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HEALTH OUTCOMES OF LOW-DOSE IONIZING RADIATION EXPOSURE AMONG MEDICAL WORKERS: A COHORT STUDY OF THE CANADIAN NATIONAL DOSE REGISTRY OF RADIATION WORKERS

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Abstract
Background: Medical workers can be exposed to low-dose ionizing radiation from various sources. The potential cancer risks associated with ionizing radiation exposure have been derived from cohort studies of Japanese atomic bomb survivors who had experienced acute, high-level exposure. Since such extrapolations are subject to uncertainty, direct information is needed on the risk associated with chronic low-dose occupational exposure to ionizing radiation. **Objectives:** To determine the occupational doses of ionizing radiation and examine possible associations with mortality rates and cancer incidence in a cohort of medical workers deriving from the National Dose Registry of Canada (NDR) over the period of 1951–1987. **Methods:** Standardized mortality and incidence ratios (SMR and SIR, respectively) were ascertained by linking NDR data for a cohort of 67 562 medical workers (23 580 males and 43 982 females) with the data maintained by the Canadian Mortality, and Cancer Incidence databases. Dosimetry information was obtained from the National Dosimetry Services. **Results:** During the follow-up period, 1309 incident cases of cancer (509 in males, 800 in females) and 1325 deaths (823 in males, 502 in females) were observed. Mortality from cancer and non-cancer causes was generally below expected as compared to the general Canadian population. Thyroid cancer incidence was significantly elevated both among males and females, with a combined SIR of 1.74 and 90% CI: 1.40–2.10. **Conclusions:** The findings confirm previous reports on an increased risk of the thyroid cancer among medical workers occupationally exposed to ionizing radiation. Over the last 50 years, radiation protection measures have been effective in reducing radiation exposures of medical workers to the current very low levels.

Key words:
Ionizing radiation, Low doses, Medical workers, Cancer mortality, Cancer incidence

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INTRODUCTION

The effect of acute exposure to high levels of ionizing radiation on human carcinogenesis has been well established [1–2], but the effect of chronic exposure to low levels is less well understood. Most of the information used in estimating cancer risk associated with low-dose chronic exposure to ionizing radiation has been derived from cohorts experiencing acute, high-intensity exposure, most notably the Japanese atomic bomb survivors [3–4]. Since such extrapolations are subject to uncertainty, direct information is needed on the risk associated with long-term low-level occupational exposure to ionizing radiation.

Medical radiation workers, including doctors, nurses and other medical staff, are exposed to low doses of ionizing radiation from a variety of sources, including diagnostic x-rays and other medical devices [5], and constitute the largest occupational group exposed to man-made sources of radiation [1]. Studies of medical radiation workers have been conducted in Canada [6–7] and in other countries [5,8–14]. Although the majority of these studies have provided some evidence of elevated cancer risk, the results have been inconsistent.

The purpose of this paper is to describe the levels of occupational exposure to ionizing radiation as well as the possible associations with cancer incidence and mortality in a cohort of medical workers ascertained by the National Dose Registry of Canada (NDR). The NDR contains dose records for individuals occupationally exposed to ionizing radiation who constitute the largest single cohort of its type that has been established at the national level.

METHODS

The National Dose Registry of Canada

The NDR, a database maintained by the Radiation Protection Bureau of Health Canada since 1950, contains records of occupational exposure to ionizing radiation for over 500 000 individuals from about 24 000 organizations. The NDR, a major part of Health Canada's ongoing population health surveillance program, accounts for virtually all the monitored radiation workers in Canada. The types of radiation exposures included in the NDR data are external (gamma rays, beta rays, x-rays, and neutrons) and internal (tritium and radon progeny). Further details on the NDR are provided elsewhere [6–7].

Cohort definition

Of the 256 425 radiation workers registered in the NDR as of 31 December 1987, a total of 65 383 workers were excluded because of insufficient identifying information for record linkage and/or missing information on gender or year of birth. The remaining 191 042 individuals had been included in the previously conducted mortality and incidence studies [6–7]. Of this group, 67 562 were classified as medical workers, including physicians, nurses, nuclear medicine technicians, radiation technologists, physicists and other workers occupationally exposed to medical sources of radiation. The linkages used to create the NDR cohort have previously been discussed in detail [6–7]. Mortality data were obtained via a record linkage to the Canadian Mortality Database for the years 1951 to 1987. Incidence data were obtained from the Canadian Cancer Database, which was derived from the National Cancer Incidence Reporting System, for the years 1969 to 1987.

Dosimetry

Dosimetry information was obtained from the National Dosimetry Services of the Radiation Protection Bureau of Health Canada. A description of the external dosimetry used among contributors to the NDR is provided by Ashmore et al. [6] and Sont et al. [7]. There is no regulatory requirement to report internal exposures to radionuclides other than tritium because their contribution to radiation dose is considered negligible [6–7]. However, for medical workers, there is a potential for substantial doses from exposure to ^{131}I [7], but information on doses from this exposure is unavailable. Individual doses, recorded over periods ranging from biweekly to annually, were combined to obtain annual

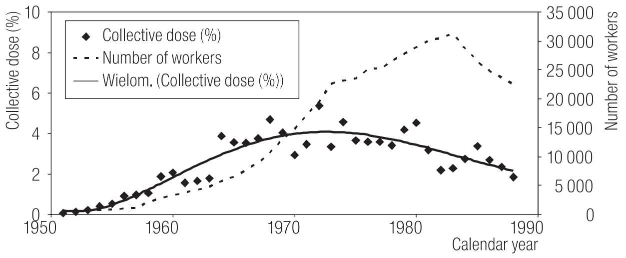

Fig. 1. Number of medical workers in the National Dose Registry cohort and their collective annual dose (as a percentage of total collective dose of 255.38 Sv) between 1951 and 1987.

doses for each member of the cohort. In the cases where the recorded dose was below the detection limit of the radiation dosimeter used (generally < 0.20 mSv), the value was recorded as zero [6–7]. The collective dose experienced by the cohort is the sum of all individual doses throughout the study period. Similarly, collective annual dose is the sum of all individual doses recorded in a given year (see Figure 1).

Statistical Methods

Individual information on radiation doses during the period from 1951 to 1987 was used to calculate excess relative risk for the Canadian medical workers. Mortality and cancer incidence of medical workers were compared to that in the general Canadian population, using standardized mortality ratios (SMRs) and standardized incidence ratios (SIRs). The data were categorized by age (5-year intervals), sex, calendar year (5-year intervals), time since first exposure (5-year intervals), and cumulative whole-body dose. All analyses were based on person-years at risk. The associated confidence intervals were calculated under the assumption that the deaths and incident cases of cancer follow a Poisson distribution [15].

RESULTS

The NDR cohort of Canadian medical workers included 67 562 subjects: 23 580 males and 43 982 females. During the follow-up period, this cohort experienced 1 309 incident cases of cancer (509 in males, 800 in females), and 1325 deaths (823 in males and 502 in females). The findings on mortality and cancer incidence are shown in Tables 1 and 2, respectively. Mortality from cancer and non-cancer causes was below expected, compared to the general Canadian population, except for the esophageal cancer in females that showed a little, non-statistically significant increase based on three observed cases (Table 1).

Thyroid cancer incidence was significantly elevated both in males and females, with a combined SIR of 1.74 (90% CI: 1.40–2.14). Also, a significantly high incidence of primary liver cancer was observed among females (SIR = 2.41; 90% CI: 1.05–4.75). All other cancer sites showed either no or slightly increased risk or a reduced incidence (Table 2).

The mean annual dose for medical workers in the NDR cohort peaked in the mid 1950's and then declined, reaching very low levels by the mid 1970's and remaining at those levels thereafter (Fig. 2). The annual average dose for the period of 1971–1987 for Canadian medical workers was 0.36 mSv or over 6-fold lower than the annual background radiation dose of 2.4 mSv [1], whereas the cumulative lifetime dose in the cohort is now 3.78 mSv.

Nuclear medicine technicians experienced the highest mean yearly dose of radiation over the follow-up period, as compared to other medical workers (Table 3). However, the mean yearly dose declined notably between the periods of 1951–1971 and 1971–1987, with current average annual doses lower than the background dose in all the job categories of medical workers listed in Table 3.

Using individual dose information, we noted that no significantly increased excess relative risk in relation to ionizing radiation exposure could be observed for leukemia, all solid cancers and for any of the cancer sites studied (data not shown).

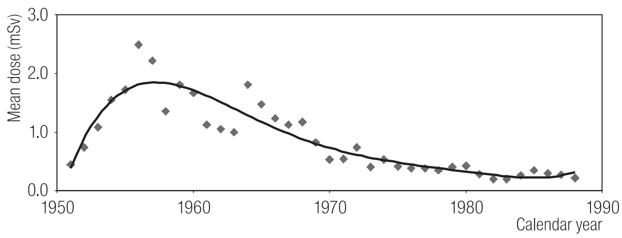

Fig. 2. Mean annual dose (mSv) for medical workers in the NDR cohort between 1951 and 1987.

Table 1. Standardized Mortality Ratio (SMR) for medical workers in the NDR cohort

Mortality	Male		Female		Total	
	N	SMR (90% CI)	N	SMR (90% CI)	N	SMR (90% CI)
Cancer						
Tongue & Mouth	4	0.76 (0.26–1.74)		–	4	0.59 (0.20–1.35)
Pharynx	5	0.82 (0.32–1.72)	1	0.62 (0.02–2.91)	6	0.78 (0.34–1.53)
Esophagus	4	0.42 (0.14–0.96)	3	1.40 (0.38–3.62)	7	0.60 (0.28–1.12)
Stomach	14	0.59 (0.36–0.93)	6	0.60 (0.26–1.19)	20	0.60 (0.40–0.87)
Colon	15	0.48 (0.29–0.74)	13	0.52 (0.31–0.83)	28	0.50 (0.35–0.68)
Rectum	4	0.31 (0.10–0.70)	4	0.60 (0.21–1.38)	8	0.41 (0.20–0.73)
Liver, primary	4	0.97 (0.33–2.21)	1	0.50 (0.02–2.37)	5	0.82 (0.32–1.71)
Gallbladder	5	1.71 (0.67–3.59)	1	0.33 (0.01–1.54)	6	1.00 (0.44–1.97)
Pancreas	15	0.71 (0.44–1.09)	6	0.55 (0.24–1.09)	21	0.44 (0.66–0.94)
Larynx	1	0.16 (0.01–0.76)		–	1	0.14 (0.01–0.67)
Lung	63	0.49 (0.39–0.60)	22	0.60 (0.53–0.68)	85	0.51 (0.42–0.61)
Melanoma	4	0.63 (0.21–1.43)		–	4	0.32 (0.11-0.73)
Breast	2	4.32 (0.75–13.6)	63	0.77 (0.62–0.95)	65	0.79 (0.64–0.97)
Ovary	0	–	20	0.99 (0.65–1.43)	20	0.99 (0.65–1.43)
Prostate	15	0.83 (0.51–1.28)		–	15	0.83 (0.51–1.28)
Bladder	3	0.37 (0.10–0.94)	1	0.50 (0.02–2.37)	4	0.39 (0.13–0.90)
Kidney	6	0.57 (0.25–1.13)	2	0.45 (0.08–1.41)	8	0.54 (0.27–0.97)
Brain, Nervous System	12	0.68 (0.39–1.11)	7	0.52 (0.25–0.98)	19	0.61 (0.40–0.90)
Thyroid	1	1.25 (0.05–5.93)		–	1	0.64 (0.03–3.03)
Non-Hodgkin's Lymphoma	11	0.79 (0.44–1.31)	4	0.43 (0.15–0.98)	15	0.65 (0.40–0.99)
Multiple Myeloma	5	0.93 (0.37–1.96)	1	0.31 (0.01–1.48)	6	0.70 (0.31–1.38)
Leukemia	11	0.66 (0.37–1.09)	6	0.43 (0.19–0.85)	17	0.56 (0.35–0.83)
Leukemia excluding CLL	9	0.69 (0.36–1.21)	6	0.50 (0.22–0.98)	15	0.60 (0.37–0.92)
Myeloid Leukemia	4	0.57 (0.19–1.29)	2	0.29 (0.05–0.90)	6	0.43 (0.19–0.84)
Acute Myeloid Leukemia	3	0.70 (0.19–1.80)	2	0.43 (0.07–1.35)	5	0.56 (0.22–1.17)
Other Cancers	2	0.16 (0.03–0.51)	12	0.38 (0.22–0.61)	14	0.32 (0.19–0.50)
All Cancers	213	0.54 (0.48–0.61)	185	0.57 (0.38–0.81)	398	0.57 (0.62–0.62)
Non-Cancer						
Infective & Parasitic	13	1.10 (0.65–1.74)	7	0.87 (0.41–1.62)	20	1.00 (0.66–1.46)
Endocrine & Metabolic	18	0.59 (0.38–0.87)	7	0.33 (0.16–0.63)	25	0.48 (0.34–0.68)
Circulatory	333	0.53 (0.49–0.58)	93	0.46 (0.38–0.54)	426	0.51 (0.47–0.56)
Respiratory	19	0.25 (0.16–0.36)	16	0.46 (0.29–0.70)	35	0.31 (0.23–0.41)
Genito-Urinary	5	0.36 (0.14–0.76)	6	0.59 (0.26–1.16)	11	0.46 (0.26–0.76)
Accidents	149	0.45 (0.39–0.52)	138	0.79 (0.68–0.91)	287	0.57 (0.51–0.63)
All Causes	823	0.50 (0.47–0.53)	502	0.58 (0.54–0.62)	1325	0.53 (0.51–0.55)

Table 2. Standardized Incidence Ratio (SIR) for medical workers in the NDR cohort

Cancer Incidence	Male		Female		Total	
	Cases	SIR (90% CI)	Cases	SIR (90% CI)	Cases	SIR (90% CI)
Tongue & Mouth	7	0.46 (0.22–0.86)	2	0.33 (0.06–1.04)	9	0.42 (0.22–0.74)
Pharynx	10	0.75 (0.41–1.27)	3	0.67 (0.18–1.74)	13	0.73 (0.43–1.16)
Esophagus	4	0.39 (0.13–0.89)	4	1.57 (0.53–3.58)	8	0.62 (0.31–1.12)
Stomach	25	0.76 (0.53–1.06)	12	0.86 (0.49–1.39)	37	0.79 (0.59–1.04)
Colon	50	0.76 (0.60–0.97)	47	0.84 (0.65–1.07)	97	0.80 (0.67–0.95)
Rectum	21	0.51 (0.34–0.73)	17	0.68 (0.43–1.02)	38	0.57 (0.43–0.75)
Liver, primary	4	0.51 (0.34–0.73)	6	2.41 (1.05–4.75)	10	1.24 (0.67–2.10)
Gallbladder	4	0.93 (0.32–2.14)	2	0.45 (0.08–1.41)	6	0.69 (0.30–1.36)
Pancreas	15	0.68 (0.42–1.04)	10	0.88 (0.48–1.49)	25	0.75 (0.52–1.04)
Larynx	3	0.15 (0.04–0.38)	3	0.84 (0.23–2.17)	6	0.25 (0.11–0.49)
Lung	86	0.51 (0.43–0.61)	39	0.71 (0.54–0.93)	125	0.56 (0.48–0.65)
Bone	2	0.55 (0.09–1.73)	2	0.49 (0.08–1.54)	4	0.52 (0.18–1.18)
Connective Tissue	2	0.26 (0.05–0.82)	7	0.84 (0.39–1.57)	9	0.56 (0.29–0.98)
Melanoma	27	1.13 (0.80–1.56)	42	0.97 (0.74–1.26)	69	1.03 (0.83–1.26)
Breast	2	1.19 (0.21–3.75)	283	0.99 (0.90–1.10)	285	1.00 (0.90–1.10)
Uterus including Cervix	0	–	104	0.78 (0.66–0.91)	104	0.78 (0.66–0.91)
Ovary	0	–	53	1.10 (0.87–1.39)	53	1.10 (0.87–1.39)
Prostate	61	0.79 (0.63–0.98)		–	61	0.79 (0.63–0.98)
Testis	15	0.87 (0.54–1.34)		–	15	0.87 (0.54–1.34)
Bladder	28	0.55 (0.39–0.76)	11	0.77 (0.43–1.28)	39	0.60 (0.45–0.78)
Kidney	21	0.86 (0.58–1.24)	12	0.95 (0.55–1.54)	33	0.89 (0.65–1.19)
Brain, Nervous System	22	0.95 (0.64–1.36)	10	0.47 (0.26–0.80)	32	0.72 (0.52–0.97)
Thyroid	14	2.10 (1.27–3.29)	51	1.66 (1.30–2.10)	65	1.74 (1.40–2.14)
Non-Hodgkin's Lymphoma	25	0.74 (0.51–1.03)	19	0.69 (0.45–1.01)	44	0.72 (0.55–0.92)
Hodgkin's Disease	16	1.15 (0.72–1.75)	15	0.88 (0.54–1.36)	31	1.00 (0.73–1.35)
Multiple Myeloma	5	0.57 (0.22–1.20)	1	0.19 (0.01–0.88)	6	0.42 (0.18–0.83)
Leukemia	15	0.59 (0.37–0.91)	9	0.44 (0.23–0.77)	24	0.53 (0.36–0.74)
Leukemia excluding CLL	10	0.61 (0.33–1.03)	9	0.55 (0.29–0.96)	19	0.58 (0.38–0.85)
Myeloid Leukemia	6	0.53 (0.23–1.05)	7	0.61 (0.29–1.14)	13	0.57 (0.34–0.91)
Acute Myloid Leukemia	4	0.62 (0.21–1.42)	4	0.56 (0.19–1.29)	8	0.59 (0.29–1.06)
Other Cancers	25	0.42 (0.29–0.58)	39	0.82 (0.61–1.07)	64	0.59 (0.48–0.73)
All Cancers except Lung Cancer	423	0.69 (0.64–0.75)	761	0.90 (0.85–0.96)	1184	0.81 (0.78–0.85)
All Cancers	509	0.66 (0.61–0.71)	800	0.89 (0.84–0.94)	1309	0.78 (0.75–0.82)

Table 3. Mean yearly dose for medical workers, by job category

Job category	Mean yearly dose (mSv)			
	Cancer incidence		Mortality	
	1951–1970	1971–1987	1951–1970	1971–1987
Nuclear medicine technician	10.37[a]	1.89[a]	10.40[a]	1.90[a]
Radiologist (therapeutic)	2.63	0.91	2.59	0.85
Radiologist (diagnostic)	1.70	0.54	1.66	0.54
Radiation therapist	1.92	1.07	1.90	1.08
X-ray technologist	1.13	0.32	1.13	0.32
Medical physicist	1.41	0.49	1.34	0.49
Gynecologist	1.32	0.35	1.11	0.36
Nurse	0.92	0.34	0.89	0.34
Physician	0.75	0.33	0.75	0.33
Ward aid/orderly	0.66	0.20	0.65	0.20
Veterinarian	0.51	0.16	0.51	0.16
Laboratory technician	0.38	0.18	0.38	0.18
Other medical workers	1.30	0.30	1.29	0.30
Not available	0.61	0.28	0.62	0.28
Total	1.14	0.36	1.13	0.36

[a] When 12 workers with the yearly dose over 10 mSv/yr had been excluded, the mean yearly doses for nuclear medicine technicians were 2.95; 1.82 (incidence) and 2.96; 1.83 (mortality).

DISCUSSION

The carcinogenic effects of ionizing radiation on humans have been well established [1–2]. However, current estimates of the risk associated with very low levels of exposure are subject to some uncertainty. In the NDR cohort, a significantly increased risk of thyroid cancer was observed. The radiosensitivity of the thyroid to ionizing radiation is well recognized [2,16]. Thyroid cancer has been related to high doses of ionizing radiation both in children irradiated for diseases of the head and neck [17] and in atomic bomb survivors [4], and it has also been reported among medical workers [7,18–20]. It seems unlikely that the increase in the thyroid cancer incidence in the Canadian medical workers is related to external radiation exposure, since no similar increase was observed in other occupational groups included in the NDR and exposed to higher external doses [7]. Medical workers can be exposed to ^{131}I used in medical procedures [7]. Since no information on the doses from exposure to ^{131}I is available, the dose-response analysis could not be conducted. It should be noted that there is no convincing evidence of association between internal radiation exposure to ^{131}I and thyroid cancer among individuals exposed as adults [2,16]. In our study, the observed increase in thyroid cancer incidence in the cohort over that in the general population may, at least partly, be explained by an easier access to medical care and, consequently, earlier detection of this malignancy among medical workers. Other risk factors may be responsible for this increase as well.

Recent studies have suggested an increase in the risk of breast cancer in female medical workers [10,19,21]. This observation was not confirmed in our study; in fact the SIR and SMR for female breast cancer were decreased in comparison with the general Canadian population. The lack of an association between breast cancer and radiation exposure in the present study may be the result of the low level of radiation exposure among Canadian medical workers. The increase in SIR of primary liver cancer among female members of the NDR cohort observed in this study has not been reported previously and may be a chance finding.

The majority of studies on medical workers are lacking detailed dosimetry information at the individual level. Because the NDR contains this information, it was possible to estimate cancer risk associated with lifetime dose. Although a non-significant increase in excess relative risk was observed for several types of cancer, based on internal comparisons within the cohort of individuals exposed to different doses, these effects were not apparent when external comparisons based on SMRs or SIRs were applied.

Even though the use of radiation-emitting devices has greatly increased over the last 20 years [1], the doses currently received by medical workers are substantially lower than those received 50 years ago [5]. Besides, the mean yearly dose has also declined within each job category in the last two decades of the follow-up period of 1951–1987. The time period in which the dose was received is important in the development of cancer, as many more cancers occurred in workers exposed to ionizing radiation before 1950 [5,8,21,22]. The risk appears to have declined with the reduction in cumulative dose since the 1950's. This trend demonstrates the effectiveness of the measures which have been implemented to reduce and prevent radiation exposure in occupational settings [1].

Several factors limit the findings of this study. Firstly, and most importantly, there is very scarce information on other known cancer risk factors in the NDR, which precludes an opportunity to examine the joint effects of radiation and risk factors for occupational cancer. There are also several limitations relating to radiation exposure assessment among medical workers. The recording of low doses of radiation (< 0.20 mSv) will underestimate exposure. However, a recent study revealed that the significance of the ERR would not be affected [23]. The placement of the dosimeter can affect the dose reading, particularly when the dosimeter is worn underneath a lead apron. While this provides a more accurate estimate of the whole- body dose, the dosimeter will underestimate the dose to portions of the body not protected by the apron. Although there are currently no regulations mandating where a dosimeter is to be placed, Health Canada does recommend that the dosimeter of an x-ray worker be worn at the chest height and under the lead apron [24]. Since it is not possible to determine the level of compliance with these recommendations, an assessment of the effect of dosimeter placement on the recorded dose is currently not feasible.

Although medical workers are at an increased risk for some cancers, occupational exposures have been declining over the last 50 years. Continued adherence to occupational exposure guidelines [25] is recommended in order to protect medical workers from the adverse health effects of ionizing radiation.

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