Nuclear shipyard worker study (1980–1988): a large cohort exposed to low-dose-rate gamma radiation

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Abstract: This paper is a summary of the 1991 Final Report of the Nuclear Shipyard Worker Study (NSWS), a very comprehensive study of occupational radiation exposure in the US. The NSWS compared three cohorts: a high-dose cohort of 27,872 nuclear workers, a low dose cohort of 10,348 workers, and a control cohort of 32,510 unexposed shipyard workers. The cohorts were matched by ages and job categories. Although the NSWS was designed to search for adverse effects of occupational low dose-rate gamma radiation, few risks were found. The high-dose workers demonstrated significantly lower circulatory, respiratory, and all-cause mortality than did unexposed workers. Mortality from all cancers combined was also lower in the exposed cohort. The NSWS results are compared to a study of British radiologists. We recommend extension of NSWS data from 1981 to 2001 to get a more complete picture of the health effects of ^{60}Co radiation to the high-dose cohort compared to the controls.

Keywords: low-dose-rate gamma radiation; nuclear shipyard workers; cohort; cardiovascular disease; cancer; mortality.

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Biographical notes: Professor John R. Cameron was trained in nuclear physics but spent most of his career applying physics to medicine. In the 1960s, he and his graduate students developed thermoluminescent dosimetry (TLD) and invented bone densitometry for detection of osteoporosis. In 1981, he was the founding chair of the Medical Physics Department at the University of Wisconsin. From 1980–1988, he was a member of the external panel that advised scientists doing the US nuclear shipyard worker study. He was disappointed that the scientists who did the research chose not to publish the details of this excellent study.

Ruth Sponsler has an MS in Entomology from Auburn University and is interested in biostatistics. She also has active hobby interests in geology.

1 Introduction

This paper provides information from the unpublished final report of the nuclear shipyard worker study (NSWS) (Matanoski, 1991), herein referred to as 'Final Report'. The NSWS is the world's largest and most thorough study of health effects of low-dose- rate ionising radiation to nuclear workers. The detailed results of the NSWS have not yet been published in any journal even 14 years after the study was finished. The NSWS was a rigorously performed search for health risks of radiation to civilian employees of eight shipyards that overhauled and repaired nuclear-propelled US Navy ships and submarines under the leadership of Adm. Hyman G. Rickover. Neither author of this paper was directly involved with the research. The second author was a member of the Technical Advisory Panel (TAP) of the NSWS that reviewed the study twice per year from 1980 to 1988.

The NSWS was performed by the School of Public Health of Johns Hopkins University under a contract with DOE at a cost of about $10 million. The principal investigator for the contract was Professor Genevieve Matanoski, an epidemiologist and Head of the Department of Epidemiology. The study was initiated in response to a small study at the Portsmouth N.H. shipyard, where excess leukaemia mortality had been reported (Najarian and Colton, 1978). Rinsky et al. (1981) subsequently refuted these results.

The present paper is the first publication of a comprehensive report of the NSWS results that details radiation doses and causes of death. Brief summaries of main points of the NSWS results were previously published (Cameron, 1992, 2001; Matanoski, 1993; Pollycove, 1998; Boice, 2001).

The US Department of Energy (DOE) received the contractor's report in 1991, more than three years after the completion of the study. The report is in the public domain. The NSWS was peer reviewed twice a year from 1980 to 1988 by a Technical Advisory Panel (TAP) as called for in the DOE contract. The TAP also reviewed the final report of the study. The TAP consisted of eight external scientists with relevant expertise: Arthur Upton, (chair); Gilbert Beebe, John Cameron (co-author of this paper), Carter Dennison (resigned in 1983), Merrill Eisenbud, Philip Enterline, Philip Sartwell and Roy Shore. The TAP members reviewed and approved the final NSWS report early in 1988. The final report shows no criticism of the study by any of the TAP members.

The NSWS is the only radiation study where nuclear workers were compared to age-matched and job-matched unexposed workers as controls. This was designed to avoid the 'healthy worker effect', a bias introduced when workers are compared with the general population (Monson, 1986; Choi, 1992). The Final Report states (p.357): "Therefore this is an ideal population in which to examine the risks of ionising radiation in which confounding variables could be controlled".

The NSWS used a large cohort of 27,872 nuclear workers drawn from a pool of over 100,000 nuclear shipyard workers. The 32,510 controls were job and age matched to the cohort. They were chosen from nearly 600,000 non-nuclear shipyard workers. The large size of the cohort and control groups enabled a strong statistical power in the study that is uncommon in many epidemiological studies. Uniform standards for dose assessment were established in the shipyards. Nuclear shipyard workers were primarily exposed to external ^{60}Co gamma rays resulting from neutron activation of cobalt in the reactor that was deposited in pipes and valves associated with the reactor cooling systems. Dose assessment was unusually accurate because the Nuclear Navy programme had substantial discipline in assigning radiation-monitoring badges and in accurate recording of results. There was little missing personnel dosimetry data and little possibility of internal contamination or high LET exposure since few workers were involved with radiochemical environments or with any radionuclide other than external exposure to ^{60}Co. The elimination of confounding from high LET radiation or internal doses permits comparison with other large groups of radiation workers exposed to low LET radiation, such as radiologists and radiology technologists (Smith and Doll, 1981; Doody et al., 1998; Berrington et al., 2001).

Doses to the shipyard workers were relatively low compared to pre-1955 exposures to radiologists (Matanoski et al., 1975; Berrington et al., 2001). Common shipyard doses were 0.5–22.5 mGy y^{-1}, and are comparable to doses currently experienced by employees in nuclear and medical facilities, as well as to people exposed to high natural background radiation in locations such as Ramsar, Iran (10–260 mGy y^{-1}) (Ghiassi-nejad et al., 2002) and Kerala, India (approx. 7.5–70 mGy y^{-1}) (Nambi and Soman, 1987; Nair et al., 1999).

Workers in eight shipyards were studied: Charleston Naval Shipyard, Charleston SC; General Dynamics Corp. Electric Boat Division, Groton, CT; Mare Island Naval Shipyard, Vallejo CA; Newport News Shipbuilding and Drydock Co., Newport News, VA; Norfolk Naval Shipyard, Norfolk, VA; Pearl Harbor Naval Shipyard, Pearl Harbor, HI; Portsmouth Naval Shipyard, Portsmouth NH; and Puget Sound Naval Shipyard, Bremerton, WA.

NSWS data collection began with workers exposed during the first overhaul of a nuclear submarine in 1957 in the Groton, Connecticut, shipyard. Radiation doses and worker mortality were assessed through 31st December 1981.

2 Materials and methods of the NSWS

2.1 Selection of study groups

A total pool of 692,812 shipyard workers was available for the NSWS, of whom 107,976 were badged nuclear workers (p.18, Final Report). The primary cohort consisted of 27,872 nuclear workers who had received cumulative doses of 5 mGy or more by January 1, 1982 (NW = 0.5). The other two groups involved randomly selected shipyard workers who were stratified by age, number of years on the job, job classification and job hazard index to make the composition of the groups equivalent to that of the cohort (Final Report, p.44–60). The controls were 32,510 shipyard workers who did not enter radiation areas of the ships. The other study group was the low-dose cohort consisting of 10,348 nuclear workers with less than 5 mGy cumulative dose (Table 3.1.B. on p.301 of Final Report). Exposures to job hazards such as chemicals and asbestos were similar between nuclear and non-nuclear workers (Final Report, pp.237–258).

2.2 Dosimetry

The NSWS had better dosimetry records for analysis than any other radiation worker study. NSWS dosimetry and records were carefully maintained under central Naval management of the shipyards. All dosimetry data in the Final Report were given as rem or mrem. As gamma radiation has a quality factor of 1.0, we have converted those figures to mGy. Badging and recordkeeping were consistent across the shipyards and were more rigorously enforced than for radiation workers in other nuclear facility worker studies (Final Report, p.125, 133, 167). As almost all exposure was from ^{60}Co gamma rays, dosimetry lacked the problems often associated with dosimetry for mixed exposures. Doses were measured with film badges through 1976 and thermoluminescent dosimetry (TLD) after 1976. There was a transition period to TLD from 1973 to 1976 (Final Report, p.8). Most doses received by the cohort were received in annual increments of 1 mGy or greater, which probably were received in relatively short intervals rather than very gradually over the entire year (Final Report, p.154).

The Final Report (p.371) states, "In summary all data of radiation exposures to shipyard workers in the Navy nuclear propulsion program have indicated that doses are accurately recorded, carefully monitored, and are a true reflection of the dose received by the marrow which makes this population ideal for studies of effects of low-dose radiation."

The average annual dose to the cohort was 7.59 mGy y^{-1} (Table 1), while the median dose was 2.80 mGy y^{-1} and the 90th percentile dose was 22.6 mGy y^{-1}. Allowable doses ranged up to 120 mGy y^{-1} prior to 1967, although very few workers exceeded 50 mGy y^{-1}. Average annual doses declined over the span of the study, as the shipyards reduced man-rem exposure.

2.3 Mortality data

Vital status of shipyard workers was ascertained using a large number of sources including Social Security records and records of the various States (Final Report, pp.77–104). Data were recorded for 21 sites and types of cancers, including those likely to be radiogenic such as leukaemia and lymphatic and haematopoietic cancers. Data were also recorded for lung cancer and mesothelioma. Mesothelioma is strongly linked with asbestos exposure. Data were also recorded for all major causes of mortality, including diseases of the circulatory system, respiratory system, digestive system and the nervous system, also infectious diseases, mental illnesses and external causes. SMRs (standardised mortality ratios) for total mortality and various causes of death were computed by comparing mortality of cohort, low-dose cohort and controls with mortality of US white males (Final Report, p.289). This provided numbers of expected deaths for comparison of the shipyard cohorts with the US white male population. Internal comparisons between the three shipyard study groups were made for all causes of mortality (Final Report, pp.290–303) as well as for leukaemia, lymphatic and haematopoietic cancers, mesothelioma and lung cancer (Final Report, pp.304–324). The internal comparisons of mortality between groups of shipyard workers represent a major strength of the NSWS compared to other studies of nuclear workers. Sampling was stratified by age, birth year, year of hire and job hazard Final Report, pp.44–60).

Table 1 Summary statistics for annual dose equivalents received by the cohort

	Shipyard	*Mean*	*Median*	*sd*	*25*	*75*	*90*	*99*
Time period	*Location*	*Annual dose,* $mGyy^{-1}$	*Annual dose,* $mGyy^{-1}$	*%ile*	*%ile*	*%ile*	*%ile*	*%ile*
1957–1981	All Shipyards	7.59	2.8	12.32	0.54	9.7	22.6	46.3
1957–1973	All	9.31	3.53	14.38	0.7	13.01	27.83	50
1973–1981	All	7.2	3.61	9.37	0.7	10.51	20.35	35.23
1974–1981	All	4.35	1.76	6.85	0.28	5.52	12.11	28.41

Shipyard dosimetry adapted from Tables 2.7.N. on p.189 and 2.7.S on p.194 of Final Report.

Original figures have been converted to mGy.

Excludes privately owned shipyards Groton and Newport News.

Percentage columns represent percentiles of the dose range.

Beginning year for each shipyard is the first year that the shipyard conducted nuclear overhaul (see Table 2.1.A., p.18 of Final Report).

2.4 Selection bias considerations

The NSWS used numerous techniques to reduce 'selection bias', also known as the 'healthy worker effect' (Choi, 1992; Chen and Seaton, 1996). These techniques are listed below:

- Workers were compared with other shipyard workers, rather than with the general population or with workers not exposed to shipyard conditions. This ensured that the nuclear worker groups and the non-nuclear group would come in contact with similar work conditions other than radiation exposure to the nuclear workers.
- Non-nuclear workers who did not work during the period that the nuclear ships were undergoing overhauls were excluded. (Final Report, p.5). Seventy percent of the excluded non-nuclear workers did not work in their shipyard during nuclear overhaul periods or had worked in the particular shipyard for less than a year. This helped to ensure the temporal consistency of the non-nuclear worker sample with the nuclear worker sample. (Final Report, p.7).
- Excluded from both the cohort and the controls were workers who had worked less than a year, non-shipyard workers, military personnel, visitors, females, persons with missing personnel records, etc. (Final Report, pp.25–40; Table, pp.42, 43).
- Each nuclear worker with a cumulative dose = 5.0 mGy was included in the cohort as long as complete data were available. (Final Report, p.44). Stratified sampling (shipyard, birth year, date of starting employment, job hazard index and number of years in shipyard prior to starting nuclear work) was used for the <5.0 mGy sample. (Final Report, pp.45–48).

- The sampling technique provided for racial consistency between the <5.0 mGy group and the = 5.0 mGy group. Racial records were not available for all shipyards. Data for certain yards indicated similar racial composition of the cohort and controls (Final Report, p.25).
- Controls were sampled randomly from blocks with similar work duration compared to nuclear workers, i.e., exposure to other aspects of working environment. Blocks were grouped to control for age and job hazard index. (Final Report, p.52).
- The controls were made equivalent to the cohort in age, job hazards and time since hire. (Final Report–Table, p.54, 55; graph, pp.56–60).
- Vital records were searched thoroughly. 'Status unknown' was equal between the cohort and controls. The low-dose cohort had a slightly higher 'status unknown' rate. (Final Report, p.101).

Virtually all of the workers involved in the NSWS were 'blue collar' workers and thus results were less susceptible to favourable socio-economic biases that may affect studies of 'white collar' occupational groups. Among occupations included in the nuclear shipyard worker study were machinists, toolmakers, pipefitters, shipfitters, electricians, engineers, carpenters, boatbuilders, welders, labourers, riggers, sheetmetal mechanics and warehouse men. Distribution of occupations amongst the cohort and controls was roughly similar in the shipyards (Final Report, p.237).

The lack of incentive pay for radiation work helped to avoid the possibility of positive selection bias that would favour more-skilled or higher-income shipyard workers. There was no prohibition on the hire of smokers for radiation work. The physical examination given to shipyard workers for radiation work was a possible source of confounding. Authorities differ on the role of the annual check-up in reducing mortality. Franks et al. (1996) found no reduction in mortality for men who received annual physicals compared to men who did not, while a 16-year study (Friedman et al., 1986) found a 30% reduction in mortality from 'potentially postponable' causes, largely colorectal cancer and hypertension. This reduction was most pronounced in the early years of the study. However, the two groups did not differ to a statistically significant degree in mortality from all other causes (84% of total mortality) or in total mortality. Nuclear workers were given radiation medical examinations prior to assignment and follow-ups every three years if they were exposed to 5.0 mGy or more in any year (Final Report, pp.124, 125).

3 Results of the NSWS

Table 2 presents all-cause mortality results from the three groups of shipyard workers. The cohort is split into three groups ranked by cumulative dose. The standardised mortality ratio (SMR) for all causes of death of the cohort (SMR = 0.76) was 24% lower (p < 10–16) than that of the 32,510 controls (SMR = 1.00) (Table 3.1.B. on p.301 of Final Report). Among the cohort, 2,215 deaths occurred whereas 2,875.9 deaths would have been expected (Final Report, p.328). Among the non-nuclear controls, 3,749 deaths occurred whereas 3,685.4 deaths would have been expected (Final Report, p.332).

Table 2 Deaths from All Causes, Death Rates** and Standardised mortality ratios with 95% confidence intervals for the cohort (NW = 5.0 mGy)); low dose cohort (NW < 5.0 mGy); and controls (NNW)

	NNW	*NW < 5.0 mGy*	*NW ≥ 5.0 mGy*	*NW ≥ 5.0 mGy*		
	Controls	*Low Dose Cohort*	*Cohort*	*Cohort*		
Subgrouping	All	All	All	0.5–	1.0–	5.0+
Number in Sample	32,510	10,348	27,872	5,431	13,357	9,084
Person-Years	4,25,070	1,39,746	3,56,091	69,489	1,72,531	1,14,071
Deaths	3,745	973	2,215	454	1,110	651
Death rate per 1000**	9	7.1	6.4	6.7	6.6	5.9
SMR	1	0.81	0.76	0.72	0.79	0.74
95% C.I.	(0.97-1.03)	(0.76–0.79)	0.73			

*Indicates that SMR is significantly lower than for NNW group at $p < 0.05$.

**Adjusted for deaths excluded from analysis due to unknown date of death.

Adapted from Tables 3.1.B and 3.1.C on pp.301, 302 of Final Report (Matanoski, 1991).

Table 3 presents a breakdown of deaths from various causes, which shows that SMRs from diseases of the circulatory system are significantly decreased in the cohort. No significant differences or trends were present between the groups from external causes including accidents and crimes.

The Final Report (p.334) states:

> "The SMRs from the categorical analysis in which the individual remains in the same group throughout follow-up (Table 4.1.A) indicate that the risks of death in the NNW group of shipyard workers are similar to that of the general population but the risks of total mortality in both groups of nuclear workers are lower than the US rate. The all cause mortality is highest for the NNW group and lowest for the NW = 0.5 [the cohort], which certainly does not suggest that radiation causes a general risk of death. In fact, in the NW = 0.5 group [the cohort], the mortality is only 76% of that of the general population and is significantly lower than would be expected."

The magnitude of the difference in mortality between cohort and the controls is so large that a physical examination for entry into the nuclear programme cannot account for the entire difference that is significant at $p < 1 \times 10^{-16}$. There was no prohibition against the hire of smokers for the nuclear programme and no incentive pay.

The dose range covered by the NSWS is relatively small but matches or is slightly higher than contemporary dose ranges [1970 and after] for nuclear workers and radiology workers. There is a pattern within the cohort of a decrease in overall mortality from the low-dose to the higher-dose groups, contrary to what all non-threshold models of radiation risk would predict. The low-dose cohort had a SMR of 0.81 (95% CI: 0.76, 0.86) compared to 0.76 (0.73, 0.79) for the cohort. The lowest SMR (0.74) was registered for the subgroup of the cohort who received 5.0 mGy or more.

Surprisingly, the text of the NSWS final report did not compare the cancer mortality of the cohort to that of the controls. Table 4 (a summary of Table 3.6 of the Final Report) indicates that SMR from all malignant neoplasms for the cohort was 0.95 (0.88, 1.03), significantly lower at $p < 0.01$ than that for the controls (1.12 (1.06, 1.20)).

The significantly lower cancer death rate of the cohort compared to the controls suggests that increased low LET radiation may have stimulated their immune systems, as reported in other irradiated populations (Calabrese and Baldwin, 2000).

Table 3 Deaths from various causes, Death Rates** and Standardised mortality ratios with 95% confidence intervals for the cohort (NW = 5.0 mGy cumulative dose); cohort (NW < 5.0 mGy); and controls (NNW). O/E = observed/expected

Category	*NNW* (*control*)		*NW<5.0* mGy (*low dose cohort*)		*NW ≥ 5.0* mGy (*cohort*)	
Cause of death	*O/E*	*SMR*	*O/E*	*SMR*	*O/E*	*SMR*
Total morality ***	3749/3685.41	1.02 (0.98–1.05)	973/1173.50	0.83 (0.78–0.88)*	2215/2875.91	0.77 (0.74–0.80)*
All diseases of circulatory system	1626/1751.85	0.93 (0.88–0.97)	418/549.86	0.76 (0.69–0.83)*	970/1325.99	0.73 (0.69–0.78)*
Arteriosclerotic heart disease	1166/1263.23	0.92 (0.87–0.98)	316/400.79	0.79 (0.70–0.88)	719/975.47	0.74 (0.68–0.79)*
Vascular lesions of CNS	183/199–38	0.92 (0.79–1.06)	37/58.60	0.63 (0.44–0.87)	96/132.81	0.72 (0.59–0.88)
Allergic, Endocrine, Metabolic	53/63.08	0.84 (0.63–1.10)	13/20.01	0.65 (0.35–1.11)	25/46.83	0.51 (0.33–0.76)
Nervous and sensory organs	29/34.50	0.84 (0.56–1.21)	4/11.16	0.38 (0.10–0.92)	12/27.78	0.43 (0.22–0.75)
All disease of digestive system	189/193.24	0.98 (0.84–1.13)	45/63.98	0.70 (0.51–0.94)	115/163.48	0.70 (0.56–0.84)
Diabetes mellitus	39/51.58	0.76 (0.54–1.03)	9/16.30	0.55 (0.29–1.06)	24/39.56	0.61 (0.39–0.90)
Cirrhosis of liver	104/114.72	0.91 (0.74–1.10)	19/38.6	0.49 (0.29–0.76)	67/102.36	0.65 (0.51–0.83)
All respiratory disease	201/208.89	0.96 (0.83–1.10)	42/64.41	0.65 (0.47–0.88)	82/151.58	0.54 (0.43–0.67)*
Pneumonia	66/66.93	0.99 (0.76–1.25)	13/20.24	0.64 (0.34–1.10)	33/47.15	0.70 (0.48–0.96)
Emphysema	42/51.08	0.88 (0.64–1.10)	11/15.52	0.71 (0.35–1.27)	14/35.74	0.39 (0.21–0.66)
Asthma	9/5.08	1.77 (0.81–3.36)	0/1.59	0.00 (0.00–230	4/3.75	1.07 (0.29–2.73)
All genito-urinary	44/37.36	1.18 (0.66–1.58	9/11.31	0.80 (0.32–1.64)	11/26.06	0.42 (0.21–0.76)
Mental and personality	27/26.37	1.02 (0.67–1.49)	7/8.78	0.80 (0.32–1.64)	10/22.83	0.44 (0.21–0.81)
All infectious and parasitic	18/28.58	0.63 (0.37–1.00)	2/9.12	0.22 (0.02–0.79)	19/22.05	0.86 (0.52–1.35)
All external causes	413/474.26	0.87 (0.79–0.86)	133/153.99	0.86 (0.72–1.02)	253/388.20	0.65 (0.57–0.74)*
All accidents	245/305.10	0.80 (0.71–0.91)	91/98.89	0.92 (0.74–1.13)	168/245.70	0.68 (0.58–0.80)
Motor vehicle accidents	120/155.62	0.77 (0.64–0.92)	50/50.04	1.00 (0.74–1.33)	95/123.52	0.77 (0.62–0.94)
Suicide	1.6/109.82	0.97 (0.79–1.17)	27/36.10	0.75 (0.49–1.09)	60/92.51	0.65 (0.49–0.83)

*Indicates that SMR is significantly lower than for NNW group at $p < 0.05$.

**Adjusted for deaths excluded from analysis due to unknown date of death.

***Using age-calendar time specific rates for US white males.

Adapted from pp.326–333 of Final Report (Matanoski, 1991).

Table 4 Cancer mortality classified by site. Also includes figures for mortality from all cancers and groupings of sites. Standardised mortality ratios with 95% confidence intervals for cohort (NW = 5.0 mGy cumulative dose)); low-dose cohort (NW < 5.0 mGy); and controls (NNW). O/E = observed/expected

Category	*NNW (control)*		*NW<5.0 mGy (Low dose cohort)*		*NW≥5.0 mGy (cohort)*	
Cause of death	*O/E*	*SMR*	*O/E*	*SMR*	*O/E*	*SMR*
All malignant neoplasms	878/784.60	1.12 (1.06-1.20)	243/254.23	0.96 (0.84–1.08)	603/632.30	0.95 (0.88–1.03)*
Cancers of digestive organs	224/199.40	1.12 (0.96–1.28)	65/63.72	1.02 (0.79–1.30)	146/156.08	0.94 (0.79–1.10)
Buccal cavity and pharynx	23/24.63	0.93 (0.59–1.40)	6/8.18	0.73 (0.27–1.60)	15/20.82	0.72 (0.40–1.19)
Esophagus	27/18.47	1.46 (0.96–2.13)	7/6.08	1.15 (0.46–2.37)	16/15.37	1.04 (0.59–1.69)
Stomach	48/32.25	1.49 (1.10–1.97)	13/10.15	1.28 (0.68–2.19)	23/24.52	0.94 (0.59–1.41)
Large intestine	59/67.55	0.87 (0.66–1.13)	21/21.48	0.98 (0.60–1.49)	41/52.42	0.78 (0.56)–1.06)
Rectum	20/20.44	0.98 (0.60–1.51)	7/6.46	1.08 (0.43–2.23)	6/5.59	1.03 (0.59–1.67)
Liver	15/13.68	1.10 (0.61–1.81)	3/4 34	0.69 (0.14–2.02)	17/10.53	1.61 (0.94–2.58)
Pancreas	48/41.57	1.15 (0.85–1.53)	11/13.43	0.82 (0.41–1.47)	26/33.25	0.78 (0.51–1.15)
All respiratory system cancers	323/288.93	1.12 (1.00–1.25)	110/95.54	1.15 (0.95–1.39)	259/242.27	1.07 (0.94–1.21)
Lung cancer	306/274.61	1.11 (0.99–1.25)	98/90.83	1.08 (0.88–1.31)	237/230.41	1.03 (0.90–1.17)
Mesothelioma[†]		2.41 (1.15–4.43)		5.75 (2.48–11.33)		5.11 (3.03–8.08)
Skim	18/17.80	1.06 (0.63–1.67)	7/5.62	1.25 (0.50–2.57)	7/14.47	0.48 (0.91–1.00)
Kidney	26/20.26	1.28 (0.84–1.69)	4/6.68	0.60 (0.16–1.53)	15/16.95	0.89 (0.50–1.46)
Bladder	17/19.68	0.86 (0.50–1.38)	6/5.99	1.00 (0.37–2.18)	18/13.86	1.30 (0.77–2.05)
Testis	6/5.38	1.12 (0.41–2.44)	1/1.73	0.58 (0.01–3.21)	1/4.28	0.33 (0.00–1.30)
Cancer of prostate	55/41.51	1.32 (1.09–1.72)	13/11.93	1.09 (0.56–1.86)	27/25.99	1.04 (0.58–1.51)
Cancer of brain and CNS	29/26.43	1.09 (0.73–1.58)	4/8.98	0.45 (0.12–1.14)	22/23.24	0.95 (0.59–1.43)
Bone	4/3.43	1.17 (0.31–2.89)	0/1.10	0.00 (0.00–1.35)	0/2.68	0.00 (0.00–1.37)
Leukemia	29/30.96	0.94 (0.63–1.39)	4/9.67	0.42 (0.11–1.04)	21/24.20	0.87 (0.54–1.33)
All lymphopoietic cancer	84/79.07	1.06 (0.85–1.32)	13/25.59	0.51 (0.27–0.87)	50/63.59	0.79 (0.58–1.04)
Hodgkins disease	12/9.78	1.23 (0.63–2.14)	1/3.21	0.31 (0.00–1.73)	5/8.00	0.62 (0.20–1.46)
Lymphosarcoma Reticulosarcoma	18/16.10	1.12 (0.84–1.77)	4/5.26	0.76 (0.20–1.95)	5/13.11	0.38 (0.12–0.89)
Other lymphatic tissue	24/21.33	1.13 (0.72–1.67)	4/6.96	0.57 (0.15–1.47)	17/17.56	0.97 (0.56–1.55)

*Indicates that SMR is significantly lower than for NNW group at $p < 0.05$.

[†]Related to asbestos exposure. Mesothelioma data adapted from Table 3.4.A., p.317 of Final Report.

Source: Adapted from Table 3.6.B (pp.328–329), Table 3.6.C (pp.330–331), and Table 3.6.D (pp.332–333) of Final Report (Matanoski, 1991). Adjusted for deaths excluded because of unknown date of death. See Tables 3.1.A (p. 296) and 3.1.B (p. 301) of Final Report (Matanoski, 1991)

In addition, the cohort had lower rates for the most radiation-sensitive cancers, leukaemia and haematopoietic cancers than the controls: the unadjusted SMRs were 1.06 (0.85, 1.32) for the controls; 0.79 (0.58, 1.04) for the cohort; and 0.51 (0.27, 0.87) for the low-dose cohort. The Final Report (p.334) states:

> "The SMRs for leukaemia and all lymphatic and haematopoietic cancers indicate risks of these diseases among nuclear workers which are below those of the general population."

The cohort had a higher rate of mesothelioma than did the controls, who also had excess mesothelioma. This is likely related to asbestos exposure in the cramped conditions of submarine work.

4 Discussion

The Summary of the Final Report did not mention the 24% lower SMR from all causes of the cohort ($p < 10^{-16}$) compared to the controls. A 24% lower SMR implies a 2.8-year increase in average lifespan.

The NSWS results are in general agreement with reductions in overall mortality from other studies of workers in nuclear facilities and radiology practice in the USA, UK, Canada and Australia (Smith and Doll, 1981; Smith and Douglas, 1986; Fraser et al., 1993; Gilbert et al., 1993; Luckey, 1994, 1997; Boice et al., 1995; Rodriguez et al., 1997; Doody et al., 1998; Berrington et al., 2001; Sont et al., 2001; Habib, 2002). Most of these studies also demonstrated reductions in all-cancer mortality of the radiation workers.

Workers in many professions experience reduced mortality compared to the general population due to the 'healthy worker effect'. This is because employee populations do not include individuals who are too sick to work or to commute. There are also fewer individuals with serious alcohol and drug abuse problems among employee populations. For this reason, a study that compares radiation workers with a group of unexposed similar workers is preferable to a study that compares radiation workers with members of the general population.

The 100-year study of British radiologists (Berrington et al., 2001) shows health benefits from radiation, which agree qualitatively with those of the NSWS. The radiologists' exposures were low LET and the all-male physicians group was matched for occupation. The SMR for deaths from all causes for British radiologists who joined a radiological society from 1955–1979 was 32% lower ($p < 0.001$) than that of all male physicians in England and Wales.

A comparison of doses between the British radiologists and US shipyard workers along with their respective relative risks (SMRs of exposed group compared to control group) is of interest. Both studies involved chronic radiation exposure for multiple years at low-dose rates 3–5 times natural background dose rate.

It is estimated that the 1955–1979 British radiologists were exposed to 5 mGy each year, reaching a cumulative lifetime (20 years) dose of 100 mGy (Berrington et al., 2001). The main cohort of shipyard workers was exposed to a median dose of 2.80 mGy each year (Table 1). The average number of working years of the main shipyard cohort was 12.8 years (obtained by dividing the value of 356091 person-years by the sample number of 27872 in Table 2). Therefore, the median cumulative dose for the main cohort of shipyard workers is 35.8 mGy (2.8 mGy × 12.8 years).

The SMRs for British radiologists registered from 1955–1979 are 0.68 for deaths from all causes and 0.71 for deaths from cancer, while those for the cohort of shipyard workers are 0.76 for deaths from all causes and 0.85 (0.95/1.12) for deaths from all cancer. The reduction in all-cause death in the NSWS was greater than that for cancer deaths in both the cohort and the low-dose cohort. Low-dose-rate radiation has been shown to have anti-inflammatory properties (Rodel et al., 2002). Cardiovascular disease and stroke have been linked with inflammatory processes (Ridker et al., 1997; Leinonen and Saikku, 2000; Kaplan and Frischman, 2001; Koenig, 2001). It is conceivable that low-dose-rate radiation, through a mechanism involving immune response, protects against inflammatory processes involved in the development of cardiovascular disease and stroke.

If the degree of the beneficial effect of radiation on human health depends on the dose rate (up to an optimum dose rate), the British radiologists would be expected to display a stronger beneficial effect, (smaller SMR) for both all-cause death and cancer death than the shipyard cohort, if both groups received doses that are below the optimum dose rate (maximum benefit). This is seen in the results from the two groups, since the shipyard cohort, exposed to a median of 2.8 mGy y^{-1}, experienced a 24% reduction in SMR for all causes, compared to a 32% reduction in SMR for the 1955–1979 radiologists with an estimated 5 mGy y^{-1}. The optimum dose rate may be higher than the annual dose rate received by 1955–1979 British radiologists.

The health benefits of radiation shown in the NSWS and the British radiologist study suggest radiation stimulation of the immune system (Congdon, 1987; Caratero et al., 1998; Calabrese and Baldwin, 2000, 2002; Cameron, 2001, 2002). The results are consistent with the lower cancer mortality of individuals exposed to high natural background levels in mountain regions of the USA (Frigerio et al., 1973; Jagger, 1998).

The DOE contract for the NSWS was to examine 'risks' rather than 'health benefits'. The Conclusion of the Final Report (p.357) states correctly, 'The [exposed] population does not show any risk which can be clearly associated with radiation exposure in the current analysis'. Even though the NSWS was looking for risks, it would have been appropriate for the authors to mention the significant health benefits found among the nuclear workers. If the goal of the study had been to look for health benefits of low-dose-rate radiation, it would have been a success.

Since the NSWS was rigorously designed to eliminate confounding factors as much as possible and had the overview of outside experts, health benefits from radiation are almost certainly present. The Final Report discusses the possibility that selection favours the cohort compared to the controls. There may be a slight selection factor related to medical examinations for acceptance into the nuclear programme, despite the lack of financial incentive. This weak 'healthy worker effect' should diminish with time after beginning of employment. Thus, it would be expected to be stronger for workers recently selected to be nuclear workers (i.e., the low-dose cohort) than for those working long enough to qualify to be in the cohort. However, this is contradicted by the reduced mortality for the cohort, compared to the low-dose cohort. The Final Report states (p.336): "… all cause mortality, (Tables 3.1.A-3.1.B) cardiovascular mortality (Tables 3.6.B-3.6.D) and lung cancer mortality (Tables 3.5.A-3.5.B) actually show higher mortality rates in the NW < 0.5 rem [low-dose cohort] than in the NW = 0.5 rem [cohort].” While historical high acute and chronic exposures have been demonstrated to increase cancer mortality (Matanoski et al., 1975; Koshurnikova et al., 1994; Kossenko and Degteva, 1994; Berrington et al., 2001; Nyberg et al., 2002), doses below 200 mGy (acute) have not been demonstrated to be hazardous (Heidenreich et al., 1997). Residents of mountain states have lower cancer rates than residents of Coastal Plain states (Frigerio et al., 1973; Jagger, 1998). Additionally, life expectancies in mountain states are approximately one year greater than in Coastal Plain states (Murray et al., 1998). Natural background (excluding dose from radon progeny) in mountain regions is approximately twice that of Coastal Regions (NCRP, 1988). The average shipyard dose rate of ~7.6 mGy y^{-1} is somewhat higher than most natural background levels in the USA, but is within the range of high natural background areas worldwide (Ghiassi-nejad et al., 2002).

The shipyard and radiologist data provide assurance that it would be ethical to do a double blind randomised controlled trial of giving increased background radiation to senior citizens in the US Gulf States equal to the dose rate found in the mountain states (Cameron, 2001).

Boice (2001) states that the relatively small doses and small range of doses in the NSWS ‘limits interpretation’. This is not a limitation since the range is the typical dose range for modern radiation workers.

Decreased mortality at relatively young ages in a group such as the shipyard workers or radiologists results in increased average longevity, similar to an observation of US radiologists (Matanoski et al., 1987).

The key comparisons in the NSWS were between non-nuclear and nuclear workers with the same jobs and ages and among dose-ranked groups of nuclear workers. Since cohorts and controls were compared to each other, there should be little ‘healthy worker effect’, especially of the magnitude of a 24% difference in SMR. The second author (JRC), who was also a member of the Technical Advisory Panel (TAP), recalls no discussion of ‘selection bias’ during the many meetings of the TAP. All TAP members approved the NSWS Final Report and evidence of selection bias could have been brought up at that time.

Omission of publication of ‘null-harm’ or ‘benefit’ studies such as the NSWS may contribute to a publication bias (Stern and Simes, 1997) in favour of studies that yield harmful effects. Lea et al. (2000) and Pollycove and Feinendegen (1999) noted errors in methodology and small sample sizes in smaller published studies that have been cited as evidence of harm from low-dose-rate radiation where harm did not exist.

5 Conclusion and recommendations

The NSWS is the world’s largest and most rigorously controlled study of radiation workers. Significantly lower total mortality was observed in both groups of nuclear workers. Significantly lower mortality from all causes was observed among the cohort of nuclear workers who were exposed to an average dose rate of 7.59 mGy y^{-1} and median dose rate of 2.80 mGy y^{-1} than among unexposed controls. In addition, the cohort had significantly reduced mortality for all cardiovascular disease, arteriosclerotic heart disease, respiratory diseases and cancer. This significantly lower mortality contradicts the linear non-threshold (LNT) model of radiation risk.

It is possible that healthy workers would be able to spend more time at work to accumulate the higher doses than unhealthy employees, who might have accumulated lower doses because they spent fewer years on the job. This may be partly responsible for the lower cardiovascular and all-cause mortality among the higher-dose group. We recommend an extension of the NSWS data collection and analysis from 1981 to 2001 to help resolve these questions.

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