Cancer Epidemiology 49 (2017) 8–18

Contents lists available at ScienceDirect

Cancer Epidemiology

The International Journal of Cancer Epidemiology, Detection, and Prevention

journal homepage: www.cancerepidemiology.net

Cancer incidence in the Western Australian mining industry (1996–2013)

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ARTICLE INFO

Article history:
Received 15 November 2016
Received in revised form 30 March 2017
Accepted 4 May 2017
Available online 18 May 2017

Keywords:
Cancer incidence
Miners
Occupational cohort
Smoking
Underground mining

ABSTRACT

Background: Miners are frequently exposed to established and potential carcinogens. We aimed to assess cancer incidence in miners relative to the general population and identify high-risk subgroups.
Methods: Incident cancers in Western Australian miners (n = 153,922; 86% male) during 1996–2013 were identified. Indirectly standardised incidence ratios (SIRs) were calculated and mixed-effects Poisson models were used to calculate Incidence Rate Ratios (IRRs) to identify high-risk within-cohort subgroups.
Results: Compared with the general population, the overall cancer incidence in miners (n = 4194 cases) was lower for both females (SIR:0.83, 95%CI:0.74–0.92) and males (SIR:0.96, 95%CI:0.93–0.99). Overall, cancer incidence did not differ by employment duration or employment commencement time. Ever-underground work was associated with lung cancer (IRR:1.81, 95%CI:1.11–2.93). Relative to multi-ore miners, IRRs for specific cancers were significantly different when exclusively mining: iron (prostate:0.73, 95%CI:0.56–0.94); gold (lung:1.77, 95%CI:1.04–3.01 and colorectum:1.70, 95%CI:1.16–2.51); and other metals (urinary tract:1.85, 95%CI:1.03–3.31 and leukaemia:0.36, 95%CI:0.14–0.96).
Conclusion: Working underground emerged as a significant determinant of lung cancer risk in our contemporary mining cohort. Increased risks of lung, prostate, colorectal and urinary tract cancers and leukaemia were identified in miners of specific ores. These findings underline the importance of continued surveillance of the health and exposures of this relatively young cohort of miners.

1. Introduction

Miners have frequently been identified as having higher lung cancer risk than the general population [1,2]. A recent pooled analysis of case-control studies of lung cancer identified a 55% greater smoking-adjusted risk in male miners [1]. Apart from smoking [3], this association can be attributed to several established and potential carcinogenic exposures including respirable crystalline silica, asbestos, nickel, chromium, arsenic [4], ionising radiation [5] and diesel engine exhaust [6]. However, miners' risks of non-lung cancers, such as prostate, colon, bladder, thyroid, leukaemia and others have been studied less frequently [2,7–11].

Most studies have focussed on specific ore-types to investigate putative causal associations between specific mining exposures and cancers (e.g. radon and non-lung solid cancers in uranium miners [8]; and diesel exhaust and lung cancer in non-metal miners [2]). However, heterogeneity in case definitions exists, using both incidence and mortality for estimating cancer risks. Mortality data is susceptible to competing causes and less reliable diagnoses than incidence data, particularly for cancers with low case fatality rates (e.g. prostate) while this is less of an issue for highly fatal cancers (e.g. lung) [7,12]. Moreover, there is limited information on female miners' cancer risks despite their increasing numbers [13].

This study used an actively employed industry-wide mining cohort, including 14% females, living in Western Australia (WA) during 1996–2013.Over 40% of Australian miners work in more than 1000 WA mines, with nearly 60,000 miners employed in 2013–2014 [14]. WA miners work in metal-ore mining, industrial

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http://dx.doi.org/10.1016/j.canep.2017.05.001
1877-7821/

mineral and coal mining, mine exploration and oil and gas extraction, plus many mining support services. Miners thus face heterogeneous exposures dependent on their jobs, ore-types, work locations, equipment handled and lifestyle choices. For example, underground miners experience higher exposures than surface workers to various carcinogens such as diesel exhaust [15,16], arsenic, respirable crystalline silica, nickel, asbestos, chromium, polycyclic aromatic hydrocarbons [4] and radon [5]. Moreover, considerable heterogeneity remains even among miners of a specific ore-type that may, for example, be influenced by the mineral abundance at a particular geographical location. For instance, iron ore miners operating in the Northern regions of WA (e.g. Hamersley province) have a higher probability of exposure to asbestiform minerals than those mining elsewhere [17].

We aimed to: i. compare the overall and site-specific cancer incidence in miners relative to the general WA population; and ii. identify miner sub-groups at increased risk of individual cancers through within cohort comparisons.

2. Methods

2.1. Data sources and variables

The WA Department of Mines and Petroleum conducted 5-yearly health assessments on its mining employees from January 1996 until January 2013. Employees considered to have negligible occupational exposure to hazardous substances, including office, residential or recreational facility workers, contractors employed occasionally for under 1-month periods and/or cumulatively for less than 3-months annually, were not assessed [18]. Data collected included demographic details, work histories, respiratory symptoms and smoking histories, and spirometry and audiometry tests. The dataset was probabilistically linked through the WA Data Linkage System [19] to: (i) the WA Cancer Registry (1996–2013) for information on all incident malignant lesions except non-melanocytic skin cancer; (ii) the WA Death Register (1996–2013) for State-wide deaths; and (iii) the WA Electoral Roll (1988–2013) to identify WA residents and out-of-State migrations.

Work histories identified specific ores mined, classified as iron, gold, other metals (including nickel, alumina and base metals such as copper, zinc and lead) and non-metals (including industrial minerals); and 'ever-underground' work through any underground production or service job titles. In the absence of employment termination dates, miners were assumed to have been employed for 2.5 years (half of the 5-year re-assessment period) subsequent to their last health assessment, unless this date was truncated by emigration, cancer diagnosis, death or termination of study follow-up. Four employment duration categories were thus created: $\leq$2.5 years, 2.6–5 years, 5.1–10 years and >10 years.

Socio-economic disadvantage is strongly associated with cancer and occupation [20] and thus a potential confounder. Area-level social disadvantage was adjusted through the Index of Relative Socioeconomic Disadvantage, a summary measure of disadvantage in terms of accessibility to education, employment and income [21]. Residential postcodes at first health assessment were used to create quintiles, ranging from most disadvantaged to least disadvantaged, based on the closest national census year (1996, 2001, 2006 or 2011).

2.2. Study population

During 1996–2013, 243,539 WA miners underwent at least one health assessment. Nearly 47% of WA miners are estimated to be drive-in drive-out or fly-in fly-out workers [22], some possibly living in other States or neighbouring countries. WA-based registries may, therefore, not capture their complete health information. Preliminary analyses identified a nearly 3-fold greater cancer incidence in miners listed on the WA Electoral Roll than those not, confirming the likely under-ascertainment of cases for the latter. Therefore, we restricted our cohort to miners registered on the WA Electoral Roll which includes only Australian citizens. We further excluded 3520 people with non-WA residential postcodes on their health assessments, as they had likely moved out of the State. After excluding 89,617 (36.8%) people, the selected cohort included 153,922 miners. Miners were classified as pre-inception and inception if they had commenced work in WA mines before or after the cohort recruitment date of 1st January 1996, respectively.

2.3. Case ascertainment and follow-up time

Cancers were classified as per the topography codes of the 3rd edition of the International Classification of Diseases for Oncology [23]. Morphology codes identified mesothelioma, lymphoma and leukaemia [23]. Miners' person-years accumulated from their first health assessment date until the date of specific cancer diagnosis, emigration, death or follow-up end on 31st December 2013, whichever came first. General population person-years for 1996–2013 were obtained from the estimated annual age- and sex-specific WA population [24].

2.4. Statistical analysis

Person-years were stratified by sex, 5-year age-groups and 5-calendar-year-groups. Indirectly Standardised Incidence Ratios (SIRs) were estimated as the ratio of observed cases in miners to the expected numbers based on the whole WA population age, sex and calendar period specific rates for individual cancers.

Mixed-effects Poisson regression models were used to evaluate employment commencement time (pre-inception vs. inception) and trend with increasing employment duration categories defined above (coded 1–4) as predictors of cancer incidence within the cohort after adjusting for age, sex, socio-economic disadvantage, ever-smoker status (classified as ever-smoker if smoked one or more cigarettes per day for at least one year [25]) and calendar-year; all included as fixed effects enabling calculation of Incidence Rate Ratios (IRRs). Miners' ID was included as a random effect. Further analyses evaluating cancer risks for specific ore-types (gold, iron, other metals and non-metals) and ever-underground work were restricted to the cohort subset with complete ore-type information (n = 84,291, 55% of cohort); multi-ore and never-underground miners being the respective reference groups. All statistical analyses were performed using SAS version 9.4 [26].

3. Results

The WA mining cohort (n = 153,922) was predominantly male (85.7%) with 80% aged between 15 and 44 years at their first health assessment (Table 1). Over half of the miners had ever smoked (54.2%) and over one-third lived in socio-economically disadvantaged areas (35%). The cohort largely comprised of inception miners (87.5%), 46% with employment durations under 2.5 years and 24% between 2.6-5 years until censored (data not presented). Conversely, pre-inception miners (12.5%) had a median work duration of 19.5 years, with 86% employed for more than 10 years and none under 2.5 years (data not presented). Ore-type information was complete for 55% of miners (n = 84,291) with a similar demographic profile as the full cohort. One-sixth of this sub-cohort (17.5%) had mined multiple ore-types and 27.2%, 19.4%, 26.7% and 9.3% had exclusively mined iron, gold, other metals and

Table 1
Demographic characteristics of the WA mining cohort (1996–2013).

Characteristic	Full cohort		Sub-cohort	
	N	%	n	%
Total miners	1,53,922	100	84,291	100.0
Sex				
Females	21,945	14.3	13,917	16.5
Males	1,31,977	85.7	70,374	83.5
Smoking status				
Ever-smoker	83,409	54.2	45,089	53.5
Never-smoker	70,489	45.8	39,186	46.5
Unknown	24	0.0	16	0.0
Socio-economic disadvantage (SEIFA quintiles)				
Most disadvantage	24,253	15.8	14,364	17.0
More disadvantage	29,193	19.0	15,383	18.3
Average disadvantage	33,288	21.6	19,042	22.6
Less disadvantage	34,214	22.2	17,964	21.3
Least disadvantage	29,241	19.0	15,555	18.5
Missing	3733	2.4	1983	2.4
Year of employment commencement in WA mines				
1938–1995 (Pre-inception cohort)	19,227	12.5	10,836	12.9
1996–2013 (Inception cohort)	1,34,695	87.5	73,455	87.1
Year of first health assessment				
1996–1999	40,879	26.6	25,898	30.7
2000–2004	30,750	20.0	15,231	18.1
2005–2009	46,126	30.0	25,230	29.9
2010–2013	36,167	23.5	17,932	21.3
Age at first health assessment				
15–24 years	38,051	24.7	19,737	23.4
25–34 years	50,175	32.6	27,468	32.6
35–44 years	35,268	22.9	20,000	23.7
45–54 years	22,997	14.9	12,972	15.4
55–64 years	7060	4.6	3915	4.6
65–80 years	371	0.2	199	0.2
Mean age (Standard deviation)	34.4 (11.1)	–	34.7 (11.1)	–
Median age (Inter quartile range)	32.4 (25.1–42.4)	–	32.9 (25.4–42.7)	–
Estimated employment duration in WA mines				
≤2.5 years	62,203	40.4	32,902	39.0
2.6–5 years	32,873	21.4	19,986	23.7
5.1–10 years	25,853	16.8	13,745	16.3
>10 years	32,993	21.4	17,658	21.0
Mean duration (Standard deviation)	6.6 (6.9)	–	6.6 (6.8)	–
Median duration (Inter quartile range)	2.8 (2.5–8.6)	–	2.8 (2.5–8.5)	–
Ore type				
Incomplete information	69,631	45.2	–	–
Multiple ores	14,707	9.6	14,707	17.5
Iron only	22,901	14.9	22,901	27.2
Gold only	16,311	10.6	16,311	19.4
Other metals only	22,500	14.6	22,500	26.7
Non-metals only	7872	5.1	7872	9.3
Work location				
Incomplete ore type information	69,631	45.2	–	–
Ever-underground	5475	3.6	5475	6.5
Never-underground	78,816	51.2	78,816	93.5

Table 2
Standardised Incidence Ratios (SIRs) of various malignancies in miners by sex, adjusted for age and calendar-year (1996–2013).

Cancer site/morphology	ICD-O-3 code	Males (n = 131,977)			Females (n = 21,945)		
		O	E	SIR (95% CI)	O	E	SIR (95% CI)
All cancers	C000-C809	3876	4034.4	0.96 (0.93, 0.99)	318	385.1	0.83 (0.74, 0.92)
Lip, oral cavity & pharynx	C000-C149	246	250.6	0.98 (0.86, 1.10)	7	8.2	0.85 (0.22, 1.48)
Lip	C000-C009	121	94.6	1.28 (1.05, 1.51)	<5	2.8	0.73 (0.00, 1.73)
Gum & mouth	C030-C069	23	31.7	0.73 (0.43, 1.02)	<5	1.1	1.84 (0.00, 4.38)
Tongue	C010-C029	33	41.4	0.80 (0.53, 1.07)	<5	1.6	0.61 (0.00, 1.81)
Pharynx	C090-C149	58	70.5	0.82 (0.61, 1.03)	0	2.5	–
Digestive organs	C150-C269	714	770.4	0.93 (0.86, 0.99)	35	41.6	0.84 (0.56, 1.12)
Oesophagus	C150-C159	56	63.4	0.88 (0.65, 1.11)	<5	1.0	0.96 (0.00, 2.84)
Stomach	C160-C169	69	72.6	0.95 (0.73, 1.17)	<5	3.1	1.28 (0.03, 2.53)
Small intestine	C170-C179	29	22.8	1.27 (0.81, 1.74)	<5	1.2	0.84 (0.00, 2.49)
Colon & rectum	C180-C209	444	460.7	0.96 (0.87, 1.05)	23	29.7	0.77 (0.46, 1.09)
Liver	C220-C229	41	59.5	0.69 (0.48, 0.90)	<5	1.8	0.55 (0.00, 1.62)
Gall bladder	C230-C249	22	20.3	1.08 (0.63, 1.54)	0	1.2	–
Pancreas	C250-C259	60	74.0	0.81 (0.61, 1.02)	<5	3.6	0.83 (0.00, 1.77)
Respiratory & intrathoracic organs	C300-C399	360	326.2	1.10 (0.99, 1.22)	19	15.9	1.19 (0.66, 1.73)
Larynx	C320-C329	46	31.9	1.44 (1.03, 1.86)	0	0.3	–
Lung	C330-C349	255	279.7	0.91 (0.80, 1.02)	17	14.8	1.15 (0.60, 1.70)
Bone & articular cartilage	C400-C419	21	11.1	1.89 (1.08, 2.69)	<5	1.1	1.85 (0.00, 4.42)
Melanoma	C440-C449	786	600.3	1.31 (1.22, 1.40)	65	54.1	1.20 (0.91, 1.49)
Connective & soft tissue	C490-C499	30	26.2	1.15 (0.74, 1.56)	<5	2.6	0.78 (0.00, 1.86)
Breast	C500-C509	6	6.3	0.96 (0.19, 1.73)	110	142.3	0.77 (0.63, 0.92)
Female genitalia	C510-C589	–	–	–	28	42.7	0.66 (0.41, 0.90)
Male genitalia	C600-C639	1228	1242.6	0.99 (0.93, 1.04)	–	–	–
Prostate	C619	1112	1113.0	1.00 (0.94, 1.06)	–	–	–
Testis	C620-C629	111	123.1	0.90 (0.73, 1.07)	–	–	–
Urinary tract	C640-C689	196	222.1	0.88 (0.76, 1.01)	5	8.3	0.60 (0.07, 1.13)
Kidney	C649	132	146.4	0.90 (0.75, 1.06)	<5	6.6	0.30 (0.00, 0.72)
Bladder	C670-C679	55	64.1	0.86 (0.63, 1.08)	<5	1.3	1.58 (0.00, 3.77)
Central nervous system	C700-C729	88	97.0	0.91 (0.72, 1.10)	6	6.9	0.87 (0.17, 1.56)
Brain	C710-C719	68	81.7	0.83 (0.63, 1.03)	6	5.9	1.01 (0.20, 1.82)
Endocrine glands	C730-C759	78	72.6	1.07 (0.84, 1.31)	22	28.4	0.78 (0.45, 1.10)
Thyroid	C739	71	67.5	1.05 (0.81, 1.30)	21	28.0	0.75 (0.43, 1.07)
Mesothelioma	M905	45	36.7	1.23 (0.87, 1.58)	0	0.6	–
Lymphoma	M959-M972	187	213.8	0.87 (0.75, 1.00)	23	16.6	1.39 (0.82, 1.96)
Leukaemia	M980-M994	83	106.3	0.78 (0.61, 0.95)	<5	7.6	0.39 (0.00, 0.84)

O: Observed cases; E: Expected cases; CI: Confidence Interval.

non-metals, respectively. Additionally, 6.5% of this sub-cohort had ever worked underground.

3.1. General population comparisons

Female miners had 17% lower incidence of all cancers collectively (95% Confidence Interval (CI):0.74–0.92) relative to WA females, particularly breast and genital cancers (Table 2). Male miners had 4% lower incidence of all cancers collectively (95% CI:0.93–0.99) compared with WA males, especially leukaemia, digestive organ cancers and lung cancer (Table 2). However, male miners were more likely to have cancers of bone and cartilage, larynx and lip and melanoma than WA males.

3.2. Within cohort comparisons

Overall, cancer incidence did not differ significantly either by employment duration or employment commencement time, but there were some exceptions. Pre-inception miners had higher rates of mesothelioma (IRR:3.21, 95%CI:1.19–8.67), brain (IRR:2.54, 95% CI:1.16–5.58), larynx (IRR:2.31, 95%IC:1.00–5.33) and lung (IRR:1.56, 95%CI:1.07–2.27) cancer but lower rates of prostate (IRR:0.76, 95%CI:0.63–0.92) and urinary tract (IRR:0.65, 95% CI:0.41–1.02) cancer than inception miners (Table 3). An increasing trend with increasing employment duration categories was identified for breast (IRR:1.10, 95%CI:1.01–1.18) and prostate (IRR:1.05, 95%CI:1.03–1.07) cancer (Table 3). However, lung (IRR:0.95, 95%CI:0.91–1.00) and brain (IRR:0.86, 95%CI:0.78–0.96) cancer showed an inverse relationship with employment duration (Table 3). Estimates for employment duration and commencement time variables remained consistent in the sub-cohort analyses on miners with complete ore-type information (results not presented).

There were no significant differences for all cancers collectively between multi-ore miners and all single-ore miners combined (IRR:0.99, 95%CI:0.89–1.10) (results not presented). Compared with multi-ore miners, higher cancer rates were found in exclusive miners of: (i) gold for lung (IRR:1.77, 95%CI:1.04–3.01) and colorectal (IRR:1.70, 95%CI:1.16–2.51) cancer; and (ii) other metals for urinary tract cancer (IRR:1.85, 95%CI:1.03–3.31) (Table 4). Conversely, lower rates than multi-ore miners were observed for exclusive miners of (i) iron for prostate cancer (IRR:0.73, 95% CI:0.56–0.94); and (ii) other metals for leukaemia (IRR:0.36, 95%CI: 0.14–0.96) (Table 4). Lastly, ever-underground mining emerged as a significant determinant of lung cancer (IRR:1.81, 95%CI:1.11–2.93), but no other cancer (Table 4).

Similar patterns were observed for many cancers on comparing these ore-type subsets of miners with the general population (Appendix A). For example, compared with the general population, exclusive gold miners had higher rates of colorectal and lung cancer. Similarly, lower than expected rates were found for prostate cancer in iron ore miners and leukaemia in other metal miners.

4. Discussion

WA miners had lower incidence of all cancers collectively and most individual cancers than the age-matched general population

Table 3
Cancer Incidence Rate Ratios (IRRs) in WA miners with respect to employment commencement and duration (1996–2013)[a].

Cancer site/morphology	ALL N	Trend for increasing employment duration groups[b] IRR (95% CI)	Pre-inception n	Inception n	Pre-inception vs. inception cohort IRR (95% CI)
All cancers	4085	1.00 (0.99, 1.01)	989	3096	0.96 (0.86, 1.06)
Lip, oral cavity & pharynx	246	1.00 (0.95, 1.05)	54	192	0.77 (0.51, 1.18)
Lip	121	1.02 (0.96, 1.10)	30	91	0.81 (0.46, 1.45)
Gum & mouth	24	1.04 (0.89, 1.23)	7	17	0.83 (0.25, 2.74)
Tongue	32	1.03 (0.90, 1.17)	5	27	0.43 (0.12, 1.52)
Pharynx	56	0.91 (0.83, 1.01)	11	45	1.25 (0.50, 3.10)
Digestive organs	728	0.99 (0.96, 1.02)	204	524	1.19 (0.94, 1.49)
Oesophagus	54	0.97 (0.87, 1.08)	14	40	1.14 (0.47, 2.74)
Stomach	71	1.02 (0.94, 1.11)	18	53	0.87 (0.44, 1.73)
Small intestine	30	0.92 (0.83, 1.01)	7	23	1.56 (0.61, 3.98)
Colon & rectum	458	0.98 (0.94, 1.02)	129	329	1.26 (0.93, 1.70)
Liver	41	1.05 (0.94, 1.16)	13	28	0.98 (0.39, 2.47)
Gall bladder	22	0.98 (0.86, 1.12)	7	15	1.58 (0.59, 4.29)
Pancreas	58	1.03 (0.94, 1.12)	17	41	0.99 (0.46, 2.11)
Respiratory & intrathoracic organs	374	0.95 (0.91, 0.98)	128	246	1.90 (1.38, 2.60)
Larynx	46	0.95 (0.85, 1.07)	19	27	2.31 (1.00, 5.33)
Lung	269	0.95 (0.91, 1.00)	82	187	1.56 (1.07, 2.27)
Bone & articular cartilage	21	0.94 (0.84, 1.06)	6	15	2.11 (0.78, 5.74)
Melanoma	832	0.99 (0.96, 1.02)	179	653	0.91 (0.72, 1.16)
Connective & soft tissue	31	1.03 (0.92, 1.16)	7	24	0.92 (0.36, 2.35)
Breast	114	1.10 (1.01, 1.18)	13	101	0.61 (0.29, 1.29)
Female genitalia	28	0.85 (0.74, 0.98)	<5	25	1.25 (0.37, 4.23)
Male genitalia	1191	1.05 (1.03, 1.08)	297	894	0.74 (0.61, 0.88)
Prostate	1078	1.05 (1.03, 1.07)	272	806	0.76 (0.63, 0.92)
Testis	108	1.03 (0.95, 1.11)	23	85	1.25 (0.66, 2.37)
Urinary tract	193	1.01 (0.96, 1.07)	38	155	0.65 (0.41, 1.02)
Kidney	127	1.00 (0.94, 1.07)	25	102	0.72 (0.42, 1.25)
Bladder	56	1.04 (0.95, 1.15)	10	46	0.46 (0.18, 1.14)
Central nervous system	92	0.92 (0.84, 1.00)	23	69	1.90 (0.93, 3.87)
Brain	72	0.86 (0.78, 0.96)	17	55	2.54 (1.16, 5.58)
Endocrine glands	93	1.00 (0.92, 1.09)	19	74	1.17 (0.56, 2.43)
Thyroid	85	1.01 (0.92, 1.10)	16	69	1.04 (0.48, 2.26)
Mesothelioma	44	0.94 (0.82, 1.07)	20	24	3.21 (1.19, 8.67)
Lymphoma	206	0.95 (0.90, 1.01)	46	160	1.31 (0.83, 2.06)
Leukaemia	82	1.03 (0.95, 1.12)	19	63	0.75 (0.38, 1.46)

CI: Confidence Interval.
[a]: All models adjusted for employment duration, employment commencement year, ever-smoker status, socio-economic disadvantage, calendar-year, sex and age.
[a]:These models include 150,165 miners after excluding those with missing socio-economic quintile (n = 3733) or smoking status (n = 29).
[b] Trend test for increasing employment duration categories namely: ≦2.5, 2.6–5, 5.1–10 and >10 years.

Table 4
Cancer Incidence Rate Ratios (IRRs) in major ore-types and work locations in WA miner subgroups (1996–2013)[a].

Cancer site/ morphology	Ever-under ground	Never-under ground	Ever- vs. never-underground	Multiple ores (Reference group)	Iron only	Iron only vs. multiple ores	Gold only	Gold only vs. multiple ores	Other metals only	Other metals only vs. multiple ores	Non-metals only	Non-metals only vs. multiple ores
	n	n	IRR (95% CI)	n	n	IRR (95% CI)	n	IRR (95% CI)	n	IRR (95% CI)	n	IRR (95% CI)
All cancers	178	2352	1.05 (0.90, 1.23)	437	529	0.96 (0.85, 1.10)	465	1.07 (0.94, 1.23)	771	0.98 (0.86, 1.10)	328	1.07 (0.92, 1.24)
Lip, oral cavity & pharynx	13	136	1.10 (0.61, 2.00)	33	23	0.64 (0.37, 1.10)	26	0.92 (0.54, 1.56)	45	0.94 (0.59, 1.50)	22	1.21 (0.70, 2.09)
Lip	8	64	1.27 (0.58, 2.80)	20	11	0.57 (0.27, 1.18)	13	0.79 (0.39, 1.62)	18	0.69 (0.37, 1.31)	10	1.01 (0.47, 2.15)
Gum & mouth	<5	12	1.38 (0.32, 5.93)	<5	<5	0.43 (0.04, 4.82)	<5	2.12 (0.42, 10.8)	6	2.41 (0.45, 13.0)	<5	0.91 (0.08, 10.7)
Tongue	0	20	–	<5	<5	2.91 (0.28, 30.8)	<5	3.89 (0.37, 41.0)	6	3.91 (0.50, 30.3)	7	12.4 (1.54, 99.0)
Pharynx	<5	34	1.24 (0.35, 4.34)	8	6	0.53 (0.18, 1.56)	7	0.79 (0.28, 2.24)	12	0.87 (0.32, 2.31)	<5	0.73 (0.21, 2.51)
Digestive organs	28	434	0.81 (0.55, 1.20)	77	98	0.96 (0.71, 1.31)	96	1.25 (0.92, 1.71)	135	0.91 (0.68, 1.21)	56	0.94 (0.66, 1.33)
Oesophagus	0	33	–	6	<5	0.47 (0.13, 1.75)	<5	0.62 (0.16, 2.38)	13	1.12 (0.37, 3.40)	6	1.22 (0.36, 4.06)
Stomach	5	39	1.98 (0.74, 5.31)	9	11	1.17 (0.49, 2.81)	<5	0.48 (0.14, 1.65)	14	0.97 (0.40, 2.34)	6	1.04 (0.36, 3.00)
Colon & rectum	17	287	0.72 (0.43, 1.18)	44	60	1.01 (0.68, 1.51)	76	1.70 (1.16, 2.51)	89	1.00 (0.69, 1.46)	35	0.99 (0.63, 1.56)
Gall bladder	<5	12	1.16 (0.18, 7.51)	<5	<5	1.01 (0.15, 6.93)	<5	1.17 (0.19, 7.25)	<5	0.45 (0.05, 3.93)	<5	1.50 (0.21, 10.7)
Pancreas	<5	31	1.36 (0.42, 4.45)	7	9	1.14 (0.43, 3.08)	<5	0.61 (0.18, 2.09)	9	0.73 (0.27, 1.99)	5	1.00 (0.33, 3.08)
Respiratory & intrathoracic organs	29	207	1.80 (1.19, 2.71)	30	57	1.48 (0.94, 2.32)	57	1.65 (1.05, 2.59)	61	1.06 (0.68, 1.66)	31	1.29 (0.78, 2.14)
Larynx	<5	26	1.26 (0.36, 4.37)	7	6	0.67 (0.22, 2.07)	6	0.85 (0.26, 2.75)	7	0.61 (0.21, 1.77)	<5	0.62 (0.16, 2.42)
Lung	21	149	1.81 (1.11, 2.93)	21	41	1.52 (0.89, 2.59)	43	1.77 (1.04, 3.01)	42	0.99 (0.58, 1.70)	23	1.31 (0.72, 2.38)
Melanoma	39	482	1.09 (0.78, 1.53)	95	111	0.99 (0.75, 1.31)	110	1.19 (0.90, 1.58)	140	0.85 (0.65, 1.12)	65	1.06 (0.77, 1.45)
Breast	<5	74	0.59 (0.08, 4.33)	12	21	1.18 (0.56, 2.48)	16	0.90 (0.42, 1.94)	12	0.66 (0.29, 1.50)	14	1.71 (0.78, 3.72)
Male genitalia	54	699	1.12 (0.84, 1.49)	134	133	0.76 (0.59, 0.97)	116	0.86 (0.67, 1.11)	258	0.96 (0.77, 1.19)	112	1.07 (0.82, 1.38)
Prostate	52	643	1.19 (0.89, 1.60)	119	118	0.73 (0.56, 0.94)	107	0.89 (0.68, 1.16)	243	0.99 (0.79, 1.24)	108	1.09 (0.84, 1.43)
Testis	<5	54	0.21 (0.03, 1.57)	14	15	0.98 (0.46, 2.12)	8	0.55 (0.22, 1.34)	14	0.81 (0.39, 1.71)	<5	0.64 (0.21, 1.95)
Urinary tract	7	115	0.98 (0.45, 2.14)	14	25	1.50 (0.78, 2.91)	17	1.37 (0.67, 2.82)	50	1.85 (1.03, 3.31)	16	1.60 (0.78, 3.26)
Kidney	7	68	1.59 (0.72, 3.53)	12	17	1.40 (0.65, 2.99)	10	1.01 (0.42, 2.39)	29	1.40 (0.72, 2.74)	7	0.89 (0.36, 2.25)
Bladder	0	38	–	<5	7	2.46 (0.51, 11.9)	6	2.91 (0.59, 14.4)	15	2.97 (0.70, 12.6)	8	4.41 (0.94, 20.6)
Central nervous system	<5	43	0.39 (0.05, 2.71)	5	9	1.23 (0.40, 3.75)	<5	0.70 (0.19, 2.61)	18	2.03 (0.75, 5.49)	8	2.21 (0.71, 6.81)
Brain	<5	36	0.41 (0.06, 2.87)	5	5	0.76 (0.22, 2.66)	<5	0.67 (0.18, 2.48)	17	1.92 (0.70, 5.24)	6	1.60 (0.49, 5.28)
Endocrine glands	5	56	1.25 (0.48, 3.30)	12	12	0.87 (0.39, 1.95)	12	0.92 (0.41, 2.04)	19	1.12 (0.54, 2.30)	6	0.94 (0.35, 2.52)
Thyroid	5	50	1.50 (0.57, 3.97)	9	11	1.07 (0.44, 2.60)	11	1.11 (0.46, 2.68)	19	1.49 (0.68, 3.29)	5	1.05 (0.35, 3.16)
Mesothelioma	<5	25	2.15 (0.72, 6.39)	<5	7	1.70 (0.45, 6.49)	8	1.90 (0.54, 6.72)	7	1.05 (0.32, 3.45)	<5	1.39 (0.35, 5.54)
Lymphoma	<5	107	0.56 (0.20, 1.55)	18	25	0.97 (0.52, 1.80)	16	0.75 (0.38, 1.50)	36	1.20 (0.66, 2.18)	16	1.30 (0.63, 2.65)
Leukaemia	<5	49	0.52 (0.12, 2.37)	12	11	0.69 (0.29, 1.61)	10	0.83 (0.36, 1.91)	8	0.36 (0.14, 0.96)	10	1.20 (0.51, 2.84)

a: All models adjusted for employment duration, employment commencement year, ever-smoker status, socio-economic disadvantage, calendar-year, sex and age.
a: These models include 82,292 miners with known ore-type after excluding those with missing socio-economic quintile (n = 1983) or smoking status (n = 16).

for both sexes. This observation suggests a healthy worker effect, whereby healthy people are more likely to start and continue employment in contrast with the less healthy who tend to be excluded from employment but remain included in the general population [27]. Consequently, increased disease risks among the employed population may be potentially obscured, although specific effects may vary by sex and cancer type [28].

Male miners had higher incidence of some cancers than the general population, namely bone and articular cartilage, larynx, lip and melanoma. These increased risks could plausibly be an underestimation of the true risk due to the healthy worker effect, which may be more pronounced with longer follow-up. More detailed lifestyle-related and occupational exposure information for both miners and the general population for site-specific carcinogens [3–5] would be necessary to explain these findings.

The healthy worker effect may also bias within-cohort comparisons whereby healthier workers continue employment longer than their counterparts and sicker or more sensitive people may leave work sooner and thereby incur less exposure [29]. Our finding of an inverse trend of lung (and brain) cancer incidence with increasing employment duration, with the highest incidence in miners employed for under 2.5 years, is potentially suggestive of this bias. A similar pattern was reported by Taeger and colleagues whereby miners and quarrymen employed for 10–19 years had lower lung cancer risks compared with those employed for 1–9 years, although the risk rose for those with longer employment [1]. While this contrasts with some other studies [2,30], yet the possibility of terminating employment on account of work-related exposures cannot be excluded. A recent publication on lung cancer in underground non-metal miners identified higher occupational diesel exposure to be associated with shorter employment tenures [29]. This knowledge is relevant for casual or contractual workers who are known to be at higher risk of exposure to workplace hazards than full-time permanent employees [31], possibly related to their limited knowledge and/or training regarding potential hazards and appropriate controls [32], and/or because they were more likely to accept dirtier jobs and/or work longer hours due to job insecurity [33].

On the other hand, prostate and breast cancers were found to increase with increasing employment duration. Due to unceasing day-and-night mining operations, shift-work involving circadian disruption, a probable human carcinogen [34], may be implicated here. However, current evidence on the association between shift-work and prostate [35] and breast [36] cancers is inconclusive and causal evidence still lacking.

Pre-inception miners had higher rates of mesothelioma, brain, larynx and lung cancers than inception miners, after adjusting for employment duration. Although the pre-inception miners likely represented the healthiest subset of all miners employed in the industry before 1996, their relatively longer follow-up period potentially allowed for the development and detection of more cancers with long latency periods. Additionally, less stringent occupational hygiene measures previously may have contributed to these higher cancer risks.

Our study identified similar incidence of lung cancer in male miners as expected, which is in contrast to previous Australian [7] and international studies [1,11,37,38] that reported higher rates among miners. We consider these differences to be most likely due to a healthy worker effect in the current study, as well as reducing occupational exposures to carcinogens like diesel [16], silica [39] and asbestos [40] over time. Moreover, within-cohort comparisons showed that lung cancer risk was increased among ever-underground and exclusive gold miners. These finding are consistent with other international studies suggesting hard-rock mining processes, the use of heavy diesel equipment and insufficient ventilation in underground mines leading to higher air concentrations of respirable carcinogens [2,15,37,41]. Radon is an established lung carcinogen in underground mines, however, WA has no active uranium mines and the average annual radon exposures for Australian miners are reported to be substantially lower than the permissible limit of 20mSv [42].

Prostate cancer incidence among miners was as expected. This finding is different from a review that reported a significantly lower risk of prostate cancer in miners, although not attributed to the healthy worker effect by the authors [9]. However, a previous report on WA goldminers assessed during 1961–1975 and followed until 2011 described miners, especially underground miners, as being at greater risk of prostate cancer than the general population [7], possibly due its longer follow-up period than our study. Miners in our study who had exclusively mined iron had a lower risk of prostate cancer but ever-underground workers did not. Heavy metals such as arsenic and cadmium have been implicated as potential carcinogens for prostate cancer [43]. Variations in prostate-specific antigen testing practices have been known to influence prostate cancer incidence internationally [44]. However, it is unlikely that there would be any between- or within-cohort differences (e.g. by ore-type) in accessing this screening procedure.

There is limited knowledge on colorectal cancer risk among miners. A recent review on colorectal cancer and occupational exposures found lower risks of colon cancer in metal miners (Risk Ratio:0.57, 95%CI:0.08–4.30) based on two studies [45]. We identified a similar rate of colorectal cancer in miners as the general population, although gold miners were identified to have elevated rates even on internal comparisons.

Socio-economic disadvantage was considered a proxy of working in high-exposures jobs and miners with the greatest disadvantage (i.e. lowest education, skill-levels and income) were anticipated to have been allocated and working in jobs with highest exposure [46]. However, adjusting for this did not change any estimates for occupational variables, suggesting that variables other than job type, like employment year and ore-type, were potentially more likely to explain any of the observed differences in cancer risks identified within this mining cohort.

To our knowledge, this is the first and largest industry-wide longitudinal study on miners internationally, exploring the full spectrum of cancers and various ore-types. The cohort was restricted to Australian citizens living in WA to avoid information bias of health status for miners residing elsewhere. Assumption of continuous employment in the industry from work commencement until 2.5 years after the last health assessment may have led to possible misclassification of employment duration categories. However, this is likely to be non-differential misclassification, is independent of the cancer outcomes investigated and would have biased the findings towards the null [27]. The limited follow-up time was a drawback for accurate risk assessments for cancers with long latencies, although increased rates observed may be an underestimation of the true rates arising from the healthy worker effect. Although we have adjusted for socio-economic disadvantage, residual confounding may have been present from unmeasured personal and lifestyle-related factors including family history, race, diet, alcohol consumption, obesity and physical activity. While we expect most of these personal and lifestyle level confounders to be similar among miners working across the various ore-types and job locations, some differences may be present. For instance, underground mining operations may be more physically demanding than open-cut mining which is more mechanised [47].

Ore-type information was complete for 55% of the cohort allowing identification of ore-specific cancer risks, although this reduction in sample size may have led to reduced precision and wider confidence intervals. Identifying an 'ideal' comparison group for meaningful inferences was a challenge. We considered using the general population for this purpose and performed stratified SIR analyses by ore-type (Appendix A). However, these analyses could not be adjusted adequately for employment-related variables and smoking history, which are important predictors of cancer. Therefore, internal comparisons were considered superior and we resorted to using a less ideal comparison group of multi-ore miners with heterogeneous exposures to identify ore-specific risks in internal comparisons. The comparability of the rates from external and internal comparisons suggests that the heterogeneous multi-ore miner group was in fact well-suited for this purpose. Although a proportion of multi-ore miners would at some time have mined the ore to which they were being compared (e.g. gold or iron), this would only lead to an under-estimation of any differences between the two groups and bias our results towards the null. Nevertheless, we need to exercise caution in our interpretations despite finding cancer associations with specific ore-types as mining practices and processes are complex with exposure to various elements which have not been evaluated in this study. We anticipate these findings to stimulate further research identifying individual-level carcinogenic occupational exposures in specific mining sectors so as to develop targeted preventive measures to reduce miners' cancer risks.

In conclusion, ever-underground mining was associated with increased risk of lung cancer in our contemporary cohort. Increased risks of lung, prostate, colorectal and urinary tract cancers and leukaemia were identified for mining specific ore-types. These findings underline the importance of continued surveillance of the health and exposures of this relatively young cohort.

Conflict of interest

None.

Authorship contribution statement

SP, AR, LF, AWM, RV and NdK conceptualised and designed the study. SP directed the project and is responsible for its overall design. NSB, NdK and SP were responsible for the data analysis and interpretation. The paper was drafted by NSB and revised with contributions from all authors. All authors have critically reviewed and approved the final version of the manuscript.

Acknowledgements

This study was funded by the Australian National Health and Medical Research Council (NHMRC #1069535) and the WA Department of Health (Targeted Research Fund 2012 – Round 2). Lin Fritschi is supported by fellowships from the NHMRC and the Cancer Council WA. We thank the WA Department of Mines and Petroleum for providing miners' health assessment data and the custodians of the WA Electoral Roll, the WA Cancer Registry and the WA Registry of Births, Deaths and Marriages for the provision of service data. We also thank the Data Linkage Branch at the WA Department of Health for data linkage and client support services, Marc Padros Goossens for data management, and the study Advisory Committee members, namely Simon Ridge, Andrew Chaplyn, Odwyn Jones, Nic Ormonde and Patrick Gilroy for overseeing the conduct of the study.

Appendix A.

Table A1

Table A1
Standardised Incidence Ratios (SIRs) of various malignancies by mine-type, adjusted for age, sex and calendar-year (1996–2013).

Cancer site/morphology	Iron only (n = 22,901)			Gold only (n = 16,311)			Other metals only (n = 22,500)			Non-metals only (n = 7872)			Multiple ores (n = 14,707)		
	O	E	SIR (95% CI)	O	E	SIR (95% CI)	O	E	SIR (95% CI)	O	E	SIR (95% CI)	O	E	SIR (95% CI)
All cancers	533	589	0.90 (0.83, 0.98)	475	474.7	1.00 (0.91, 1.09)	801	843.2	0.95 (0.88, 1.02)	339	335.1	1.01 (0.90, 1.12)	453	476.3	0.95 (0.86, 1.04)
Lip, oral cavity & pharynx	23	33.1	0.70 (0.41, 0.98)	27	26.4	1.02 (0.64, 1.41)	47	46.6	1.01 (0.72, 1.30)	22	18.3	1.20 (0.70, 1.71)	34	30.3	1.12 (0.74, 1.50)
Lip	11	11.9	0.93 (0.38, 1.47)	13	10.2	1.27 (0.58, 1.96)	19	16.8	1.13 (0.62, 1.64)	10	6.4	1.57 (0.60, 2.54)	20	11.9	1.69 (0.95, 2.43)
Pharynx	6	9.5	0.63 (0.13, 1.14)	8	7.1	1.13 (0.35, 1.92)	13	13.2	0.99 (0.45, 1.52)	<5	5.3	0.76 (0.02, 1.50)	8	8.3	0.96 (0.29, 1.63)
Digestive organs	100	108.6	0.92 (0.74, 1.10)	99	84.5	1.17 (0.94, 1.40)	143	160	0.89 (0.75, 1.04)	57	64.1	0.89 (0.66, 1.12)	79	86	0.92 (0.72, 1.12)
Oesophagus	<5	8.6	0.47 (0.01, 0.92)	<5	6.4	0.62 (0.01, 1.23)	15	12.7	1.18 (0.58, 1.78)	6	5.1	1.17 (0.23, 2.11)	6	7	0.86 (0.17, 1.54)
Stomach	12	10.1	1.19 (0.52, 1.87)	5	7.9	0.63 (0.08, 1.18)	14	15	0.93 (0.44, 1.42)	6	6	1.00 (0.20, 1.80)	9	8.1	1.12 (0.39, 1.85)
Small intestine	5	3.1	1.60 (0.20, 3.00)	0	2.5	–	<5	4.4	0.90 (0.02, 1.79)	<5	1.8	0.57 (0.00, 1.68)	<5	2.7	1.48 (0.03, 2.92)
Colon & rectum	60	65.7	0.91 (0.68, 1.15)	77	51.7	1.49 (1.16, 1.82)	93	96.9	0.96 (0.76, 1.16)	35	38.8	0.90 (0.60, 1.20)	46	51.5	0.89 (0.64, 1.15)
Liver	6	8.2	0.73 (0.15, 1.32)	7	6.1	1.14 (0.30, 1.99)	7	11.7	0.60 (0.15, 1.04)	0	4.7	–	5	6.7	0.74 (0.09, 1.40)
Pancreas	10	10.4	0.96 (0.36, 1.55)	<5	8.1	0.50 (0.01, 0.98)	11	15.5	0.71 (0.29, 1.13)	6	6.3	0.96 (0.19, 1.72)	7	8.1	0.87 (0.22, 1.51)
Respiratory & intrathoracic organs	57	46.4	1.23 (0.91, 1.55)	58	36.2	1.60 (1.19, 2.01)	61	71.7	0.85 (0.64, 1.06)	33	28.9	1.14 (0.75, 1.53)	30	34	0.88 (0.57, 1.20)
Heart, mediastinum & pleura	8	0.3	25.8 (7.94, 43.8)	8	0.3	31.4 (9.66, 53.2)	8	0.4	18.7 (5.75, 31.7)	5	0.2	30.5 (3.76, 57.2)	<5	0.3	6.87 (0.00, 16.4)
Larynx	6	4.3	1.39 (0.28, 2.49)	6	3.3	1.83 (0.37, 3.30)	7	6.6	1.06 (0.27, 1.85)	<5	2.7	1.12 (0.00, 2.40)	7	3.4	2.09 (0.54, 3.63)
Lung	41	40	1.02 (0.71, 1.34)	44	31.3	1.40 (0.99, 1.82)	42	62.3	0.67 (0.47, 0.88)	24	25.1	0.96 (0.57, 1.34)	21	28.8	0.73 (0.42, 1.04)
Melanoma	111	82.9	1.34 (1.09, 1.59)	112	72.5	1.54 (1.26, 1.83)	143	118.5	1.21 (1.01, 1.40)	68	46.3	1.47 (1.12, 1.82)	98	75.5	1.30 (1.04, 1.55)
Breast	21	23.5	0.89 (0.51, 1.28)	17	26.7	0.64 (0.33, 0.94)	12	25.7	0.47 (0.20, 0.73)	14	12.5	1.12 (0.53, 1.71)	12	13.9	0.87 (0.38, 1.36)
Female genitalia	7	6.7	1.04 (0.27, 1.82)	6	8.3	0.72 (0.14, 1.30)	<5	7.2	0.28 (0.00, 0.66)	<5	3.4	0.59 (0.00, 1.41)	<5	<5	0.25 (0.00, 0.73)
Male genitalia	135	167	0.81 (0.67, 0.94)	117	123.9	0.94 (0.77, 1.12)	271	247.6	1.09 (0.96, 1.23)	117	98.4	1.19 (0.97, 1.40)	140	129.4	1.08 (0.90, 1.26)
Prostate	120	152.8	0.79 (0.64, 0.93)	108	109.9	0.98 (0.80, 1.17)	256	228.5	1.12 (0.98, 1.26)	112	91.9	1.22 (0.99, 1.44)	124	112.9	1.10 (0.91, 1.29)
Testis	15	13.5	1.11 (0.55, 1.68)	8	13.3	0.60 (0.19, 1.02)	14	17.9	0.78 (0.37, 1.19)	5	6	0.83 (0.10, 1.56)	15	15.8	0.95 (0.47, 1.43)
Urinary tract	25	30.4	0.82 (0.50, 1.14)	19	23.7	0.80 (0.44, 1.16)	53	44.4	1.19 (0.87, 1.51)	17	17.6	0.97 (0.51, 1.42)	14	25	0.56 (0.27, 0.85)
Kidney	17	20	0.85 (0.45, 1.25)	12	15.6	0.77 (0.33, 1.20)	31	28.2	1.10 (0.71, 1.49)	8	11.2	0.72 (0.22, 1.21)	12	17.4	0.69 (0.30, 1.08)
Bladder	7	8.8	0.80 (0.21, 1.39)	6	6.8	0.88 (0.18, 1.58)	16	13.8	1.16 (0.59, 1.73)	8	5.5	1.46 (0.45, 2.48)	<5	6.4	0.31 (0.00, 0.74)
Central nervous system	9	13.3	0.68 (0.23, 1.12)	5	11.2	0.45 (0.06, 0.84)	18	18.6	0.97 (0.52, 1.41)	8	7.3	1.10 (0.34, 1.86)	6	12	0.50 (0.10, 0.90)
Thyroid	11	12.7	0.87 (0.36, 1.38)	11	12.3	0.89 (0.37, 1.42)	20	15.7	1.27 (0.72, 1.83)	6	6	1.00 (0.20, 1.79)	10	11	0.91 (0.35, 1.47)
Mesothelioma	7	5.1	1.38 (0.36, 2.40)	8	3.9	2.03 (0.62, 3.44)	7	8.3	0.85 (0.22, 1.48)	5	3.3	1.52 (0.19, 2.85)	<5	3.5	0.86 (0.00, 1.82)
Lymphoma	25	29.7	0.84 (0.51, 1.17)	16	24.8	0.65 (0.33, 0.96)	37	41.5	0.89 (0.60, 1.18)	16	16.1	0.99 (0.51, 1.48)	20	25.9	0.77 (0.43, 1.11)
Leukaemia	11	14.7	0.75 (0.31, 1.19)	10	12.3	0.81 (0.31, 1.32)	9	21.1	0.43 (0.15, 0.70)	10	8.3	1.21 (0.46, 1.96)	13	12.5	1.04 (0.47, 1.60)

O: Observed cases; E: Expected cases; CI: Confidence Interval.

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