	Expected NSW	SIR NSW	(95% CI)
Smoking related cancers[a] (140–150, 157, 161–162, 188, 189[c])	18	21.01	0.86	(0.54, 1.36)	40	73.30	**0.55**	**(0.40, 0.74)**	58	94.31	**0.62**	**(0.48, 0.80)**
Cancers not related to smoking (140–208 except 140–150, 157, 161–162, 188, 189)	58	71.64	0.81	(0.63, 1.05)	147	145.24	1.01	(0.86, 1.19)	205	216.87	0.95	(0.82, 1.08)
Radiosensitive solid cancers[b] (150, 151, 153, 162, 174, 188, 189, 191, 192)	34	40.10	0.85	(0.61, 1.19)	73	86.27	0.85	(0.67, 1.06)	107	126.37	0.85	(0.70, 1.02)
Non-radiosensitive solid cancers (140–149, 152, 154–161, 163–173, 175–187, 190, 193–199)	37	45.15	0.82	(0.59, 1.13)	100	114.69	0.87	(0.72, 1.06)	137	159.84	0.86	(0.73, 1.01)
Hemato- and lymphopoeitic cancers (200–208)	5	7.41	0.68	(0.28, 1.62)	14	17.58	0.80	(0.47, 1.34)	19	24.99	0.76	(0.49, 1.19)
All cancers (140–208)	76	92.65	0.82	(0.66, 1.03)	187	218.53	**0.86**	**(0.74, 0.99)**	263	311.19	**0.85**	**(0.75, 0.95)**

[a]According to IARC (1986)[31]. [b]According to BEIR V (1990)[26]. [c]The NSW rates for cancers of the renal pelvis (ICD9 189.1) was not available separately, so ICD9 code 189 (kidney) was included in the smoking related cancers.

believe, probably due to unmeasured exposures in the cohort, such as asbestos exposure; this has been described previously[18]. As for cancer of the small intestine, the SIR was based on only 3 registrations, all of which were observed in the monitored group. This type of cancer is not classified as a radiosensitive cancer according to BEIR V (1990)[26] and the significant increase in the SIR was unexpected and may be a chance finding.

Leukemia has been previously associated with external exposure to ionising radiation in studies of nuclear industry workers[6, 7, 13, 27, 28]. Our findings showed more incident leukemias than expected in the monitored group, although this excess did not reach statistical significance, and less than expected in the non-monitored group.

The significant deficit in the SIRs for lung cancer, buccal and pharynx cancers which are also smoking related, in addition to the group of all smoking related cancers, supports the argument that workers at LHSTC smoked less than the NSW population. Without smoking data in our cohort, the plausibility of confounding by cigarette smoking could not be assessed in our analyses. Socio economic status (SES) was instead used as a broad indicator of health related behaviors. In particular, it is known that people at lower SES levels generally smoke more than those of higher SES[29].

Of particular interest is the significant deficit noticed for lung cancer, buccal and pharynx cancers and all smoking related cancers in the monitored group. Most workers in the monitored group were of higher SES job classification [“Managerial & Professional” (28.8%) or “Technical” (38.4%)], and so probably can be assumed to have smoked less than the non-monitored workers of whom most belonged to lower SES job categories [“Administration” (34.1%) or “Craftsperson” (27.7%)].

It should also be mentioned that the SIR for the group of smoking related cancers (58 registrations) was largely affected by the rates for lung cancer (25 registrations), which constituted 43% of the number of events in that group of cancers.

A lack of association between exposure to radiation and all cancers has been seen in a similar study in Finland[15], and also in combined analyses of three UK studies[7] and three US studies[30]. A pooled analysis of US, Canada, and UK studies suggested a modest but non-statistically significant increased risk of cancer. On the other hand, an international collaboration that studied nuclear industry workers, including our cohort, showed an excess cancer risk associated with radiation exposure[25]. The aim of this analysis was to compare the cancer incidence rates in LHSTC cohort to that in the general NSW population and to add to and complement the mortality results that have been previously published[18]. Although our analysis did not intend to validate or disprove the carcinogenicity of ionising radiation per se, it gave little evidence of an increased risk of cancers in the LHSTC cohort compared to the NSW population.

There are methodological limitations to our study. Potential occupational and lifestyle related risk factors were not accounted for which may have confounded some of the relationships observed. Furthermore, the observed cancer cases were obtained via linkage to national and state cancer registers. Linkage may have been incomplete; especially, it missed cancer cases diagnosed and registered outside NSW between 1972 and 1981. Misclassification and other recording errors may have occurred, although this would not be expected to effect individual cancers. In addition, the small number of observed events implies a limited precision in estimating the effects of radiation exposure on specific cancers. Finally, the relatively short follow-up period did not allow detection of radiosensitive cancers of long latency, such as brain tumours, among workers with recent employment at LHSTC.

We believe that LHSTC workers were a particularly suitable group to study using the passive data linkage methods we adopted in our study. The workforce is relatively stable compared with nuclear power plants in Europe where it is easier for workers to change their workplace or migrate. Since LHSTC is the only nuclear establishment in Australia, there are limited opportunities for workers to move within the nuclear industry.

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References

1) Beral V, Fraser P, Carpenter L, Booth A and Rose G: Mortality of employees of the atomic weapons establishment, 1951–1982. BMJ 297, 757–770 (1988)
2) Wiggs LD, Cox-de-Vore CA, Wilkinson GS and Reyes M: Mortality among workers exposed to external ionizing radiation at a nuclear facility in Ohio. J Occup Med 33, 632–637 (1991)
3) Wing S, Shy CM, Wood JL, Wolf S, Cragle DL and Frome EL: Mortality among workers at Oak Ridge national laboratory. Evidence of radiation effects in follow-up through 1984. JAMA 265, 1397–1402 (1991)
4) Fraser P, Carpenter L, Maconochie N, Higgins C, Booth M and Beral V: Cancer mortality and morbidity in employees of the United Kingdom atomic energy authority, 1946–86. BJC 67, 615–624 (1993)
5) Gilbert ES, Omohundro JA, Buchanan JA and Holter NA: Mortality of workers at the hanford site: 1945–1986. Health Phys 64, 577–590 (1993)
6) Gribbin MA, Weeks JL, Howe GR: Cancer mortality (1956–1985) among male employees of atomic energy of Canada limited with respect to occupational exposure to external low-linear-energy-transfer

ionizing radiation. Radiat Res 133, 375–380 (1993)
7) Carpenter L, Higgins C, Douglas A, Fraser P, Beral V and Smith P: Combined analysis of mortality in three United Kingdom nuclear industry workforces, 1946–1988. Radiat Res 138, 224–238 (1994)
8) Frome EL, Cragle DL, Watkins JP, Wing S, Shy CM, Tankersley WG and West CM: A mortality study of employees of the nuclear industry in Oak Ridge, Tennessee. Radiat Res 148, 64–80 (1997)
9) Muirhead CR, Goodill AA, Haylock RGE, Vokes J, Little MP, Jackson DA, O'Hagan JA, Thomas JM, Kendall GM, Silk TJ, Bingham D and Berridge GLC: Occupational radiation exposure and mortality: second analysis of the national registry for radiation workers. J Radiol Prot 19, 3–26 (1999)
10) Rogel A, Carre N, Amoros E, Bonnet-Belfais E, Goldberg M, Imbernon E and Calvez T: Mortality of workers exposed to ionizing radiation at the French National Electricity Company. Am J Ind Med 47, 72–82 (2005)
11) Hadjimichael OC, Ostfeld AM, D'Atri DA and Brubaker RE: Mortality and cancer incidence experience of employees in a nuclear fuels fabrication plant. J Occup Med 25, 48–61 (1983)
12) Douglas AJ, Omar RZ and Smith PG: Cancer mortality and morbidity among workers at the sellafield plant of British nuclear fuels. BJC 70, 1232–1243 (1994)
13) Omar RZ, Barber JA and Smith PG: Cancer mortality and morbidity among plutonium workers at the sellafield plant of British nuclear fuels. BJC 79, 1288–1301 (1999)
14) McGeoghegan D and Binks K. The mortality and cancer morbidity experience of employees at the chapelcross plant of British nuclear fuels LTD, 1955–1995. In: Thorne MC ed. Proceedings of the sixth SRP International Symposium Held in Southport, 14–18 London: June. The Society for Radiological Protection, 1999: 261–264.
15) Auvinen A, Pukkala E, Hyvonen H, Hakama M and Rytomaa T: Cancer incidence among Finnish nuclear reactor workers. JOEM 44, 634–638 (2002)
16) Ferguson D. Survey of health of employees in the research establishment of the Australian Atomic Energy Commission at Lucas Heights, Sydney, Second Report, Interpretation of Hazard and Recommendations. Sydney: The University of Sydney and Australian Department of Health, 1979.
17) Report of the Research Reactor Review. Sydney: Commonwealth of Australia, 1993.
18) Habib RR, Abdallah SM, Law MM and Kaldor J: Mortality rates among nuclear industry workers at lucas heights science and technology centre. Aust NZJ Public Health 29, 229–237 (2005)
19) Australian Bureau of Statistics. Australian Demographic Statistics. Cat. No. 3101.0. Canberra: Australian Bureau of Statistics, 2000.
20) Cardis E, Esteve J and Armstrong BK: Meeting recommends international study of nuclear industry workers. Health Phys 63, 465–466 (1992)
21) Hardy CJ. Atomic Rise and Fall—The Australian Atomic Energy Commission 1953–1987. Peakhurst, NSW Australia: Glen Haven Publishing, 1999.
22) World Health Organization. International Classification of Diseases, Injuries and Causes of Death, 9th Revision, 1975. Geneva: WHO, 1977.
23) Tracey E, Roder D, Bishop J, Chen S and Chen W. Cancer in New South Wales incidence and mortality 2003. Australia: Cancer Institute NSW, NSW Central Cancer Registry, 2005.
24) Clayton D, Hills M: Ssa10: Analysis of follow-up studies with stata 5.0. Stata Technical Bulletin 40, 27–39 (1997)
25) Cardis E, Vrijheid M, Blettner M, Gilbert E, Hakama M, Hill C, Howe G, Kaldor J, Muirhead CR, Schubauer-Berigan M, Yoshimura T, Bermann F, Cowper G, Fix J, Hacker C, Heinmiller B, Marshall M, Thierry-Chef I, Utterback D, Ahn Y-O, Amoros E, Ashmore P, Auvinen A, Bae J-M, Bernar Solano J, Biau A, Combalot E, Deboodt P, Diez Sacristan A, Eklof M, Engels H, Engholm G, Gulis G, Habib R, Holan K, Hyvonen H, Kerekes A, Kurtinaitis J, Malker H, Martuzzi M, Mastauskas A, Monnet A, Moser M, Pearce MS, Richardson DB, Rodriguez-Artalejo F, Rogel A, Tardy H, Telle-Lamberton M, Turai I, Usel M and Veress K: Risk of cancer after low doses of ionising radiation—retrospective cohort study in 15 countries. BMJ 331, 77–80 (2005)
26) BEIR V, Committee on the Biological Effects of Ionising Radiation. Health Effects of Exposure to Low Levels of Ionizing Radiation. Washington D.C.: National Research Council, National Academy Press, 1990.
27) Cardis E, Gilbert ES, Carpenter L, Howe G, Kato I, Armstrong BK, Beral V, Cowper G, Douglas A, Fix J, Fry SA, Kaldor J, Lave C, Salmon L, Smith PG, Voelz GL and Wiggs LD: Effects of low doses and low doses rates of external ionizing radiation: cancer mortality among nuclear industry workers in three countries. Radiat Res 142, 117–132 (1995)
28) Kendall GM, Muirhead CR, MacGibbon BH, O'Hagan JA, Conquest AJ, Goodill AA, Butland BK, Fell TP, Jackson DA, Webb MA, Haylock RGE, Thomas JM and Silk TJ: Mortality and occupational exposure to radiation: first analysis of the national registry for radiation workers. BMJ 304, 220–225 (1992)
29) Hill DJ, White VM and Gray NJ: Australian patterns of tobacco smoking in 1989. Med J Aust 154, 797–801 (1991)
30) Gilbert ES, Cragle DL and Wiggs LD: Updated analyses of combined mortality data for workers at the hanford site, Oak Ridge national laboratory, and rocky flats weapons plant. Radiat Res 136, 408–421 (1993)
31) International Agency for Research on Cancer. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Tobacco Smoking. IARC Monograph Volume 38. Lyon: IARC, 1986.