Mortality rates among nuclear industry workers at Lucas Heights Science and Technology Centre

Rima R. Habib

Faculty of Health Sciences, American University of Beirut, Lebanon

Samer M. Abdallah

Faculty of Engineering and Architecture, American University of Beirut, Lebanon

Matthew Law, John Kaldor

National Centre in HIV Epidemiology and Clinical Research, University of New South Wales

Abstract

Objectives: To assess whether workers at Lucas Heights Science and Technology Centre (LHSTC) have different levels of mortality from the New South Wales (NSW) and Australian populations.

Methods: 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. Deaths registrations in the cohort were identified to 1998 through electronic linkage of records with NSW and national registers of cancer incidence and mortality. Two inception cohorts were defined as including 4,717 and 3,543 workers in employment between 1972-98 and 1980-98, to examine cancer mortality and all-cause mortality respectively.

Results: All-cause mortality was 31% lower than the national rates; all-cancer mortality was 19% below the NSW rate. Of 37 specific cancers and groups of cancers examined, statistically significant excesses relative to NSW rates were observed only for pleural cancer mortality (SMR=21.11; 95% CI 8.79-50.72).

Conclusions: 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.

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The long-term health of people working in industrial and research facilities involving ionising radiation has been the subject of extensive investigation over the past two decades.[1-36] The known effects of acute exposure to higher levels of radiation have led to questions about the health risks associated with lower-level chronic exposures.

The Lucas Heights Science and Technology Centre (LHSTC), the site of Australia's only nuclear reactor, has been in operation since 1959 in the Sutherland Shire, about 32 kilometres south-west of Sydney's central business district.

Previous reports looked at the health of both the workers at LHSTC and the residents of the surrounding area in the Sutherland Shire.[37-40] The findings of the cross-sectional survey of the Lucas Heights facility in 1975-76 showed no evidence of an association between radiation and cancer;[37,38] likewise, the findings of the studies among Sutherland Shire residents found no such association.[39,40] However, the cross-sectional nature of the survey was not the best to explore diseases of long latency such as malignancies.[38] Taylor et al. (1993) suggested that if adverse health effects were arising as a result of reactor operation, they would be more apparent in LHSTC workers rather than in local residents.[40]

This paper presents the first longitudinal study to investigate the effects of external exposure to ionising radiation in workers at LHSTC. This study had two objectives:[47-49]

- To assess whether workers at LHSTC had different levels of mortality, specifically cancer mortality, from the New South Wales (NSW) and Australian populations. Given the limitations in the studies carried out to date, the potential value of a historical cohort study of all personnel who had worked in the plant became apparent.[40]
- To contribute to the International Collaborative Study of Cancer Risk among Radiation Workers in the Nuclear Industry, co-ordinated by the International Agency for Research on Cancer (IARC). This large study brings together data on approximately half a million nuclear industry workers from 14 countries including Australia, Europe, the United States and others;[41-46] it aims to estimate as precisely as possible the risk of contracting cancer from long-term exposure to low levels of ionising radiation at the workplace.

Materials and methods

A retrospective cohort study, based on records of exposure and employment at LHSTC and linking with State and national

Correspondence to:
Dr Rima R. Habib, Department of Environmental Health, Faculty of Health Sciences, American University of Beirut, 3 Dag Hammarskjold Plaza, 8th floor, NY, New York 10017-2303, USA.
E-mail: rima.habib@aub.edu.lb

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registries of cancer and death, was undertaken to estimate the cancer risks of exposure to low levels of ionising radiation among LHSTC workers.[48]

Ethical issues such as privacy and confidentiality were addressed to comply with the recommendations provided by the National Health and Medical Research Council (NHMRC) of Australia.[50,51] Approvals were obtained from the Committee on Experimental Procedures Involving Human Subjects at the University of New South Wales, and the ethics committees at both the Australian Institute of Health and Welfare (AIHW) and the New South Wales Cancer Council.[49]

Data were collected and abstracted from hard copy files of personnel, dosimetry, and medical records. Identifying and demographic information including surname, given names, maiden name, date of birth, sex, last known address, in addition to job history and job classification, were abstracted from personnel files.

All LHSTC workers entering radiation classified areas with potential for exposure to radiation were required to wear a personal dosimeter (film badge) to monitor external radiation to the body. Measurements of employees' external radiation exposure were recorded in historical personal dosimetry files. In this paper, workers were classified according to whether they were monitored or not for external exposure to ionising radiation based on dosimetry files. Employees without dosimetry records were considered not to have been exposed.

Collected data were entered into an Access database with a unique identifying number assigned to each worker. This identifier was then used in the analyses.

Study population and inception cohorts

The study population consisted of 7,076 workers who were employed at LHSTC between 1 January 1957 and 31 December 1998.

The period of follow-up for mortality and cancer was dictated by the establishment of State and national case registries. Specifically, cancer mortality data in NSW were available from 1972 at the NSW Central Cancer Registry (NSW CCR), and national all-cause mortality data were available from 1980 at AIHW. This led to the adoption of two inception cohorts for the purpose of the risk analysis, defined on the basis of period of employment. These inception cohorts, [72-98] and [80-98], reflected the coverage of follow-up achieved and were used to examine cancer mortality and all-cause mortality respectively. Inception cohort [72-98] included workers in employment on or after 1/1/1972 up to 31/12/1998; inception cohort [80-98] included workers in employment on or after 1/1/1980 up to 31/12/1998.

Follow-up strategies

Deaths in the cohort were identified through electronic linkage with the national register of mortality and the NSW cancer registry for a passive follow-up of workers to the end of 1998. The linkage with the registries was undertaken using the probabilistic record linkage package Automatch.[62]

For the follow-up period 1980-1998, vital status and specific causes of deaths among LHSTC workers were ascertained by matching the cohort names, sex and date of birth to the computerised National Death Index (NDI) covering deaths in Australia since 1980. The AIHW compiled the NDI data from the Registrars of Births, Deaths, and Marriages in each State and

Table 1: Comparison of the inception cohorts used in the analyses. Also included are the groups of people excluded from the analyses, and the total study cohort.

	Inception cohorts				Excluded workers		Total study cohort	
	[72-98]	%	[80-98]	%	Left 1957-71	%	1957-98	%
Number of workers	4,717	100.0	3,543	100.0	2,306	100.0	7,023	100.0
Men	3,402	72.1	2,544	71.8	1,810	78.5	5,212	74.2
Women	1,315	27.9	999	28.2	496	21.5	1,811	25.8
SES job classification								
Unknown	42	0.9	34	1.0	18	0.8	60	0.9
Management and professional	1,116	23.7	978	27.6	251	10.9	1,367	19.5
Technical	1,429	30.3	934	26.4	766	33.2	2,195	31.3
Administration	815	17.3	581	16.4	458	19.9	1,273	18.1
Craftsperson	1,315	27.9	1,016	28.7	813	35.3	2,128	30.3
Period of first employment								
Pre-1960	276	5.9	191	5.4	495	21.5	771	11.0
1960s	753	16.0	512	14.5	1,671	72.5	2,424	34.5
1970s	1,459	30.9	611	17.3	140	6.1	1,599	22.8
1980s	1,232	26.1	1,232	34.8	–	–	1,232	17.5
1990s	997	21.2	997	28.1	–	–	997	14.2
Non-monitored	2,113	44.8	1,466	41.4	1,158	50.2	3,271	46.6
Monitored	2,604	55.2	2,077	58.6	1,148	49.6	3,752	53.4
Person-years	81,946.88		46,089.22		–		–	
Average duration of follow-up (years)	17.37		13.01		–		–	

Territory. These data include the dates and the underlying causes of deaths, which were coded according to the 9th revision of the International Classification of Diseases (ICD-9)[52] by the Australian Bureau of Statistics. The associated causes of death are not included.

The gap in the follow-up was narrowed by ascertaining cancer deaths in the period 1972-79 through electronic linkage with the NSW CCR, which has been recording cancer incidence and cancer mortality in NSW since January 1972. The NSW CCR has since been passively following up cases registered with cancer on its database; when death occurs, the cause and date of death based on the medical certificate are recorded on the NSW CCR.

Hence the period 1980-98 has the most complete follow-up, as deaths occurring in workers in this period could potentially be recorded. The period 1972-79 had a recording of deaths, mainly from cancer causes, in NSW only; deaths from causes other than cancer remained largely untraced.

Data collected from various sources, at the cancer and death registers and at LHSTC, were validated and verified for consistency. The overlap in the follow-up period among the registers served as a validation tool to identify inconsistencies in the mortality data. Assessment of the methodology of linkage results was also carried out by checking deaths in workers at LHSTC from other sources such as information on cause of death when available on personnel, medical or dosimetry files archived at LHSTC.

Statistical methods

Standardised mortality ratios (SMRs) were computed to compare the study outcomes in workers at LHSTC with the general population of Australia or NSW. The SMRs were based on age-, sex-, and calendar year-specific death rates for Australia or NSW.

The analyses of all-cause and all-causes other than cancer mortality were based on inception cohort [80-98], which had the most complete follow-up for all-cause mortality.

Cancer mortality analyses were based on inception cohort [72-98], which had the longer follow-up period for cancer deaths.

Co-variables considered in the analyses included period of first employment, socio-economic status, age at risk and time since first employment.[47] ‘Period of first employment’ was stratified into five categories: pre-1960s, 1960s, 1970s, 1980s and 1990s. Socio-economic status was based on job classification (SES job), where four categories were used: management and professional (merged into one category), technical, administration, craftsperson; these job categories were based on the job held for the longest duration. The time-dependent variables ‘time since first employment’ and ‘age at risk’ were used as measures to examine the healthy workers’ effect.[53] The age at risk is the attained age at the end of follow-up, that is the minimum of the ‘age at death’ and the ‘age at the end of follow-up’. For ‘time since first employment’, person-years and events were stratified in categories of less than 10 years, 10-19 years, 20-29 years and 30 years or more. As for ‘age at risk’, it was stratified in three categories (<65, 65-74, ≥75 years). 95% confidence intervals for SMRs were calculated using the quadratic approximation to the Poisson log likelihood.[54] Microsoft Access was used for data processing and STATA 5.0 (Stata Corporation, College Station, Texas) was used for statistical analyses.

Results

Because of incomplete data, 53 workers were excluded from the total study cohort; they all did not have an employment date, 48 did not have a termination date, eight had missing date of birth, and six had missing information regarding sex. All 53 excluded workers were not monitored for radiation. Of the remaining 7,023 workers, 5,212 (74.2%) were men and 1,811 (25.8%) were women (see Table 1). They were distributed almost equally among non-monitored (3,271, 46.6%) and monitored (3,752, 53.4%) workers. Men (64.4%) formed the majority of the monitored group.

Table 2: Vital status of the inception cohort [72-98] of LHSTC workers as of 31 December 1998.

Date of last termination	[72-79]	%	[80-98]	%	Total	%
Inception cohort [72-98] In employment on or after 1/1/72 – 31/12/98	1,174	100.0	3,543	100.0	4,717 [g]	100.0
Vital status						
Alive	4 [a]	0.3	930	26.2	934	19.8
Assumed alive	27 [b]	2.3	2,420	68.3	2,447	51.9
Dead	169 [c]	14.4	193 [d]	5.4	362	7.7
Unknown	974 [e]	83.0	0 [f]	0.0	974 [h]	20.6
Total number of workers for whom vital status was accounted for	200	17.0	3,543	100.0	3,743	79.4

Notes:
(a) Four were still alive at the end of the study period as they died after 31 December 1998 (Death sources: 3 from NDI; and 1 from NSW CCR).
(b) Vital status accounted for as follows: 27 were registered as having developed cancer after 31 December 1979, and were assumed alive at the end of the study period.
(c) Death sources: 125 from NDI; 21 from NSW CCR; and 23 from LHSTC files.
(d) Death sources: 185 from NDI; six from NSW CCR; and 2 from LHSTC files.
(e) Of these 974 workers, three were registered by the NSW CCR as having developed cancer between 1972-1979, and their vital status was not ascertained. All 974 workers were included as alive in the analyses.
(f) Overseas migration is not accounted for.
(g) Consists of 2,113 (44.8%) non-monitored and 2,604 (55.2%) monitored workers.
(h) Consists of 576 (59.1%) non-monitored and 398 (40.9%) monitored workers.

Inception cohorts [72-98] and [80-98] consisted of 4,717 and 3,543 workers respectively. The key characteristics of these cohorts are summarised in Table 1. The average duration of follow-up was 17.4 and 13.0 years for inception cohorts [72-98] and [80-98] respectively. The mean cumulative external dose in the monitored employees was 18.7 mSv and 20.11 mSv for cohort [72-98] and cohort [80-98] respectively.

Workers excluded from the inception cohorts were those who left employment between 1957 and 1971 (see Table 1). They consist of 2,306 workers divided equally between monitored (49.6%) and non-monitored (50.2%) workers. The distributions among the categories of socio-economic status for this excluded group were also comparable to that of the two inception cohorts. The majority (72.5%) of this excluded group, however, was first employed at LHSTC in the 1960s.

Linkage results are summarised in Table 2. Cross-checks between the file resulting from the linkage with the NDI and the file resulting from the linkage with the NSW CCR database identified four additional cancer deaths that were caught by the NDI linkage and were missed by the linkage with the NSW CCR database. Additional verifications proved that the four cancer deaths were recorded on the NSW CCR database but were missed by the NSW CCR linkage process. Four NSW cancer deaths based on matched pairs resulting from the linkage with the NDI seemed acceptable matches based on limited information provided by the NDI, but were later dismissed as true cases based on additional information obtained from the NSW CCR. Five cancer deaths and two non-cancer deaths were caught by the linkage with the NSW CCR database but were missed by the NDI linkage even though they all occurred after 1980.

Table 3: Standardised mortality ratios (SMRs) for (1) all-cause mortality comparing rates in the study population to those of Australia (AUS) – inception cohort [80-98]; (2) all causes other than cancer mortality, comparing rates in the study population to those of Australia (AUS) – inception cohort [80-98]; and (3) all cancer mortality, comparing rates in the study population to those of New South Wales (NSW) – inception cohort [72-98].

	All-cause mortality Inception cohort [80-98]			All-causes other than cancer mortality Inception cohort [80-98]			All cancer mortality Inception cohort [72-98]		
	Observed	SMR AUS	95% CI	Observed	SMR AUS	95% CI	Observed	SMR NSW	95% CI
All workers	193[a]	**0.69**	**0.60-0.80**	112[a]	**0.60**	**0.50-0.73**	135	**0.81**	**0.69-0.96**
Sex									
Men	172	**0.68**	**0.58-0.79**	103	**0.60**	**0.50-0.73**	113	**0.78**	**0.65-0.93**
Women	21	0.82	0.53-1.26	9	0.63	0.33-1.22	22	1.09	0.72-1.65
SES job classification									
Unknown	0	0.00	–	0	0.00	–	1	0.60	0.08-4.27
Management and prof.	29	**0.33**	**0.23-0.48**	18	**0.31**	**0.20-0.49**	16	**0.39**	**0.24-0.63**
Technical	63	**0.71**	**0.56-0.91**	33	**0.55**	**0.39-0.78**	45	0.98	0.73-1.32
Administration	36	1.06	0.76-1.47	20	0.94	0.60-1.45	25	1.03	0.69-1.52
Craftsperson	65	0.96	0.75-1.22	41	0.90	0.66-1.22	48	0.91	0.68-1.21
Period of first employment									
Pre-1960	39	**0.62**	**0.45-0.84**	21	**0.51**	**0.33-0.78**	29	0.73	0.50-1.04
1960s	85	**0.76**	**0.61-0.94**	50	**0.68**	**0.52-0.90**	63	0.86	0.67-1.10
1970s	41	**0.71**	**0.52-0.97**	26	0.69	0.47-1.01	30	0.77	0.54-1.10
1980s	25	**0.64**	**0.43-0.95**	14	**0.51**	**0.30-0.86**	11	0.95	0.52-1.71
1990s	3	0.41	0.13-1.28	1	0.18	0.03-1.29	2	1.17	0.29-4.67
Time since first employment									
<10 years	20	**0.52**	**0.33-0.80**	12	**0.42**	**0.24-0.74**	16	0.88	0.54-1.44
10-20 years	45	**0.74**	**0.56-0.99**	29	0.72	0.50-1.03	32	0.74	0.52-1.04
20-30 years	73	**0.74**	**0.59-0.93**	42	**0.65**	**0.48-0.88**	51	0.84	0.64-1.11
≥30 years	55	**0.68**	**0.52-0.88**	29	**0.56**	**0.39-0.80**	36	0.83	0.60-1.15
Age at risk									
<65 years	104	**0.67**	**0.55-0.81**	66	**0.63**	**0.50-0.81**	60	**0.73**	**0.57-0.94**
65-75 years	70	**0.70**	**0.56-0.89**	34	**0.53**	**0.38-0.74**	55	0.97	0.75-1.27
≥75 years	19	0.78	0.50-1.23	12	0.69	0.39-1.22	20	0.75	0.48-1.15
Monitored									
No	49	0.86	0.65-1.13	30	0.81	0.56-1.15	33	0.75	0.53-1.06
Yes	144	**0.65**	**0.55-0.76**	82	**0.55**	**0.45-0.69**	102	0.84	0.69-1.02
Number of workers	3,543			3,543			4,717		
Average follow-up (years)	13.01			13.01			17.37		

Notes:
Figures in bold: p<0.05
(a) Includes two deaths from non-linkage source with unknown cause (LHSTC files).

All-cause mortality analyses were based on 193 deaths in the 3,543 workers in cohort [80-98] with 135 cancer deaths in the 4,717 workers in cohort [72-98] (see Table 3).

All-cause mortality

All-cause mortality in workers at LHSTC was 31% lower than in the national population (SMR=0.69; 95% CI 0.60-0.80 based on 193 deaths) (see Table 3). Mortality from causes other than cancer was even lower at 40% below the national rates (SMR=0.60; 95% CI 0.50-0.73). The SMRs remained low even after 30 years of employment (SMR=0.68; 95% CI 0.52-0.88), suggesting that factors other than the selection of healthy workers into the workforce have contributed to the low mortality rates in LHSTC workers.

The overall all-cause SMR for monitored workers was significantly in deficit (SMR=0.65; 95% CI 0.55-0.76), and lower than for non-monitored workers (SMR=0.86; 95% CI 0.65- 1.13). A significant deficit in all causes other than cancer SMR was also observed for monitored workers (SMR=0.55; 95% CI 0.45-0.69).

Cancer mortality

Mortality from all cancers combined based on inception cohort [72-98] was 19% below that of the NSW population (SMR=0.81; 95% CI 0.69-0.96) based on 135 cancer deaths, but was substantially higher than the SMR from all causes other than cancer (SMR=0.60; 95% CI 0.50-0.73) (see Table 3).

Socio-economic status was inversely related to the cancer mortality rates in workers at LHSTC. The lowest SMR for all-cancer mortality was observed for workers in the management and professional category (SMR=0.39; 95% CI 0.24-0.63), with the highest SMRs seen for workers in the lowest SES categories (see Table 3).

All-cancer SMR in monitored workers was in deficit (SMR=0.84; 95% CI 0.69-1.02), but higher than the SMR in non-monitored workers (SMR=0.75; 95% CI 0.53-1.06) (see Table 3).

Mortality from cancer of the pleura and other thoracic organs

The only significant excess in comparing cancer mortality in workers at LHSTC to the NSW rates occurred for cancer of the pleura and other thoracic organs (SMR=21.11; 95% CI 8.79-50.72) (see Table 4). Rates were significantly elevated in both monitored (SMR=23.53; 95% CI 8.83-62.69) and non-monitored workers (SMR=14.97; 95% CI 2.11-106.24). The SMR in the non-monitored group was based on the death of one woman from cancer of the thymus (ICD-9 164.0). In the monitored group, the SMR was based on the death of four men from cancer of the pleura (ICD-9 164.9). Confidence intervals were very wide due to the small number of cases.

Mortality from lung cancer

There were 26 deaths from lung cancer identified in the study cohort, with an SMR of 0.63 (95% CI 0.43-0.92) (see Table 4). Monitored workers also showed a deficit in lung cancer mortality (SMR=0.55; 95% CI 0.35-0.87).

Table 5: Mortality from cancer groups (SMRs). Observed and expected numbers of cancer mortality, and SMRs, for groups of cancer sites among non-monitored and monitored workers.

Inception cohort [72-98]	Non-monitored workers				Monitored workers				All workers			
Cancer mortality Cancer site (ICD-9 codes)	Observed	Expected NSW	SMR NSW	95% CI	Observed	Expected NSW	SMR NSW	95% CI	Observed	Expected NSW	SMR NSW	95% CI
Smoking related cancers[a] (140-150, 157, 161-162, 188, 189[c])	13	14.64	0.89	0.52-1.53	35	52.13	**0.67**	**0.48-0.94**	48	66.77	**0.72**	**0.54-0.95**
Cancers not related to smoking (140-208 except 140-150, 157, 161-162, 188, 189)	20	29.33	0.68	0.44-1.06	67	69.68	0.96	0.76-1.22	87	99.00	0.88	0.71-1.08
Radiosensitive solid cancers[b] (150, 151, 153, 162, 174, 188, 189, 191, 192)	19	22.57	0.84	0.54-1.32	57	61.64	0.92	0.71-1.20	76	84.21	0.90	0.72-1.13
Non-radiosensitive solid cancers (140-149, 152, 154-161, 163-173, 175-187, 190, 193-199)	12	17.15	0.70	0.40-1.23	36	49.14	0.73	0.53-1.02	48	66.29	**0.72**	**0.55-0.96**
Hemato- and lymphopoeitic cancers (200-208)	2	4.25	0.47	0.12-1.88	9	11.02	0.82	0.43-1.57	11	15.27	0.72	0.40-1.30
All cancers (140-208)	33	43.97	0.75	0.53-1.06	102	122.80	0.84	0.69-1.02	135	165.77	**0.81**	**0.69-0.96**

Notes:
Figures in bold: $p<0.05$
(a) According to IARC (1986).[60]
(b) According to BEIR V (1990).[61]
(c) The NSW rates for cancers of the renal pelvis (ICD-9 189.1) were not available separately, so ICD-9 code 189 (kidney) was included in the smoking-related cancers.

Table 4: Cancer mortality by monitoring status (SMRs). Observed and expected numbers of cancer mortality, and SMRs, for specific cancer sites among non-monitored and monitored workers.

Inception cohort [72-98]	Non-monitored workers				Monitored workers				All workers			
Cancer mortality Cancer site (ICD-9 codes)	**Observed**	**Expected NSW**	**SMR NSW**	**95% CI**	**Observed**	**Expected NSW**	**SMR NSW**	**95% CI**	**Observed**	**Expected NSW**	**SMR NSW**	**95% CI**
Buccal and pharynx (140-149)	2	1.18	1.70	0.42-6.78	2	4.32	0.46	0.12-1.85	4	5.50	0.73	0.27-1.94
Oesophagus (150)	0	0.78	0.00	–	4	2.73	1.47	0.55-3.91	4	3.51	1.14	0.43-3.04
Stomach (151)	1	1.84	0.54	0.08-3.86	5	6.06	0.83	0.34-1.98	6	7.90	0.76	0.34-1.69
Small intestine (152)	0	0.11	0.00	–	1	0.29	3.48	0.49-24.67	1	0.40	2.49	0.35-17.71
Colon (153)	1	3.55	0.28	0.04-2.00	14	9.54	1.47	0.87-2.48	15	13.08	1.15	0.69-1.90
Rectum (154)	0	2.00	0.00	–	2	6.31	0.32	0.08-1.27	2	8.32	**0.24**	**0.06-0.96**
Liver (155)	0	0.48	0.00	–	1	1.67	0.60	0.08-4.26	1	2.14	0.47	0.07-3.31
Gall bladder (156)	0	0.48	0.00	–	0	1.17	0.00	–	0	1.66	0.00	–
Pancreas (157)	0	1.71	0.00	–	2	4.91	0.41	0.10-1.63	2	6.62	0.30	0.08-1.21
Nasal cavity and sinuses (160)	0	0.09	0.00	–	0	0.27	0.00	–	0	0.36	0.00	–
Larynx (161)	0	0.33	0.00	–	0	1.48	0.00	–	0	1.81	0.00	–
Lung (162)	8	8.79	0.91	0.46-1.82	18	32.71	**0.55**	**0.35-0.87**	26	41.50	**0.63**	**0.43-0.92**
Pleura & other thoracic organs (163-164)	1	0.07	**14.97**	**2.11-106.24**	4	0.17	**23.53**	**8.83-62.69**	5	0.24	**21.11**	**8.79-50.72**
Bone (170)	0	0.12	0.00	–	0	0.24	0.00	–	0	0.36	0.00	–
Connective tissue (171)	0	0.25	0.00	–	1	0.60	1.66	0.23-11.77	1	0.85	1.18	0.17-8.34
Melanoma of the skin (172)	4	1.69	2.37	0.89-6.30	7	4.51	1.55	0.74-3.25	11	6.20	1.77	0.98-3.20
Breast (174)[a]	5	4.19	1.19	0.50-2.87	2	0.76	2.62	0.66-10.49	7	4.95	1.41	0.67-2.97
Cervix uteri (180)[a]	0	0.69	0.00	–	0	0.14	0.00	–	0	0.83	0.00	–
Body of uterus (182)[a]	0	0.26	0.00	–	0	0.04	0.00	–	0	0.30	0.00	–
Ovary (183)[a]	0	0.97	0.00	–	0	0.17	0.00	–	0	1.14	0.00	–
Prostate (185)[b]	3	2.40	1.25	0.40-3.87	9	10.53	0.85	0.44-1.64	12	12.94	0.93	0.53-1.63
Testis (186)[b]	0	0.11	0.00	–	0	0.26	0.00	–	0	0.38	0.00	–
Bladder (188)	2	0.84	2.39	0.60-9.56	4	3.03	1.32	0.50-3.52	6	3.86	1.55	0.70-3.46
Kidney (189)	1	1.01	0.99	0.14-7.00	5	2.95	1.69	0.71-4.08	6	3.96	1.51	0.68-3.37
Eye (190)	0	0.08	0.00	–	0	0.19	0.00	–	0	0.27	0.00	–
Brain and CNS (191-192)	1	1.56	0.64	0.09-4.54	5	3.88	1.29	0.54-3.10	6	5.44	1.10	0.50-2.45
Thyroid (193)	0	0.09	0.00	–	1	0.21	4.77	0.67-33.89	1	0.30	3.34	0.47-23.69
Ill-defined & unspecified (159, 165, 195, 199)	2	3.39	0.59	0.15-2.36	6	9.53	0.63	0.28-1.40	8	12.92	0.62	0.31-1.24
Non-hodgkin lymphoma (200, 202)	1	1.77	0.56	0.08-4.01	2	4.48	0.45	0.11-1.79	3	6.25	0.48	0.15-1.49
Hodgkin's disease (201)	1	0.25	4.03	0.57-28.63	1	0.55	1.81	0.26-12.87	2	0.80	2.50	0.63-10.00
Multiple myeloma (203)	0	0.63	0.00	–	0	1.88	0.00	–	0	2.51	0.00	–
All leukemias (204-208)	0	1.60	0.00	–	6	4.11	1.46	0.66-3.25	6	5.71	1.05	0.47-2.34
All cancers except leukemia (140-203)	33	42.37	0.78	0.55-1.10	96	117.69	**0.82**	**0.67-1.00**	129	160.06	**0.81**	**0.68-0.96**
All cancers (140-208)	33	43.97	0.75	0.53-1.06	102	122.80	0.84	0.69-1.02	135	165.77	**0.81**	**0.69-0.96**

Notes:
Figures in bold: p<0.05
(a) Women only.
(b) Men only.

Mortality from other cancers

Mortality from cancer of the rectum was significantly in deficit when compared with the NSW rates (SMR=0.24; 95% CI 0.06-0.96) (see Table 4).

Because of the relatively small number of deaths from many types of cancers, other analyses were based on broader groups of cancers, including smoking-related cancers, cancers not related to smoking, radiosensitive solid cancers, non-radiosensitive solid cancers, and hemato- and lymphopoeitic solid cancers (see Table 5).

Mortality from smoking-related cancers

Cancer mortality from the group of smoking-related cancers was significantly in deficit in monitored workers (SMR=0.72; 95% CI 0.72-0.95) and all workers combined (SMR=0.67; 95% CI 0.48-0.94) (see Table 5). The low SMR for smoking-related cancers was influenced by the SMR for lung cancer, which represented 54% (26 of 48) of all deaths from smoking-related cancers.

Mortality from radiosensitive and non-radiosensitive solid cancers

The SMR for the group of radiosensitive solid cancers was in deficit, although not significantly so (SMR=0.90; 95% CI 0.72-1.13) (see Table 5). In contrast, mortality from the group of non-radiosensitive solid cancers was significantly in deficit (SMR=0.72; 95% CI 0.55-0.96).

Discussion

All-cause mortality

Low SMRs are not unique to this study. Other studies of workers in the nuclear industry have also found lower overall mortality rates compared with those of the general population.[11,18,20,21,23,24,30,33] It has been recognised that employed people have lower rates of mortality than the general population. This 'healthy worker effect' results from the fact that a requirement for participation in most workforces is an absence of major chronic illnesses.[53,55-57] The initial recruitment into the workforce on the basis of good health suggests that SMRs are usually lowest in the first few years after first employment.[57] Later, other factors such as socio-economic characteristics and better health-related behaviours continue to ensure a lower mortality level in the longer term among the employed.[36]

In this study, the SMRs remained low even after 30 years of employment, suggesting that factors other than the selection of healthy workers into the workforce have contributed to the low mortality rates in LHSTC workers.

One reason for the low SMRs observed in the overall cohort at LHSTC might be the preponderance of workers of higher socio-economic status. A similar phenomenon was reported in Los Alamos National Laboratory workers[25] and in Rocketdyne/Atomics International employees.[33] Socio-economic status, as assessed by job description, was strongly inversely related to the death rates in the LHSTC workforce.

Mortality differentials by socio-economic status may be partly due to differences in specific health-related behaviours, such as smoking and alcohol consumption, between the LHSTC workforce and the national population. In this study, only very limited information on health-related behaviours could be abstracted and their effects therefore could not be systematically examined.

Cancer mortality

While the healthy worker effect is known to affect the outcome of the overall mortality rates, it is generally believed that it has a limited effect on death from cancers.[2]

An increased risk of pleural cancer has been previously reported in other studies of nuclear industry workers, including the Sellafield study,[24] the UK combined analysis,[23] and the NRRW study,[30] although the UK combined and the NRRW cohorts overlapped considerably and both included the Sellafield cohort. However, the raised overall mortality from cancer of the pleura and other thoracic organs in workers at LHSTC is unlikely to be related to radiation exposure, since SMRs were elevated for both monitored and non-monitored workers.

Exposure to asbestos is recognised to be a major risk factor for pleural cancer, and in particular for mesothelioma.[58] All four pleural cancer deaths occurring in the monitored group were among male workers who were first employed at LHSTC before 1964, when asbestos was widely used in many industries. Senior occupational hygienists at LHSTC indicated that asbestos was used on site during the construction of the reactor in the late 1950s, and continued to be used in the 1960s. Asbestos removal by LHSTC employees took place from 1986 until December 1992 to remove asbestos lagging on pipes, boilers and hot water containers. It is also possible that workers were exposed in previous employment.

In the absence of smoking data for workers at LHSTC, confounding by cigarette smoking could not be evaluated directly. Instead, the socio-economic status (SES) was used as a broad indicator of health-related behaviours as it is known that people at higher SES levels generally smoke less than those of lower SES.[59]

One explanation of the significant deficits in the SMRs for lung cancer and smoking-related cancers in monitored workers at LHSTC is that they smoked less than the NSW population. While the majority of workers in the monitored group in the inception cohort [72-98] belong to the higher SES job classifications (management and professional 28.8% or technical 37.9%), the majority of workers in the non-monitored group are of lower SES job categories (administration 33.0% or craftsperson 28.4%). This suggests that monitored workers might have smoked less than non-monitored workers.

Although solid cancers have been previously found to be associated with occupational radiation exposure,[33] in our study the SMR for radiosensitive solid cancers at sites recognised to be radiosensitive was in deficit, although not significantly so. A possible explanation is the limited level of exposure received by this cohort. Leukemia excluding chronic lymphocytic leukemia has also been associated with occupational radiation exposure in previous studies.[7,19,22-24] In our study, a non-significant small excess for all leukemias was reported (SMR=1.46; 95% CI 0.66-3.25) among monitored workers. The wide confidence interval, reflecting a limited number of cases, as well as the low exposure levels compared with some other occupational cohorts, are plausible explanations.

Study limitations

As with many retrospective cohort studies, this study is subject to methodological limitations. First, it was not possible to collect information on a range of potential risk factors, both occupational and lifestyle related. It is therefore possible that unadjusted confounding has contributed to some of the relationships observed. For instance, information on exposure to asbestos, had it been available, may have allowed further investigation of the elevated SMR for cancer of the pleura found in workers at LHSTC. Similarly, the possible role of smoking could not be evaluated in this cohort because of the lack of information on smoking status.

A second limitation of this study was the incomplete ascertainment of vital status (see Table 2). Assuming no death in those who may have left Australia after 1980, approximately 80% of workers in cohort [72-98] were accounted for because (1) they were still employed by the end of the study, (2) they were recorded as having died, or (3) they left employment after 1980 and were assumed to be alive because there was no record of their death on the NDI, which documents death in Australia from 1980. The remaining 20% of workers with unknown vital status left employment between 1972-79 and were not recorded as having died or developed cancer. In the analyses, it was assumed that all those workers with unknown vital status were alive at the end of the study (31 December 1998). If in fact some had died, this assumption has the effect of inflating person-years at risk and thus slightly decreasing SMRs.[53]

Third, the ascertainment of vital status and causes of deaths were based on linkage to routine registers. Linkage results may be incomplete and misclassification of causes of death and other recording errors may have occurred. A sensitivity analysis of the linkage with the NDI and the NSW CCR death records revealed that 81 of the 83 deaths recorded on LHSTC files between 1980 and 1998 were identified by the electronic linkage. The remaining two deaths that were originally missed were identified in a second round of verifications on the NDI database. Therefore, it appeared that the sensitivity of the linkage was high and it was likely that most deaths occurring past 1980 were accounted for.

Since the associated causes of death are not recorded in the National Death Index, only the underlying causes of death were accounted for. The rates used for SMR calculations were based on the same principle, and are therefore a valid basis for calculation of the mortality ratio. It is possible that the absolute cause-specific death rate may have differed if associated causes had been used.

Mortality data are inherently limited as a means of assessing cancer causation, because they are influenced by trends and patterns in treatment. It is possible that people who developed cancer in the cohort under study experienced different treatment outcomes compared with the NSW comparison population.

Finally, the small number of observed events for most specific cancers resulted in low precision in estimating effects of radiation exposure. For instance, the significant deficit in the mortality from cancer of the rectum was based on only two deaths in the monitored group.

Conclusion

The focus of this analysis was a comparison of mortality among LHSTC employees with the Australian and the NSW populations. All-cause and cancer-specific mortality were reduced in LHSTC workers, and were generally similar in monitored and non-monitored workers. More detailed analyses of dosimetry data will follow, as will pooled analyses with similar studies internationally.

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