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Overall and cause-specific mortality rates among men and women with high exposure to indoor air pollution from the use of smoky and smokeless coal: a cohort study in Xuanwei, China

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ABSTRACT

Objectives Never-smoking women in Xuanwei (XW), China, have some of the highest lung cancer rates in the country. This has been attributed to the combustion of smoky coal used for indoor cooking and heating. The aim of this study was to evaluate the spectrum of cause-specific mortality in this unique population, including among those who use smokeless coal, considered 'cleaner' coal in XW, as this has not been well-characterised.

Design Cohort study.

Setting XW, a rural region of China where residents routinely burn coal for indoor cooking and heating.

Participants Age-adjusted, cause-specific mortality rates between 1976 and 2011 were calculated and compared among lifetime smoky and smokeless coal users in a cohort of 42 420 men and women from XW. Mortality rates for XW women were compared with those for a cohort of predominately never-smoking women in Shanghai.

Results Mortality in smoky coal users was driven by cancer (41%), with lung cancer accounting for 88% of cancer deaths. In contrast, cardiovascular disease (CVD) accounted for 32% of deaths among smokeless coal users, with 7% of deaths from cancer. Total cancer mortality was four times higher among smoky coal users relative to smokeless coal users, particularly for lung cancer (standardised rate ratio (SRR)=17.6). Smokeless coal users had higher mortality rates of CVD (SRR=2.9) and pneumonia (SRR=2.5) compared with smoky coal users. These patterns were similar in men and women, even though XW women rarely smoked cigarettes. Women in XW, regardless of coal type used, had over a threefold higher rate of overall mortality, and most cause-specific outcomes were elevated compared with women in Shanghai.

Conclusions Cause-specific mortality burden differs in XW based on the lifetime use of different coal types. These observations provide evidence that eliminating all coal use for indoor cooking and heating is an important next

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ This study used data from a large cohort that had detailed questionnaire data on lifetime fuel use for all residences of the study participants since birth.
⇒ Xuanwei has a relatively stable and homogenous population with respect to lifestyle and sociodemographic factors, and few women smoke, which minimised sources of confounding in our study.
⇒ Self-reporting of lifetime coal use patterns and use of death certificate information may result in some degree of exposure and/or outcome misclassification, but this is likely to be non-differential with respect to type of coal use.

step in improving public health particularly in developing countries.

INTRODUCTION

The global prevalence of exposure to household air pollution (HAP) is substantial, as almost 40%[1] of the world's population are exposed to HAP from solid fuel use for indoor cooking and heating. HAP resulting from the use of solid fuels is also an important contributor to the global disease burden, accounting for ~4.3 million deaths annually.[2] Coal is a predominant source of fuel for power generation in countries such as China and India, accounting for almost 40% of energy generation in these countries.[3] China is the world's largest coal producer and it is estimated that 75% of China's primary energy is supplied by domestic coal.[4]

Several studies have linked HAP exposure to malignant and non-malignant respiratory disease[3 4] and cardiovascular disease (CVD)

incidence and mortality.[4–6] Two prospective cohort studies conducted in China have evaluated the health risks associated with solid fuel use. The Kadoorie cohort, which included five rural areas in China, identified an association between solid fuel use (wood, biomass, coal) and the risk of all-cause and CVD mortality compared with use of alternative fuels (natural gas, ethanol, propane) regardless of smoking status.[6] Similarly, household solid fuel use has been associated with an increased risk of chronic obstructive pulmonary disease (COPD)[7] and a higher risk of hospital admissions and mortality for both acute and chronic respiratory diseases was observed.[8] We previously conducted an analysis in the population-based, prospective Shanghai Women's Health Study (SWHS) cohort and found that past use of coal increased the risk of all-cause mortality, cancer, ischaemic heart disease (IHD) and myocardial infarction.[5] The risk of these outcomes increased as duration of use increased, although the association of coal use with CVD mortality became weaker with increasing number of years since last use.[5]

Xuanwei (XW) county, in Yunnan province, China, has one of the highest lung cancer mortality rates in the world despite the fact that very few women in this population smoke cigarettes (<2%).[9–12] XW is a rural area where residents predominately use coal for indoor cooking and heating. The HAP generated from the use of these fuels contributes to high levels of specific pollutants, including $PM_{2.5}$, polycyclic aromatic hydrocarbons (PAHs) and gaseous pollutants.[13–15] Interestingly, levels of some pollutants (eg, SO_2) have been measured to be higher in homes burning anthracite ('smokeless' coal) whereas others (eg, PAHs) are higher in homes burning bituminous ('smoky') coal, indicating that the health risks associated with each coal type could differ.[15–17] In a large cohort study in XW, it was previously observed that never-smoking women who were lifetime users of smoky coal had an ~100-fold elevated risk of lung cancer mortality, compared with women who used smokeless coal during their entire life.[10] Smoky coal use has also been associated with respiratory diseases.[18 19] In contrast, the health effects of smokeless coal use have been less characterised, but data from the XW cohort suggest that lifetime users of this coal type may have increased risks of pneumonia[19] and IHD mortality.[20]

In this study, we aimed to evaluate the mortality burden among those who are lifetime users of smoky and smokeless coal in the XW cohort study. This is the first descriptive epidemiology study to evaluate the spectrum of cause-specific mortality burden in lifetime coal users, stratified by coal type.

METHODS
Study population and data collection
The design of the XW cohort study has been described in detail.[10 21] In brief, the study area was comprised of communes that predominantly used either of two different coal types as a primary fuel source. Residents of three communes primarily used smoky coal, whereas residents living in another commune primarily used smokeless coal. A review of administrative records was conducted in 1992 to identify all people born between 1917 and 1951 who lived in the study area. The cohort comprised 42 420 participants (age range from 25 to 59 years old at baseline) who were alive as of 1 January 1976, including a subcohort of 20 719 women, nearly all of whom never smoked cigarettes based on the baseline and follow-up questionnaires (n=20 382; 98.4%). In 1992, trained interviewers administered a standardised questionnaire directly to the study subjects or their surrogates. The questionnaire assessed lifetime residential history and lifestyle characteristics, cooking practices and household fuel use, including the amount of fuel that was used, the primary fuel source and the type of cooking apparatus that was used in the main living or cooking area (stove with chimney, portable stove, unvented fire pit and stove without a chimney) over their entire lifetime.

A follow-up questionnaire was administered between 2009 and 2011 directly to participants (or their surrogates) still alive after 1992. Participants were assigned the same exposure information for each year corresponding to the total number of years in a particular residence. Based on these questionnaire responses, participants were classified as lifetime and exclusive smoky or smokeless coal users if they reported exclusive use of these coal types, respectively, throughout their lifetime. Of the 42 420 cohort participants, 23 886 people (56%) were lifetime smoky coal users and 4521 people were lifetime smokeless coal users (11%) through 2011 follow-up. A small percentage of participants (0.8%) had unreliable and/or missing data on key variables (vital status and/or coal use) and were excluded from further analyses, resulting in 42 083 men and women of which 23 662 were lifetime smoky coal users and 4486 were lifetime smokeless coal users.

The date and cause of death for subjects in the cohort during the follow-up period (1 January 1976 to 31 December 2011) were obtained from death certificate and hospital records. Cause of death was coded by the Center for Disease Control according to the International Classification of Diseases, 9th revision (ICD-9), including for cancer (ICD-9 140–239, CVD (ICD-9 390–459), IHD (410–414), stroke (430–438), respiratory causes (ICD-9 460–519), COPD (490–496), pneumonia (500–508), gastrointestinal (GI) diseases (ICD-9 520–579) and genitourinary diseases (ICD-9 580–629). ICD-9 codes for specific cancers included in the analysis were as follows: nasopharyngeal cancer (147), oesophageal cancer (150), stomach cancer (151), colorectal cancer (153), liver cancer (155), pancreatic cancer (157), lung cancer (162), bone cancer (170), breast cancer (174), cervical cancer (180), ovarian cancer (183), bladder cancer (188) and brain cancer (191).

Patient and public involvement

Study participants or the public were not involved in the design, conduct, reporting or dissemination plans of this research.

Statistical analysis

To quantify the burden of mortality from multiple cause-specific endpoints in XW, we calculated age-adjusted mortality rates overall and stratified by sex among lifetime users of smoky and smokeless coal. Rates were adjusted to the WHO 2000–2025 world standard population within seven age groups (25–34, 35–44, 45–54, 55–64, 65–74, 75–84 and 85+) and are presented per 100 000 person-years. The average age of death for the main causes of mortality was also evaluated by coal type. To compare mortality rates between smoky and smokeless coal users, standardised rate ratios (SRR) and 95% CI were calculated for each outcome that had >10 cases in both smoky and smokeless coal users based on direct standardisation. We also compared the cause-specific mortality rates among women in the XW cohort to those in the prospective SWHS cohort based on both direct standardisation as the primary analysis and indirect standardisation as a sensitivity analysis. The SWHS recruited 74 942 Chinese women from various urban communities in Shanghai and was initiated to investigate a wide variety of lifestyle, environmental/occupational and genetic risk factors for cancer and other chronic diseases. The follow-up of the SWHS used in this analysis occurred from 1997 to 2009 and the methods and demographic characteristics for Chinese women in this study have been described in detail elsewhere.[22] For this comparison, analyses in XW were restricted to mortality occurring during 1997–2009 to be consistent with the follow-up period in the SWHS. We also restricted analyses to women≥45 years of age due to the very small number of women less than 45 years old in 1997. Comparisons were made for all women as well as never-smoking women separately in the Shanghai and XW cohorts (about 98% of the women in the XW cohort and about 97% of women in the SWHS were never smokers). Analyses were conducted using the PROC STDRATE procedure in Statistical Analysis Software (SAS) V.9.4.

RESULTS

Demographics and cohort follow-up

The mean age at cohort entry for lifetime smoky coal users in XW was similar in men (40.0±10.6) and women (39.5±10.6) (table 1). Ages at entry were also similar among men (45.1±10.8) and women (44.3±11.2) who used smokeless coal throughout their lifetime. The mean entry age was lower among smoky compared with smokeless coal users for both men and women (p<0.0001). A similarly high percentage of men in both the smoky (94.9%) and smokeless coal (94.6%) subcohorts were ever cigarette smokers, whereas the percentage of ever smokers among women was low in lifetime users of both coal types (1.6% for lifetime smoky coal users and 1.1%

Table 1 Demographic characteristics of lifetime smoky and smokeless coal users in the Xuanwei (XW) cohort study

Variable	XW total cohort demographics		XW lifetime smoky coal users (1976–2011)		XW lifetime smokeless coal users (1976–2011)		P value for smoky versus smokeless coal use (men)*	P value for smoky versus smokeless coal use (women)*
	Men	Women	Men	Women	Men	Women		
Number of subjects, n	21 535	20 548	12 436	11 226	2530	1956		
Person-years of follow-up in mortality rate analysis, n	587 033	567 018	317 024	284 489	55 128	45 108		
Mean age (±SD) at entry	39.9 (10.6)	39.4 (10.6)	40.0 (10.6)	39.5 (10.6)	45.1 (10.8)	44.3 (11.2)	<0.0001	<0.0001
Mean age (±SD) at exit	66.1 (10.7)	66.0 (10.7)	64.5 (11.1)	63.8 (10.8)	65.9 (11.3)	66.4 (11.4)	<0.0001	<0.0001
Ever smoker, n (%)	20 476 (95%)	336 (1.6%)	11 797 (94.9%)	183 (1.6%)	2393 (94.6%)	21 (1.1%)	0.57	0.07
Educational status								
<High school, n (%)	21 521 (99.93%)	20, 544 (99.98%)	12 426 (99.92%)	11 223 (99.97%)	2529 (99.96%)	1956 (100%)		
≥High school, n (%)	14 (0.07%)	4 (0.02%)	10 (0.08%)	3 (0.03%)	1 (0.04%)	–		
Unknown, n (%)	–	–	–	–	–	–		

*Comparisons for age at entry and exit were conducted using t-tests, and comparisons for ever smoking were conducted using a χ² test. Significance tests were not conducted for educational status given the high proportion of study participants in the less than high school category.
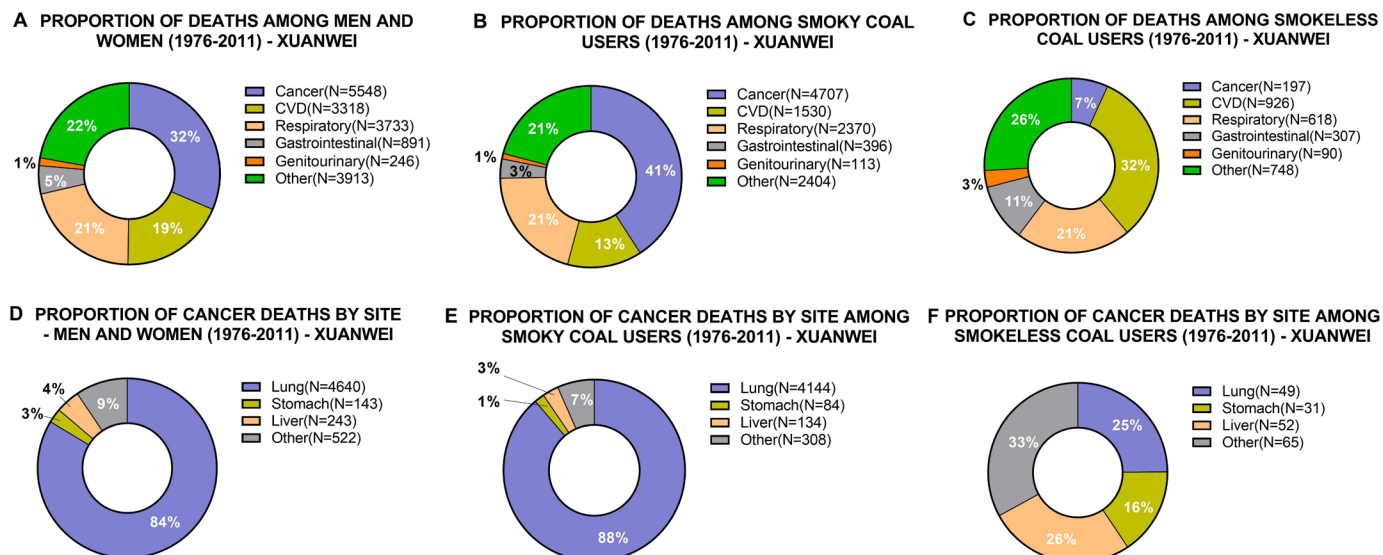
Figure 1 Proportion of cause-specific mortality among smoky and smokeless coal users in Xuanwei (XW), 1976–2011. (A) Distribution of cause-specific mortality among men and women in XW. (B) Distribution of cause-specific mortality among men and women who were lifetime smoky coal users in XW. (C) Distribution of cause-specific mortality among men and women who were lifetime smokeless coal users in XW. (D–F) Distribution of mortality by cancer site among men and women in XW (D) and stratified by coal type (E,F). CVD, cardiovascular disease.

for lifetime smokeless coal users; table 1). Nearly all of the participants in the XW cohort had less than a high school education (table 1). For the SWHS, the proportion of ever smokers in the women were comparable to those in XW (online supplemental table 1).

Distribution of mortality in XW

The proportion of cause-specific mortality among all men and women in XW is shown in figure 1A. Mortality was driven by cancer (32%), respiratory diseases (21%) and CVD (19%). Among lifetime smoky coal users, cancer (41%) and respiratory diseases (21%) accounted for the majority of deaths, while CVD accounted for 13% of deaths (figure 1B). In contrast, among lifetime smokeless coal users, CVD accounted for the majority of deaths (32%) followed by other causes (26%) and respiratory diseases (21%), whereas cancer accounted for only 7% of cause-specific mortality (figure 1C). Of the cancer deaths in men and women overall, 84% were due to lung cancer (figure 1D). Among lifetime smoky coal users, the causes of mortality were driven by cancer (41%), among which 88% were due to lung cancer (figure 1B,E). In contrast, the spectrum of cancer mortality among lifetime smokeless coal users was not predominated by lung cancer (25%) but rather was a combination of sites, including liver (26%) and stomach cancers (16%) (figure 1F). The cause-specific mortality distributions by coal type were similar among men and women (online supplemental figure 1).

Online supplemental table 2 shows the average age of death stratified by sex and type of lifetime coal use. Overall, individuals who used smoky coal died on average 3 years younger compared with individuals who used smokeless coal (61.4±11.6 vs 64.5±11.8 years, respectively).

This younger average age of death among lifetime smoky coal users was driven by lung cancer mortality (59.1±10.0 years among smoky coal users vs 63.8±9.4 years among smokeless coal users). In contrast, lifetime smokeless coal users (64.7±8.3 years) had an earlier age at death from pneumonia compared with smoky coal users (67.8±11.4 years), as well as for IHD (67.7±10.2 years among smoky coal users and 67.0±11.4 years among smokeless coal users). There was a significant difference between the average age of death between smoky coal and smokeless coal users for overall mortality, lung cancer, CVD, stroke, COPD and pneumonia (p<0.05; online supplemental table 2).

Overall and cause-specific mortality rates in XW

Table 2 shows the age-adjusted rates of mortality for specific evaluated outcomes among lifetime smoky and smokeless coal users. Among lifetime smoky coal users, the overall age-adjusted mortality rate was 1543.7 deaths/100 000 person-years. The highest cause-specific rates of mortality were from cancer (577.9 deaths/100 000 person-years) followed by respiratory diseases (323.2 deaths/100 000 person-years), CVD (208.6 deaths/100 000 person-years) and GI diseases (53.0 deaths/100 000 person-years). The cancer mortality rate among smoky coal users was driven by lung cancer (506.8 deaths/100 000 person-years), followed by liver (15.7 deaths/100 000 person-years) and stomach (10.3 deaths/100 000 person-years) cancers. Respiratory disease mortality among smoky coal users was predominately driven by COPD (234.9 deaths/100 000 person-years). Compared with smokeless coal users, smoky coal users had higher mortality rates from total cancer (SRR=4.2, 95% CI=3.5 to 4.9), lung cancer (SRR=17.6, 95% CI=13.1 to 23.8)

Table 2 Overall age-adjusted mortality rates by type of coal use in Xuanwei, 1976–2011

| Disease outcome | Smoky coal users | | Smokeless coal users | | Standardised rate ratio (95% CI)* |
	Number of deaths (N)	Overall age-adjusted rate (per 100 000 person-years)	Number of deaths (N)	Overall age-adjusted rate (per 100 000 person-years)	Smoky versus smokeless
Overall	11 520	1543.7	2886	2060.4	0.7 (0.7 to 0.8)
Cancer	4707	577.9	197	138.3	4.2 (3.5 to 4.9)
Lung cancer	4144	506.8	49	28.7	17.6 (13.1 to 23.8)
Stomach cancer	84	10.3	31	23.8	0.4 (0.3 to 0.7)
Liver cancer	134	15.7	52	35.5	0.4 (0.3 to 0.6)
CVD	1530	208.6	926	614.5	0.3 (0.3 to 0.4)
Ischaemic heart disease	161	23.1	77	54.4	0.4 (0.3 to 0.6)
Stroke	650	89.4	227	152.2	0.6 (0.5 to 0.7)
Respiratory cause	2370	323.2	618	368.6	0.9 (0.8 to 1.0)
Pneumonia	188	28.5	109	64.0	0.4 (0.3 to 0.6)
Chronic obstructive pulmonary disease	1752	234.9	330	200.7	1.2 (1.0 to 1.3)
Gastrointestinal causes	396	53.0	307	222.8	0.2 (0.2 to 0.3)
Genitourinary causes	113	15.3	90	72.0	0.2 (0.2 to 0.3)

*Mortality rates, age adjusted to the WHO 2000–2025 world standard population within seven age groups, and standardised rate ratios were only calculated for outcomes with >10 deaths for both smoky and smokeless coal users. In the Results section, some standardised rate ratios are described using smoky coal users as the reference group.
COPD, chronic obstructive pulmonary disease; CVD, cardiovascular disease.

and COPD (SRR=1.2, 95% CI=1.0 to 1.3). The mortality rates from brain cancer were also elevated in smoky coal users (7.5 cases per 100 000 person-years) compared with smokeless coal users, but an SRR was not calculated given the small number of cases among the smokeless coal users (n=2; online supplemental table 3). Mortality rates for additional cancer sites that do not have an SRR calculation due to small case numbers but >10 deaths are also shown in online supplemental table 3.

In contrast, a distinctly different mortality burden was observed among lifetime users of smokeless coal (table 2). The overall age-adjusted mortality rate among smokeless coal users was 2060.4 deaths/100 000 person-years. The highest cause-specific mortality rates among users of this coal type were observed for CVD (614.5 deaths/100 000), followed by respiratory diseases (368.6 deaths/100 000), GI diseases (222.8 deaths/100 000 person-years) and cancer (138.3 deaths/100 000 person-years). Liver cancer had the highest cancer mortality rate (35.5 deaths/100 000 person-years) followed by lung (28.7 deaths/100 000 person-years) and stomach (23.8 deaths/100 000 person-years) cancers. All-cause mortality rates (SRR=1.3, 95% CI=1.3 to 1.4), rates of CVD (SRR=2.9, 95% CI=2.7 to 3.2), respiratory diseases (SRR=1.1, 95% CI=1.0 to 1.3), GI diseases (SRR=4.2, 95% CI=3.5 to 5.1) and genitourinary diseases (SRR=4.7, 95% CI=3.3 to 6.6) were higher among lifetime smokeless coal users compared with smoky coal users.

Table 3 shows the overall and cause-specific age-adjusted mortality rates among men and women stratified by coal type. For comparisons between users of the same coal type by sex, male and female smoky or smokeless coal users had similar mortality rates for the majority of outcomes (table 3). However, among smokeless coal users the liver cancer mortality rate was nearly three times higher in men than in women (SRR=2.8, 95% CI=1.4 to 5.5). For comparisons among different types of coal users, overall cancer mortality was 3.5 (95% CI=2.8 to 4.3) times higher in male smoky coal users than in male smokeless coal users and was 5.7 (95% CI=4.3 to 7.4) times higher in female smoky coal users compared with female smokeless coal users. Male smoky coal users had a 14.7 (95% CI 10.1 to 21.5) times higher rate of mortality from lung cancer compared with male smokeless coal users, whereas for women the corresponding SRR was 23.8 (95% CI=14.6 to 39.0). Among male smokeless coal users, rates of liver cancer (SRR=2.7, 95% CI=1.8 to 4.1) and stomach cancer (SRR=2.6, 95% CI=1.5 to 4.4) were significantly higher compared with male smoky coal users. Similarly, overall mortality (SRR in men=1.4, 95% CI=1.3 to 1.5, SRR in women=1.3, 95% CI=1.2 to 1.4), CVD (SRR in men=3.0, 95% CI=2.7 to 3.5; SRR in women=2.8, 95% CI=2.5 to 3.3), IHD (SRR in men=2.2, 95% CI=1.4 to 3.5; SRR in women=2.6, 95% CI=1.6 to 4.3) and stroke (SRR in men=1.5, 95% CI=1.2 to 1.9; SRR in women=2.0, 95% CI=1.5 to 2.6) rates were all significantly higher among smokeless coal users compared with smoky coal users in both men and women (table 3). Given the high proportion of men and low proportion of women who were ever smokers, results restricted to ever male smokers and never-smoking women were largely similar to the overall analyses not stratified by smoking status (online supplemental table 4).

Comparison of age-adjusted mortality rates in XW women with women in Shanghai (1997–2009)

Online supplemental table 5 highlights the overall and cause specific mortality rates among women in Shanghai.

Table 3 Overall age-adjusted mortality rates among male and female smoky coal and smokeless coal users in Xuanwei, 1976–2011

Disease outcome	Men						Women						Male versus female Standardised rate ratio (95% CI)*	
	Smoky coal users		Smokeless coal users		Smoky versus smokeless rate ratio (95% CI)*		Smoky coal users		Smokeless coal users		Smoky versus smokeless rate ratio (95% CI)*			
	N	Overall age-adjusted rate	N	Overall age-adjusted rate			N	Overall age-adjusted rate	N	Overall age-adjusted rate			Smoky coal	Smokeless coal
Overall	6324	1599.4	1718	2238.3	0.7 (0.7 to 0.8)		5196	1478.4	1168	1854.7	0.8 (0.7 to 0.9)		1.1 (1.0 to 1.1)	1.2 (1.1 to 1.3)
Cancer	2549	588.9	133	170.6	3.5 (2.8 to 4.3)		2158	564.1	64	99.5	5.7 (4.3 to 7.4)		1.0 (1.0 to 1.1)	1.7 (1.2 to 2.4)
Lung cancer	2237	517.9	32	35.2	14.7 (10.1 to 21.5)		1907	493.4	17	20.7	23.8 (14.6 to 39.0)		1.0 (1.0 to 1.1)	1.7 (0.9 to 3.2)
Stomach cancer	52	11.4	22	29.3	0.4 (0.2 to 0.7)		32	9	9	--	--		1.3 (0.8 to 2.1)	--
Liver cancer	85	18.4	40	49.8	0.4 (0.2 to 0.6)		49	12.6	12	18	0.7 (0.4 to 1.4)		1.5 (1.0 to 2.1)	2.8 (1.4 to 5.5)
Cardiovascular disease	838	210.6	544	642.2	0.3 (0.3 to 0.4)		692	204.7	382	581.1	0.4 (0.3 to 0.4)		1.0 (0.9 to 1.2)	1.1 (0.9 to 1.3)
Ischaemic heart disease	102	25.4	43	55.6	0.5 (0.3 to 0.7)		59	20.2	34	53.2	0.4 (0.2 to 0.6)		1.3 (0.9 to 1.8)	1.0 (0.6 to 1.8)
Stroke	406	103.9	138	160.2	0.6 (0.5 to 0.8)		244	71.7	89	141.8	0.5 (0.4 to 0.7)		1.4 (1.2 to 1.7)	1.1 (0.8 to 1.5)
Respiratory cause	1242	315.7	343	376.8	0.8 (0.7 to 1.0)		1128	331	275	360.0	0.9 (0.8 to 1.1)		1.0 (0.9 to 1.0)	1.0 (0.9 to 1.3)
Pneumonia	107	29.5	62	63.7	0.5 (0.3 to 0.7)		81	27.3	47	63.4	0.4 (0.3 to 0.7)		1.1 (0.8 to 1.5)	1.0 (0.6 to 1.6)
Chronic obstructive pulmonary disease	917	228.0	189	217.9	1.0 (0.9 to 1.3)		835	242.5	141	182.9	1.3 (1.1 to 1.6)		0.9 (0.8 to 1.0)	1.2 (0.9 to 1.5)
Gastrointestinal cause	216	56.5	188	255.8	0.2 (0.2 to 0.3)		180	49.3	119	184.1	0.3 (0.2 to 0.4)		1.1 (0.9 to 1.4)	1.4 (1.0 to 1.9)
Genitourinary cause	76	19.6	58	89	0.2 (0.1 to 0.3)		37	10.2	32	53.3	0.2 (0.1 to 0.3)		1.9 (1.3 to 2.9)	1.7 (1.0 to 2.8)

*Mortality rates, age adjusted to the WHO 2000–2025 world standard population within seven age groups, and standardised rate ratios were only calculated for outcomes with >10 deaths for both smoky and smokeless coal users. In the Results section, some standardised rate ratios are described using smoky coal users as the reference group.

These data were compared against XW women who used either smokeless or smoky coal. Compared with women in Shanghai, the overall mortality rate was higher in XW women among both smoky (SRR=3.1, 95% CI=2.8 to 3.3) and smokeless coal users (SRR=3.7, 95% CI=3.2 to 4.2), respectively. Lung cancer mortality was 15.9 (95% CI=13.1 to 19.3) times higher in smoky coal users from XW compared with women in Shanghai. In addition, mortality rates were significantly elevated among women who used smoky coal in XW compared with Shanghai women for overall respiratory causes (SRR=11.2, 95% CI=7.5 to 16.8), pneumonia (SRR=16.2, 95% CI=9.1 to 28.9) and COPD (SRR=12.0, 95% CI=7.1 to 20.3). Among women in XW who used smokeless coal, overall mortality rates were 3.7 times higher (95% CI=3.2 to 4.2) than in women in Shanghai. Mortality rates of IHD and stroke were 3.1 (95% CI=1.8 to 5.5) and 3.6 (95% CI=2.5 to 5.3) times higher in XW women who used smokeless coal compared with Shanghai women, respectively. In addition, mortality associated with respiratory causes was 10.6 (95% CI=6.4 to 17.4) times higher in XW women who used smokeless coal compared with Shanghai women. This was driven by mortality from COPD (SRR=12.7, 95% CI=6.8 to 23.7). When comparisons were limited to never-smoking women, results were nearly identical (data not shown). In addition, sensitivity analyses that used indirect age adjustment to calculate standardised mortality ratios comparing women in XW by coal type to Shanghai women, based on the age-specific mortality rates in Shanghai women and person-year distributions of women in XW, produced very similar results to the primary analyses based on direct age adjustment online supplemental table 6 and 7.

DISCUSSION

This descriptive analysis using data from a unique cohort of Chinese men and women with substantial indoor air pollution exposure in China indicated that cause-specific mortality among lifetime users of smoky and smokeless coal differs dramatically. While overall mortality rates were higher among lifetime smokeless compared with smoky coal users, smoky coal users had a notable excess of cancer mortality and mortality rates for lung cancer among both men and women in XW continue to be substantially higher among smoky coal users compared with smokeless coal users. In contrast, cancer accounted for a relatively small proportion of deaths among lifetime smokeless coal users, whereas rates of CVD, respiratory disease, and GI causes were all higher than the total cancer rates. Notably, we also observed that men and women who used the same coal type had similar mortality rates of most disease outcomes, despite the fact that nearly no women smoke in XW. Finally, our novel analysis comparing age-adjusted mortality rates between women in XW and women in urban Shanghai found significantly higher rates of overall mortality and certain cause-specific outcomes (ie, lung cancer, respiratory disease, IHD,

stroke) among smoky and smokeless coal users in XW. Collectively, these findings are consistent with and extend current understanding of the health effects of indoor air pollution and emphasise the need for mitigation strategies in populations that still rely on coal for indoor cooking and heating.

The use of coal in the household for cooking and/or heating is well established to be associated with lung cancer.[23] In addition, the Kadoorie cohort observed associations between burning solid fuels indoors and increased mortality risks for CVD outcomes among participants from five rural areas in China.[6] Significantly higher risks of incident respiratory diseases including COPD in relation to solid fuel use for household cooking and heating were apparent in this cohort.[7 8] In the SWHS, use of coal indoors for cooking was also associated with higher all-cause and cause specific mortality from cancer, IHDs and myocardial infarction.[5] However, these prior studies did not evaluate risk by specific type of coal that was used by the study participants. Our current study in XW indicates that use of different coal types may result in a unique disease and/or mortality burden and provides aetiologic hypotheses relating to coal use, indoor air pollution and mortality outcomes that can be evaluated in future analyses of our cohort and potentially other studies that collect detailed information on the specific type of coal used.

Our study is the first to our knowledge to comprehensively describe the full spectrum of the disease burden in XW by use of different coal types. Previous studies in XW have elucidated the burden of lung cancer mortality because of the high levels of HAP that are present in this region. The burden of lung cancer in XW has been influenced by the proximity of the villages to highly carcinogenic types of coal.[11 24] Previous research has also indicated that clinicopathologic features including gene fusion patterns of lung cancer in this population may be distinct from other populations that have less or no exposure to coal combustion.[25 26] While proximity to coal communes in XW play a role in lung cancer burden, it is the specific constituents of the coal found in this region that is the driver of lung cancer and other diseases. For example, a population-based case–control study of lung cancer cases among never-smoking women in XW found that a cluster of 25 PAHs had the strongest association with lung cancer of 43 different household air pollutants evaluated.[12] Of these 25 PAHs, 5-methylchrysene, a mutagenic and known carcinogenic PAH, was observed to have the strongest association with lung cancer risk. In contrast, $PM_{2.5}$ was not associated with lung cancer risk in multipollutant models.

Given our recent observations in the XW cohort that use of smokeless coal is associated with mortality from IHD,[20] it is likely that distinct constituents from both smoky coal and smokeless coal are responsible for the coal-specific disease patterns observed in our study. For example, measurements of NO_2 and SO_2 in XW have suggested that levels of these pollutants are higher after burning

smokeless relative to smoky coal.[15] Ambient levels of these gaseous pollutants have each been associated with risk of IHD in studies conducted in China.[27–29] A previous exposure study in XW also suggested that while concentrations of $PM_{2.5}$ are higher in homes (geometric mean=144 µg/m^3) and personal samples (148 µg/m^3) of individuals who use smoky coal, measurable levels of $PM_{2.5}$ are also detected in the homes (96 µg/m^3) and personal samples (115 µg/m^3) of those who burn smokeless coal in XW.[14] Future-planned analyses in the XW cohort will extend our observations by directly evaluating the associations between type of coal use, levels of indoor air contaminants and risk of all-cause and cause-specific mortality outcomes.

To gain a more contextual understanding of the mortality burden in XW, we compared the rates of mortality for several outcomes to an external Shanghai population consisting of predominately never-smoking women. We found that the overall mortality rate in never-smoking women who used smoky or smokeless coal in XW was higher compared with women in Shanghai. Specifically, rates of total CVD, stroke, IHD, COPD, GI and genitourinary diseases were higher among lifetime smokeless coal users compared with Shanghai, whereas smoky coal users also had higher rates of mortality from lung cancer and pneumonia compared with the Shanghai population. Our analysis comparing rates in XW to Shanghai only focused on women since the vast majority of men in XW (>90%) and in Shanghai (70%) smoked,[30] and therefore the implications of observed differences in mortality rates with respect to the potential influence of coal use would have been uncertain. However, the rates for most outcomes were similar for both men and women who used the same coal type in XW. The Shanghai comparisons further elucidated the unique exposure patterns in XW, and also confirmed the pattern of higher mortality in XW. The previous study that evaluated coal use and mortality in the SWHS found that about 63% of the women in the cohort previously used coal, but only 1% were still using coal at the time of study enrolment.[5] Information on the specific coal type was not available in the SWHS, which precluded stratified analyses by coal type. The SWHS analysis reported an increased risk of all-cause mortality, total cancer mortality and IHD (but not stroke) for ever coal use. Notably, the risks for IHD markedly attenuated as the number of years since last use of coal increased. Collectively, these findings and patterns of coal use in Shanghai suggest that the rate ratios in our paper comparing XW to Shanghai may be conservative estimates of how the health impacts from coal use in XW compare to other regions of China.

A strength of this study is the large cohort for which we had detailed questionnaire data on lifetime fuel use for all residences of the study participants since birth. This provided a unique opportunity to evaluate the burden of mortality among lifetime and exclusive users of the two main coal types used in this region. Given that few women in XW smoke, and the patterns of our descriptive observations were largely similar in men and women, the rates of cause-specific outcomes that we observed in XW are likely to be primarily driven by coal use rather than smoking.

One limitation of this study is that data on coal use was self-reported either by the actual study participants or their surrogates (generally immediate family members). This could lead to recall bias; however, since most of the people who lived in these areas lived there for their lifetime, they are more likely to recall the type of coal they used particularly since this is to a large extent geographically determined based on the location of the residence in relation to the source coal mine. In addition, death certificates were the source of information on mortality in the cohort, which could potentially result in some outcome misclassification. However, the study participants in the cohort all resided within the geographic area of XW where the diagnostic criteria used to determine and code the cause of death are consistent. It is therefore unlikely that outcome misclassification would be differential with respect to the type of coal used in this region.

Finally, the data presented here provide an overview of the patterns and burden of mortality in this population. While the patterns of mortality provide aetiologic hypotheses that can be pursued in future studies, caution is warranted when directly attributing the observed rates to use of coal due to the descriptive nature of the study. For example, the high lung cancer mortality and earlier age at onset that has been attributed to smoky coal use may be due to competing causes of death for other outcomes that artificially lower the mortality rates of other diseases among these coal users, thus leading to challenges in the interpretation of rates among both smoky and smokeless coal users for other mortality outcomes. Other factors such as lifestyle characteristics and access to care may also explain differences in mortality between XW and Shanghai, although are less likely to explain differences among smoky and smokeless coal users in XW given the relatively homogenous population. The findings in this study may also not be generalisable to other low and middle income countries that continue to use coal for indoor cooking and heating, since the specific constituents of the coal in XW may be unique[12] and different patterns of use given the local geography and weather patterns may intensify exposures.

In addition, the XW cohort was comprised of ~95% male ever smokers and ~2% of female ever smokers. Thus, we were unable to evaluate rates in male never smokers or female ever smokers separately and could not confirm results from previous cohort studies in Chinese and Western populations that have suggested the possibility of interactions on an additive scale between air pollution exposure and smoking.[6 31 32] Our additional analysis restricted to male ever smokers and female never smokers yielded comparable results to the overall analysis. In addition, we were also unable to account for the potential influence of secondhand tobacco smoke exposure in our analysis given the high proportion of male

smokers in XW. A previous analysis in XW found that ~95% of women and ~90% of men may have exposure to secondhand tobacco smoke.[33] A similar proportion of male smoky and smokeless coal users smoked tobacco, suggesting that this factor may not have a major impact on the magnitude of the rate ratios comparing smoky and smokeless coal users.

CONCLUSION

In conclusion, this study provides insight on the spectrum and patterns of mortality among lifetime users of smoky and smokeless coal in a region with substantial indoor air pollution exposure in China. Future studies that link data on levels of individual HAP constituents to mortality outcomes in the XW cohort are planned in order to evaluate cause-specific mortality risks among users of smoky and smokeless coal. In addition to these evaluations, elucidating the role of biomarkers may also be informative for understanding potential links between smoky and smokeless coal and chronic disease. Lastly, our results suggest that coal use for indoor cooking and heating should be reduced or phased out entirely where alternative fuel sources exist.

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