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Original Article

Epidemiology of coal miners' pneumoconiosis and its social determinants: An ecological study from 1949 to 2021 in China

Huanqiang Wang[1], Qiao Ye[2], Yun Chen[1], Tao Li[1]

[1] Department of Occupational Respiratory Diseases, National Institute of Occupational Health and Poison Control, Chinese Center for Disease Control and Prevention, Beijing 100050, China;

[2] Department of Occupational Medicine and Toxicology, Clinical Center for Interstitial Lung Diseases, Beijing Institute of Respiratory Medicine, Beijing Chao-Yang Hospital Capital Medical University, Beijing 100020, China.

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ABSTRACT

Background: Pneumoconiosis is the most widely distributed occupational disease worldwide. China is currently the largest coal producer and consumer and the country with the most coal miners and cases of coal workers' pneumoconiosis (CWP). Despite more than 70 years of effort, the problem of CWP and silicosis remains serious. There is a lack of analysis of direct data on coal miners' pneumoconiosis from all over the country. This study aimed to describe the epidemiology of coal miners' pneumoconiosis and reveal some important clues regarding its social determinants.

Methods: The annual incidence rate, 20-year prevalence rate, and incidence rate of coal miners' pneumoconiosis per million tons in China from 1949 to 2021 were calculated by using the data of annual number of coal miners' pneumoconiosis diagnosed and reported from the coal mining and dressing industry, the number of coal miners, and the raw coal production, and the relationship between the incident cases of coal miners' pneumoconiosis and the death toll from coal mine safety accidents was analyzed using Pearson correlation analysis, with the aim of exploring the relationship between the incident cases of coal miners' pneumoconiosis and its social determinants with an ecological study.

Results: From 1949 to 2021, there have been more than 462,000 patients with coal miners' pneumoconiosis in China, showing double U-shaped distributions with an increasing trend, accounting for about 50.5% (462,000/915,000) of all diagnosed pneumoconiosis in China, while the incidencet rate of coal miners' pneumoconiosis presents a large W shaped distribution with three peaks over a time span of more than 50 years. From 1949 to 1986, there was a strong correlation between the incident cases of coal miners' pneumoconiosis and raw coal production, the number of coal miners, and the number of deaths from coal mine accidents ($r = 0.849$, $P < 0.001$; $r = 0.817$, $P < 0.001$; $r = 0.697$, $P < 0.001$, respectively), but there was no such correlation found from 1987 to 2006. It was estimated that the annual incidence rate of coal miners' pneumoconiosis in China from 2016 to 2020 was 3.4‰ (95% CI: 2.6–4.3‰), and the prevalence rate across the recent 20-year observation period was 4.8% (95% CI: 4.6–4.9%), both measured at the peak or around the peak over the 70 years. In particular, 1963, 1986, 2006, and 2009 were the four important turning points in time.

Conclusion: There was a sustained high level of incident cases of coal miners' pneumoconiosis with double U-shaped curve in China, which may be affected by a variety of social determinants and risk factors.

Introduction

Pneumoconiosis is the most widespread and oldest occupational disease in the world and remains one of the major global public health challenges.[1] The Global Burden of Disease Study collected and analyzed the annual number of patients with different types of pneumoconiosis, which occurred in 195 countries and regions worldwide between 1990 and 2017, increasing by 66.0% from 36,186 in 1990 to 60,055 in 2017, wherein the proportion of coal workers' pneumoconiosis (CWP) was 27% and 25%, respectively.[2]

Coal workers are exposed to silica dust, coal dust, the mixed dust of coal dust with silica dust, and other kinds of dust during coal mining due to the different types of work they engage in, which causes coal miners' penumoconiosis, including silicosis, anthracosis, anthracosilicosis,

Correspondence to: Huanqiang Wang, Department of Occupational Respiratory Diseases, National Institute for Occupational Health and Poison Control, Chinese Center for Disease Control and Prevention, Beijing 100050, China

E-mail address: wanghq@niohp.chinacdc.cn

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and other types of pneumoconiosis. Anthracosis and anthracosilicosis are collectively referred to as CWP in China. China is currently the world's largest producer and consumer of coal, accounting for nearly 50% of global coal production and 55% of global coal consumption.[3] The Chinese government and society attach great importance to the prevention and control of pneumoconiosis and have been active in the prevention and control of dust and pneumoconiosis since the 1950s. After many efforts, some achievements have been made, but the problem of pneumoconiosis in China remains serious.[4] By the end of 2021, 915,000 patients with occupational pneumoconiosis have been reported cumulatively in China. There are about 450,000 patients with occupational pneumoconiosis who survive, of which coal miners are one of the main population groups affected, indicating that coal miners' penumoconiosis is currently one of the most serious and most common occupational diseases in China.[5]

At present, the data on the incidence and prevalence rates of CWP in China mainly come from specific regions and enterprises,[6–8] meta analyses,[9] or reanalyses using global disease burden data.[10] In the past five years, the incidence of pneumoconiosis in China has shown a stepped decline, but there are a lot of coal mine mergers and acquisitions, as well as industrial restructuring, which occurred during this period, and the shutdown of a large number of small and medium-sized coal mines has also led to a sharp decrease in the number of coal workers.[11] Considering the delay in the onset of pneumoconiosis and the fact that some retired coal miners will suffer from pneumoconiosis, the prevalence rate of coal miners' pneumoconiosis may have not decreased.

Developed countries had controlled the problem of CWP, but since 2000, the prevalence rate of CWP in the United States has rebounded after nearly 30 years of continuous decline since 1975,[12] while CWP in Australia has rebounded after nearly 30 years of disappearance.[13] Researchers believe that although pneumoconiosis is clearly caused by dust inhalation, numerous other factors, including geological and mining parameters, advancements in mining practices, particle characteristics, and monitoring approaches, are considered to contribute to the recent resurgence of coal miners' pneumoconiosis in some developed countries.[14] Determining the causes of that increase and eliminating occupational lung disease in coal miners is a complex scientific, engineering, medical, regulatory, social, political, economic, and legal problem.[15] Therefore, we need to analyze and dissect this problem from a more macroscopic perspective, for example, by applying the concept and model of social determinants of health (SDH). SDH are conditions in the environment that affect a wide range of health, functioning, and quality-of-life outcomes and risks, and are advocated by the Commission on Social Determinants of Health (CSDH). Work, and its associated conditions, are key SDH.[16] A descriptive ecological study of the historical data and social determinants of coal miners' pneumoconiosis spanning more than 70 years in China was conducted to describe the epidemiology of coal miners' pneumoconiosis and reveal some important clues regarding its social determinants, which may help in the early identification and effective interventions of coal miners' penumoconiosis to reduce the health burden of such incurable diseases.

Methods

Study population

The study population consisted of employees and retired workers in the coal mining and dressing industry in China (the data of Hong Kong, Macao, and Taiwan regions of China were not obtained; the same applies below) from 1949 to 2021, collectively referred to as coal miners. Coal miners' pneumoconiosis includes CWP, silicosis, and other pneumoconioses diagnosed and reported from the study population. In China, the diagnosis of pneumoconiosis is based on a reliable history of exposure to productive dust and on the manifestation of posteroanterior chest radiography with appropriate technical quality.[17] From 1963 to 1985, the diagnostic criteria for silicosis and asbestosis were implemented according to the appendix of the Implementation of Medical Preventive Measures for Workers Exposed to Silica Dust. From 1986 to 1997, the X-ray Diagnostic Criteria and Principles of Treatment for Pneumoconiosis (GBZ5906-1986) were used. From 1998 to 2002, X-ray Diagnosis of Pneumoconiosis (GBZ5906-1997) was used. After 2002, the Diagnostic Criteria for Pneumoconiosis (GBZ70-2002), the Diagnostic Criteria for Pneumoconiosis (GBZ70-2009), and the Diagnosis of Occupational Pneumoconiosis (GBZ70-2015) were used, respectively. The classification system and accompanying standard X-ray films of pneumoconiosis in China after 1986 are similar to the classification system of the International Labour Organization (ILO).[18,19] Pneumoconiosis is caused by a lack of effective management of dust in coal production. There are some causative factors to be shared between the coal miners' pneumoconiosis and the safety accidents in coal mines. Therefore, this paper also compared and analyzed the number of deaths resulting from coal mine accidents over the years and the number of deaths resulting from coal mine accidents per million tons of raw coal, and took the results as a clue to finding and analyzing the sociological factors of pneumoconiosis.

Data sources and measures

The data related to pneumoconiosis before the end of 1986 were obtained from the National Epidemiological Survey on Pneumoconiosis from November 1987 to June 1990 in China.[20] The number of pneumoconiosis cases that occurred each year after 1986 was obtained from the national data reported on occupational diseases, specific survey reports on pneumoconiosis, annual reports of national health statistics, and data from the published literature.[21,22] The occupational disease reporting system in China was founded in 1985 based on the National Epidemiological Survey methods and research data regarding pneumoconiosis from 1949 to 1986, and the format and method of pneumoconiosis reporting were specified and unified in the form of tables.[23]

The term coal miners refer to the employed workers at the end of each year, as well as retired workers, in the coal mining and dressing industry. The data for employed workers and raw coal production were derived from the national statistical yearbooks and statistical bulletins (https://data.stats.gov.cn/), the China Labour Statistical Yearbooks, the China Energy Statistical Yearbooks (https://www.yearbookchina.com/), CEIC Data (CEIC) (https://www.ceicdata.com/zh-hans/china/coal), and academic publications.[24,25] Some pneumoconiosis patients were diagnosed after their retirement, and the number of retired workers is required to calculate the incidence rates and prevalence rates of pneumoconiosis. The number of retired coal workers was estimated based on the ratio of the population over 60 years of age to those aged 15–59 years in the general population multiplied by the total number of employed coal workers in a given year. The proportions of the number of people per age group were obtained from various censuses and national statistical yearbooks of each year. The annual death toll from accidents in coal mines came from the annual reports of the former State Administration of Work Safety and the published literature.[26,27]

Statistical analysis

The proportion of pneumoconiosis in coal mining and dressing to the overall reported (%) = 100% × number of patients with pneumoconiosis who are coal miners in the coal mining and dressing industry/number of pneumoconiosis cases reported in all industries. The incidence rate per 1000 coal miners (IRPM) = 1000‰ × number of newly diagnosed pneumoconiosis patients in the current year/(number of employed coal workers + number of retired coal workers). Pneumoconiosis is usually a chronic disease with an onset cycle of generally 15–20 years. Assuming that the prevalence rate is estimated based on 20 years as the observation cycle, the prevalence rate per 100 coal miners (PRPM) = 100% × 20 × the cumulative number of coal miners with pneumoconiosis over 20 years/cumulative number of person-years

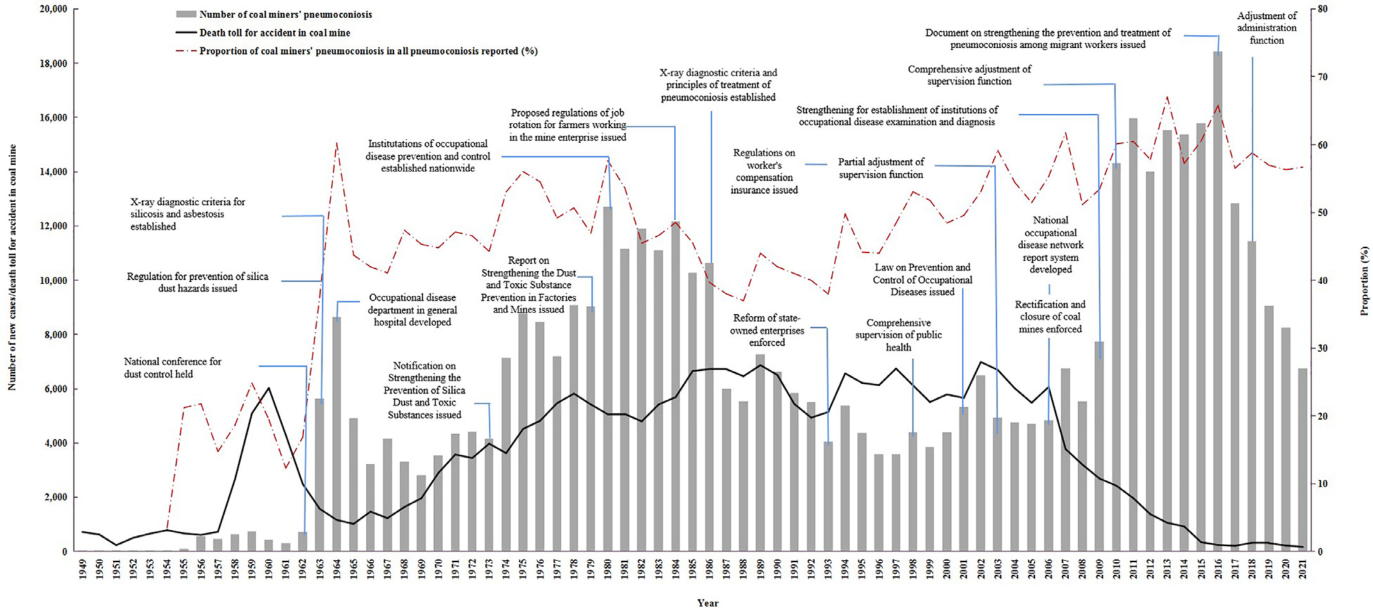

Fig. 1. Number and proportion of pneumoconiosis cases diagnosed in the coal mining and dressing industry and death toll from accidents in coal mines and milestones from 1949 to 2021 in China. For details of the milestones, please see Supplementary Table 1.

observed in coal miners over 20 years, in which the number of person-years observed included both employed coal workers and retired coal workers. The incidence rate of pneumoconiosis per million tons of raw coal (IRPPMT) = the number of pneumoconiosis cases in coal miners/production of raw coal (million tons). The average incidence rate of pneumoconiosis per million tons of raw coal (AIRPPMT) = the accumulative number of pneumoconiosis cases in coal miners/accumulative production of raw coal (million tons). The death rate per million tons (DRPMT) = deaths from coal mine accidents/production of raw coal (million tons). All statistical procedures were performed using IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA). Pearson correlation analyses were used for continuous variables with normal or near-normal data distributions. All statistical tests were two-sided at a significance level of 0.05.

Results

Temporal changes in the incident cases of coal miners' pneumoconiosis and the death toll for accidents and milestones

From the founding of the People's Republic of China in 1949 to 2021, there have been more than 462,000 coal miners' pneumoconiosis in China, accounting for about 50.5% (462,000/915,000) of all diagnosed cases of pneumoconiosis, however, this proportion was only 18.5% (4082/22,106) before 1962. The proportion dramatically increased to 60.3% (8633/14,324) in 1964, after which, although fluctuating, it has been higher than 37% and has remained around 60.0% (127,452/212,547) in the past ten years. Fig. 1 also shows the changes in the incident cases of coal miners' pneumoconiosis with an increasing trend from 1949 to 2021, presenting three distinct wave-by-wave peaks with an increasing trend, which occurred around 1964, 1980, and 2016, respectively.

Fig. 1 further shows the changes in the number of coal miners who died from coal mining accidents in each year. Before 1987, there was a strong positive correlation between the incident cases of pneumoconiosis and the death toll from accidents in coal mines (n = 38, r = 0.697, P < 0.001), and the increase and decline in the incident cases of pneumoconiosis lagged behind the increase and decline in the death toll from accidents in coal mines. When the death toll continued to remain historically high between 1987 and 2006, the incident cases of pneumoconiosis remained historically low, and the correlation between the two was not statistically significant (n = 20, r = 0.368, P = 0.110). There was an inverse correlation between the incident cases of pneumoconiosis and the death toll from 2007 to 2016 (n = 10, r = −0.879, P = 0.001). After 2016, there was no statistically significant correlation between the incident cases of pneumoconiosis and the death toll (n = 5, r = 0.381, P = 0.530).

According to the 70-year analysis, there was a strong correlation between the incident cases of pneumoconiosis and the raw coal production (n = 70, r = 0.631, P < 0.001) and the number of coal miners (n = 70, r = 0.550, P < 0.001). There were also strong correlations between the incident cases of pneumoconiosis and the production of raw coal (n = 35, r = 0.849, P < 0.001; production of raw coal from 1949 to 1951 is missing) and the number of coal miners from 1949 to 1986 (n = 38, r = 0.817, P < 0.001). From 1987 to 2006, there were no significant correlations (n = 20, r = −0.294, P = 0.208; n = 20, r = 0.198, P = 0.403). After 2006, there was no significant correlation between the incident cases of pneumoconiosis and the production of raw coal (n = 15, r = −0.389, P = 0.151), but there was a strong correlation between the incident cases of pneumoconiosis and the number of coal miners (n = 15, r = 0.543, P = 0.037).

Fig. 1 also marks the milestones of occupational health regulatory system reform, the promulgation and implementation of important policies, as well as regulations and standards related to occupational diseases and institutional construction in China at different time points. For the others, see Supplementary Table 1.

Analysis of the incidence rate of coal miners' pneumoconiosis

Fig. 2 shows the incident rate per 1000 coal miners, the number of employed coal workers, and the estimated number of retired coal workers in the coal mining and dressing industry from 1949 to 2021. It can be seen that the incidence rate of coal miners' pneumoconiosis in China presents a large W-shaped distribution with three peaks over a time span of more than 50 years, with the first trough between 1969 and 1973 and the second trough around 1995. The first peak occurred around 1964 and its duration was very short, with an average incidence rate of 1.8‰ (95% CI: 1.0–2.5‰) from 1961 to 1965; the second peak occurred around 1980, showing a plateau growth, with an average incidence rate of 2.2‰ (95% CI: 1.6–2.7‰) from 1980 to 1985; the third peak began in 2008, lasting longer, increasing rapidly, and reaching its

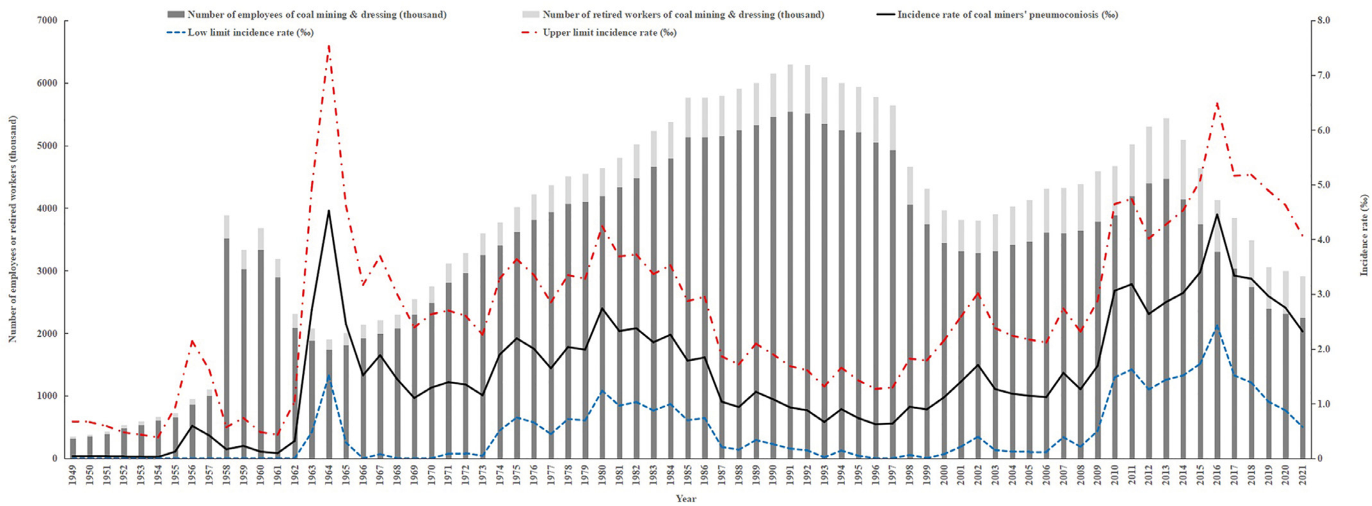

Fig. 2. Number of employed and retired workers in the coal mining and dressing industry and the incidence rate of coal miners' pneumoconiosis from 1949 to 2021 in China.

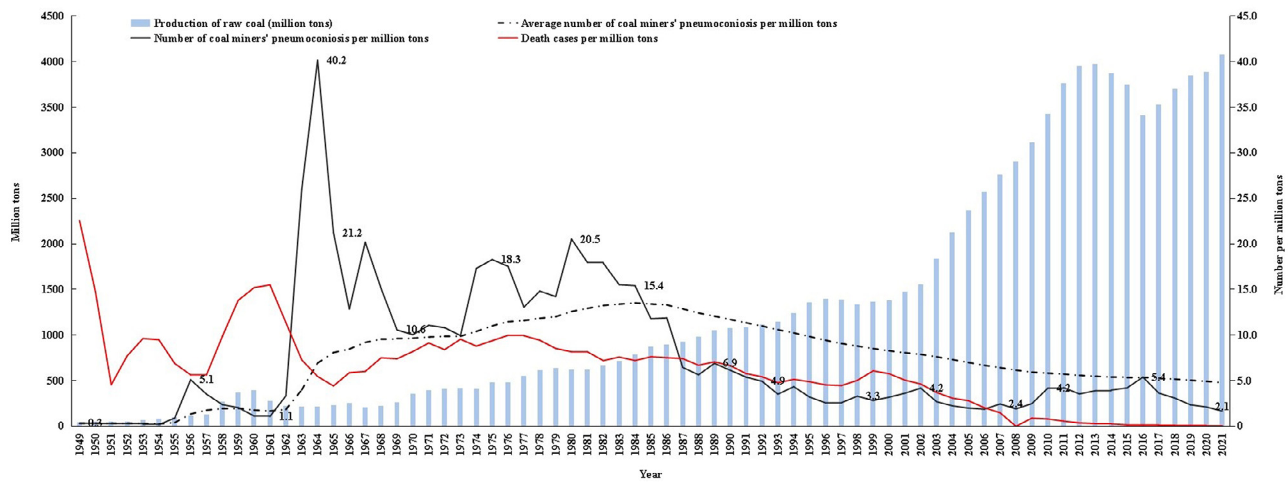

Fig. 3. The production of raw coal, IRPPMT, AIRPPMT and DRPMT from 1949 to 2021 in China. AIRPPMT: Average incidence rate of pneumoconiosis per million tons of raw coal; IRPPMT: Incidence rate of pneumoconiosis per million tons of raw coal; DRPMT: Death rate per million tons.

highest value in 2016, with an average incidence rate of 3.4‰ (95% CI: 2.6–4.3‰) from 2016 to 2020. It has declined rapidly in recent years but remains high. For incidence rate of each year, see Supplementary Table 2.

Analysis of the number of coal miners' pneumoconiosis per million tons of raw coal

Fig. 3 shows the production of raw coal, the IRPPMT, the AIRPPMT and the DRPMT from 1949 to 2021. Since 1949, the production of raw coal in China has been steadily increasing, with accelerated growth taking place after 2001, reaching 4071 million tons by 2021, which is a 100-fold increase from 1949 and a 1.9-fold increase from 2000. Before 1963, the DRPMT was high and fluctuated greatly, and the peak of raw coal production in 1960 corresponded with the second peak of accident-related deaths. The amplitude of the IRPPMT was higher than that of the DRPMT, and the lag in peak time was about five years. From 1962 to 1987, the IRPPMT was high and fluctuated greatly, which was followed by a steady decline in the DRPMT until around 2008, then slowly increased and fell again in 2017, while the DRPMT continued to decline and remained at a historically low level. Before the end of 1984, the IRPPMT curve fluctuated above the AIRPPMT curve, and then declined and remained below the AIRPPMT curve after 1984. It increased slowly after 2008 and reached the AIRPPMT curve with 5.4 incident cases of coal miners' pneumoconiosis per million tons of raw coal in 2016.

A comparative analysis of number and incidence rate of coal miners' pneumoconiosis, number of coal miners, and coal production in different provinces and during different periods

Fig. 4 shows the dynamic changes in the average annual number of pneumoconiosis cases, the incidence rate of pneumoconiosis, the number of coal miners, and the coal production in different provinces and periods from 1949 to 2020 except for 1987 to 1996. Overall, over the past 70 years, with the rapid growth of raw coal production, the number of patients with pneumoconiosis and the incidence rate showed stepped synchronous growth, while the key coal production areas had undergone significant changes. The average annual incidence rate of pneumoconiosis in large coal-producing provinces, such as Shanxi and Shaanxi, increased significantly after 2007. However, when production in Xinjiang increased markedly, the number of coal miners did not increase significantly, and the number of diagnosed patients and the incidence rate declined, while the incidence rate in Inner Mongolia increased in 2017–2020.

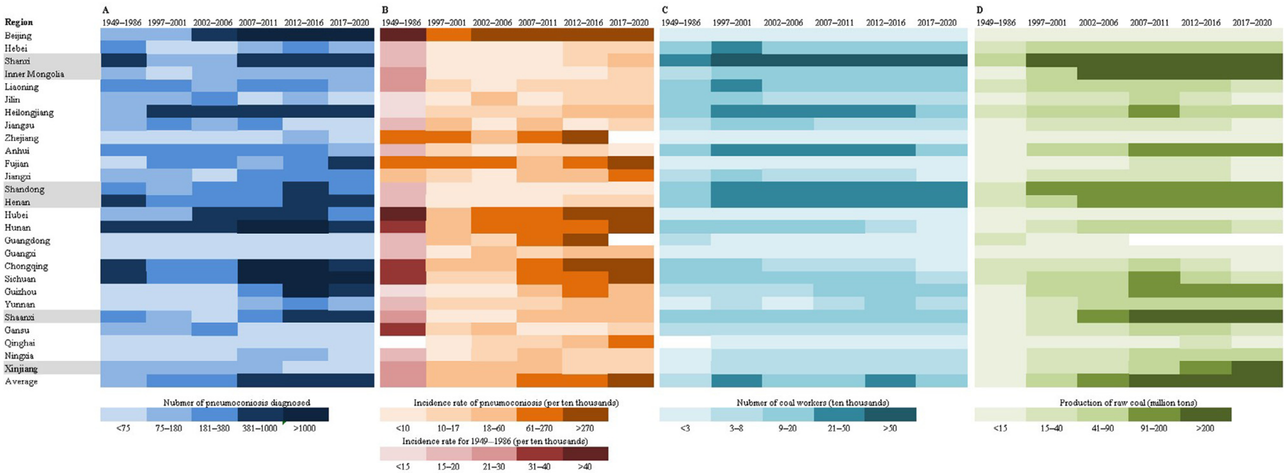

Fig. 4. Heatmaps showing the average annual cases of coal miners' pneumoconiosis diagnosed (A), average annual incidence rate of pneumoconiosis per ten thousand coal miners (B), average annual number of coal workers (C), and average annual production of raw coal (D) in different provinces during six periods from 1949 to 2020. The data from 1987–1996 were not obtained.

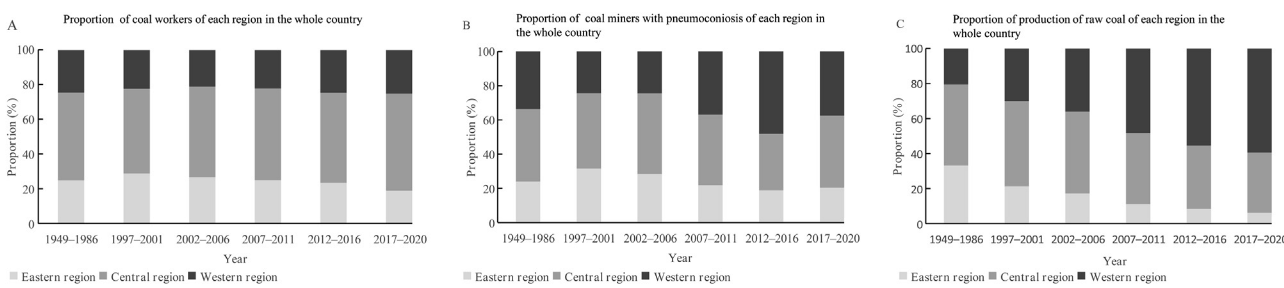

Fig. 5. Proportion of number of coal workers (A), incident cases of coal miners' pneumoconiosis (B) and production of raw coal (C) in eastern, central and western region of China from 1949 to 2020. Eastern region includes 8 provinces (municipalities): Beijing, Hebei, Liaoning, Jiangsu, Zhejiang, Fujian, Shandong and Guangdong. Data of Tianjin, Shanghai and Hainan were not obtained. Central region includes 8 provinces: Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan. Western region includes 11 provinces (autonomous regions, municipalities): Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang. Data of Tibet were not obtained. The data from 1987–1996 were not obtained.

Fig. 5 shows the proportion of coal workers, incident cases of coal miners' pneumoconiosis and raw coal production in the east, middle and west regions of China from 1949 to 2020. The proportion of incident cases gradually decreased with the decrease of the proportion of production of raw coal in the eastern region, while the proportion of incident cases in the western region increased significantly.

Trends in the prevalence rate of coal miners' pneumoconiosis every five years for twenty observed years

Table 1 shows the estimated prevalence rate of pneumoconiosis among Chinese coal workers in different periods from 1949 to 2020. It can be seen that although the prevalence rate fluctuates, it shows an overall growth trend. In recent years, the prevalence rate has been 4.8% (95% CI: 4.6–4.9%), which is the highest in history, exceeding the 3.8% (95% CI: 3.7–3.9%) observed in 1981–1985.

Discussion

Pneumoconiosis is an incurable disease, one of the interstitial lung diseases, which affects not only the patients and their families, but also the society as a whole. Coal miners' pneumoconiosis is not unique to China and is one of the most common occupational diseases worldwide. In 2017, 78 countries in the world reported patients with CWP. To the best of our knowledge, only a few countries worldwide (China, the United States, the United Kingdom, New Zealand, Germany, Finland, etc.) currently have a comprehensive occupational disease data collection system.[28] China regularly publishes data for pneumoconiosis diagnosis reports to the public every year. These data and reports play an important role in evaluating the health risks of dust-exposed workers and the current situation of pneumoconiosis prevention and control at the national and regional levels, as well as formulating national and local pneumoconiosis prevention and control plans in China. Due to a lack of statistical data regarding the number of dust-exposed workers per year in the country, it is almost impossible to accurately estimate the incidence rate and prevalence rate of pneumoconiosis. This paper collected, integrated, and used the data on pneumoconiosis published by the government over the past 70 years, combined with the statistical data on the number of coal miners, raw coal production, and the number of deaths from coal mine safety accidents in the same period to explore the trends in the incidence rate and prevalence rate of coal miners' pneumoconiosis in different time periods, at milestones, and in different regions, as well as the relationship with social determinants and potential risk factors.

Although some studies have analyzed and compared the global trends and regional differences in terms of CWP, it is not easy to compare the incidence rate and prevalence rate of pneumoconiosis among different countries and regions due to differences in definitions and diagnostic criteria, observation cycles, and data sources for pneumoconiosis. The diagnostic criteria for pneumoconiosis in China mainly refer to the classification criteria of the ILO, and the diagnostic methods are comparable. Unlike previous studies, coal workers in this study included both on-the-job and retired workers, and pneumoconiosis included not only CWP, but also other kinds of pneumoconiosis among coal miners, which

Table 1
Estimation of the prevalence rate of pneumoconiosis among coal miners in China at different periods (according to the 20-year observation period).

Time	Number of pneumoconiosis (A)	Number of employees and retired employees (thousand) (B)	Cumulative number of pneumoconiosis patients in the previous 20 years (C)	Cumulative observed person-years in the previous 20 years (thousand) (D)	Prevalence rate of pneumoconiosis (95% CI) (%) (E)
1949–1955	177	3695	177	3695	0.1 (0–0.2)
1956–1960	2870	12,967	3047	16,662	0.4 (0.3–0.5)
1961–1965	20,228	11,500	23,275	28,162	1.7 (1.5–1.8)
1966–1970	17,094	11,950	40,369	40,112	2.0 (1.9–2.2)
1971–1975	28,890	17,804	69,082	54,220	2.5 (2.4–2.7)
1976–1980	46,577	22,299	112,789	63,552	3.5 (3.4–3.7)
1981–1985	56,633	26,206	149,194	78,259	3.8 (3.7–3.9)
1986–1990	36,088	29,630	168,188	95,939	3.5 (3.4–3.6)
1991–1995	25,179	30,620	164,477	108,755	3.0 (2.9–3.1)
1996–2000	19,863	24,378	137,763	110,834	2.5 (2.4–2.6)
2001–2005	26,258	19,701	107,388	104,328	2.1 (2.0–2.1)
2006–2010	39,174	22,293	110,474	96,992	2.3 (2.2–2.4)
2011–2015	76,651	25,511	161,946	91,883	3.5 (3.4–3.6)
2016–2020	59,998	17,522	202,081	85,027	4.8 (4.6–4.9)

C = Cumulative count per 20 years of A, i.e., the sum of the current period plus the previous three time blocks of five years, and that less than 20 years is calculated as the current period plus the previous total. D = Cumulative count per 20 years of B, i.e., the sum of the current period plus the previous three time blocks of five years, and that less than 20 years is calculated as the current period plus the previous total. $E = (20 \times C)/(D \times 1000) \times 100$ (%).

allowed for a more objective and accurate estimation of the incidence rate and prevalence rate of coal miners' pneumoconiosis.

In this study, we estimated that the prevalence rate of coal miners' pneumoconiosis are at their peaks of 70 years now. The prevalence rate of coal miners' pneumoconiosis was similar to that reported in previous studies in state-owned mines in China, lower than the prevalence rate of CWP estimated in the systematic analysis of the literature conducted by Mo et al[9] on data from 2001 to 2011 from China, and significantly lower than the prevalence rate of about 10% of workers who had been exposed to coal dust from 2002 to 2013.[8] If calculated at a dust exposure rate of 74% (57,298/77,122) among coal miners in the sample survey of 83 coal mines in four provinces during 2014–2015 in China,[29] the incidence rate and prevalence rate would both increase by about 35%. There was considerable variability in the prevalence of CWP by country, with estimates ranging from 0.8% to 6.2%. A meta-analysis estimated the prevalence of pneumoconiosis in international coal mines to be 2.29% (95% CI: 2.06–2.51%) from 2011 to 2020.[30] Another paper estimated the overall pooled prevalence of international CWP among underground miners to be 3.7% (95% CI: 3.0–4.5%), with high heterogeneity between studies.[31] Therefore, the relevant departments should include pneumoconiosis in the occupational disease reporting system of migrant workers in order to accurately reflect the incidence rate of pneumoconiosis, and it is necessary to continue to strengthen the prevention and control efforts regarding coal miners' pneumoconiosis.

Based on the experience of controlling pneumoconiosis in developed countries, in addition to effective dust control measures, reducing coal production and the number of coal workers exposed to dust also played a crucial role.[32] However, raw coal production in China has been increasing since 1949, and the number of coal workers had been increasing from 1949 to 1991 and from 2000 to 2013. This study showed that there was a correlation between the number of coal miners' pneumoconiosis and the production of raw coal and the number of coal miners. The higher the production of raw coal, the greater the number of coal miners and those with pneumoconiosis, but these two correlations mainly occurred before 1987, and the correlation between the number of coal miners and incident cases of those with pneumoconiosis also occurred after 2006. At the same time, the number of coal miners' pneumoconiosis before 1987 also maintained a strong positive correlation with the death toll from coal mining accidents and showed a negative correlation after 2006. In addition, the incident cases of pneumoconiosis showed dramatic changes around 1963, 1986, and 2009, indicating that 1963, 1986, 2006, and 2009 were four important turning points in time. We can try to find clues in the changes in the disease at different stages and the important events that occurred around the years of these important turning points.

The occurrence of coal miners' pneumoconiosis is directly affected by the management level of coal mines. Coal dust is both a health and a safety concern. Although there is no national monitoring value of coal mine dust concentration over the years, the annual death toll from coal mine accidents can represent the ability to prevent and control the dust in the coal mine industry to some extent. This study identified the concomitant relationship between the incident cases of coal miners' pneumoconiosis and the death toll from coal mine safety accidents. The patients with coal miners' pneumoconiosis from 1949 to 1986 showed a strong positive correlation with the number of deaths from coal mining accidents, and the peak of the former lagged behind that of the latter, which was in line with the characteristics of pneumoconiosis as a chronic disease. Some provinces with more coal mine accidents or death toll were also areas with higher numbers of incident cases or incidence rate of coal miners' pneumoconiosis, such as Sichuan, Hunan, Chongqing, and Shanxi.[33]

The formation of temporal turning points in 1963 and 1986 may also be related to the changes in diagnostic criteria for pneumoconiosis. In 1963, the criteria for X-ray diagnoses of silicosis and asbestosis were first formulated and issued in China, which were suitable for the diagnosis of CWP as well. As a result, the incident cases of coal miners' pneumoconiosis increased abruptly to 7.7 times (5636/734) that of the previous year (1962), while there were less than 300 cases diagnosed annually before 1962. In 1986, the revised criteria for the X-ray diagnosis and management of pneumoconiosis were developed with reference to the pneumoconiosis classification of the ILO.[17] The diagnosis of pneumoconiosis was based on chest X-ray imaging compared with standard films. Pneumoconiosis cannot be diagnosed if the profusion fails to meet the diagnostic requirements, even if lung function is severely impaired. In 1987, China issued the Measures for the Administration of Occupational Disease Diagnosis,[34] and the diagnosis of pneumoconiosis required employees to visit occupational disease prevention and control institutions or designated medical and health institutions in their respective regions with their letters of introduction and certification documenting their detailed occupational medical history. The revision of the criteria might have an influence on the number of pneumoconiosis cases diagnosed, which showed a decrease in 1987.

The formation of temporal turning points in 2006 and 2009 may be related to the adjustment of coal industry policy and the development of occupational health examination institutions and occupational disease diagnosis institutions. From 2006 onward, with the strengthening safety supervision and management of the coal system, and due

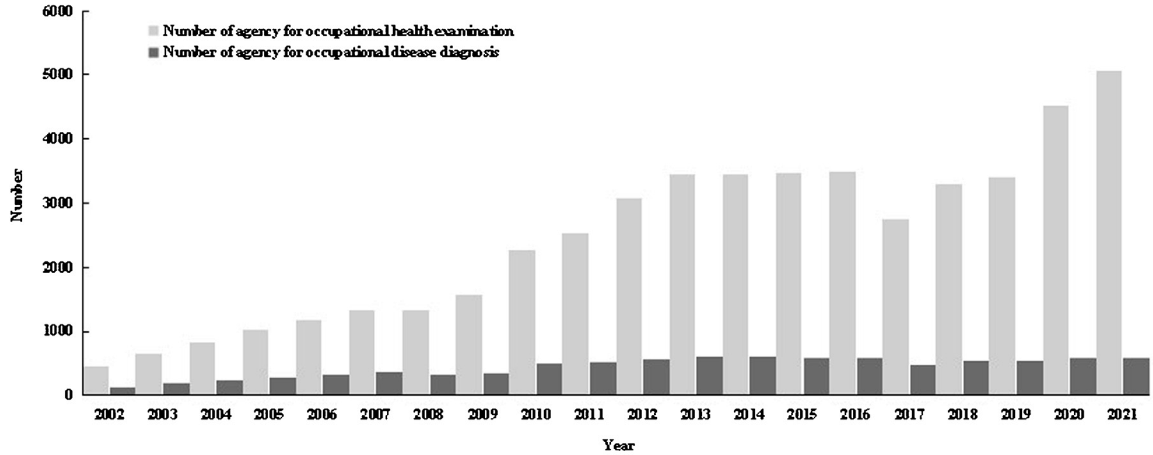

Fig. 6. Number of agency for occupational health examination and occupational disease diagnosis in China, 2002-2021. Data were from the regular press conference of National Health Commission each year.

to the influence of the adjustment of national industrial policies at the same time, the local authorities intensified the integration of coal mine resources, and a large number of small and medium-sized coal mines were cleaned up or closed. The health and social security problems of migrant coal workers have been carefully considered by the national and local governments. A large number of coal workers were found to have suspected pneumoconiosis during the physical examinations when leaving their posts. For example, Chongqing initiated the first coal mine closure in 2009, and the number of pneumoconiosis reports increased by 109% in 2010 compared with that in 2009. By 2019, a total of 989 coal mining enterprises in Chongqing were closed, 113,000 cases of pneumoconiosis were under treatment, more than 23,000 cases of pneumoconiosis were newly diagnosed.[35] In 2009, both the society and the media began to pay more attention to the diagnosis of pneumoconiosis in migrant workers, and the legal and regulatory documents were finally modified to simplify the diagnostic procedures for pneumoconiosis and the requirements for supporting materials.[36] In 2010, with the comprehensive adjustment of the occupational health supervision function of relevant departments by the State Council and the further clarification of the administrative responsibilities of various departments, the occupational health supervision coverage rate and occupational health examination rate increased significantly.[37] At the same time, China began to develop occupational health examination institutions and occupational disease diagnosis institutions according to the National Occupational Disease Prevention and Control Plan from 2009 to 2015, and the number of relevant institutions started to grow rapidly as shown in Fig. 6. Under the comprehensive effect of these factors, the incident cases of coal miners' pneumoconiosis showed blowout growth and remained at an annual average of 9876 cases over the next seven years.

From 1987 to 2006, the death toll from coal mine accidents remained high, while the number of coal miners' pneumoconiosis remained low, and the correlation between the two disappeared. In addition to the influence of the diagnostic criteria for pneumoconiosis, it may also be closely related to the development of township and village coal mines and the massive employment of migrant workers in coal mines. In 1988, there were more than 80,000 township and village coal mines, with more than 2 million employees, accounting for more than 38% (2 million/5.25 million) of all coal workers, most of whom were migrant workers.[38] Many previous surveys have shown that the order of pneumoconiosis hazard degrees is township and village coal mines > state-owned local coal mines > state-owned key coal mines. The dust concentration in some township and village coal mines might exceed the standard, mainly because their production technology is generally lagging behind, and the dust concentrations in these production environments lack control.[39] So, why does the incidence rate of pneumoconiosis remain at a low level during the rapid development of township and village coal mines with potential dust hazards? It might be related to the lack of occupational health examinations of migrant workers. Chen et al[40] reported that from 1986 to 1997 in Shanxi, 94.56% (278/294) of township and village coal mines in the province did not carry out physical examinations of dust-exposed workers. Dust-exposed workers in township and village coal mines accounted for 55.67% of the province (370,689/665,914), while pneumoconiosis patients diagnosed accounted for only 3.09% (635/20,558). At the same time, in order to solve the problem regarding the source of the labor force in the coal industry, the state-owned coal mines employed a large number of migrant workers.[41] In 2007, the results of sampling inspections on three types of coal mines in five provinces of China showed that the physical examination rates of state-owned key coal mines, state-owned local coal mines, and township and village coal mines were 71.71% (10,753/14,996), 48.33% (2401/4967), and 7.14% (50/700), respectively, of which the physical examination rate of township and village coal mines came only from one province, while the township and village coal mines sampled in the other four provinces had no physical examination data available, and three provinces also had no physical examination data for the state-owned local coal mines.[42]

Due to the low rates of occupational health examinations of migrant workers in township and village coal mines and some state-owned coal mines, a large number of pneumoconiosis patients became an invisible group, constituting a U-shaped gap in the number of patients and the incidence rate from 1986 to 2006. Outsourced labor for coal mining is a common trend in the international coal mining industry.[43] Surveys in the United States have also shown that coal miners working in mines with fewer than 50 employees have a higher prevalence rate of CWP compared to coal miners working in mines with 50 and more employees.[44] The incidence rate among coal workers in the United States is also characterized by a U-shaped curve, and whether there are similar causes deserves further investigation. In addition, the number of cases of coal miners' pneumoconiosis has gradually increased since 1998, which is similar to the rebound of CWP in the United States within the time cycle, and whether this is related to the mechanization of longwall coal mines that are widely used in China and the mining of thin coal seams after resource depletion needs further study. Studies in the United States have found that modern mechanization leads to increased underground dust concentration and dispersion and that thin coal seam mining increases workers' exposure to high concentrations of silica dust, which will greatly increase the risk of pneumoconiosis.[45]

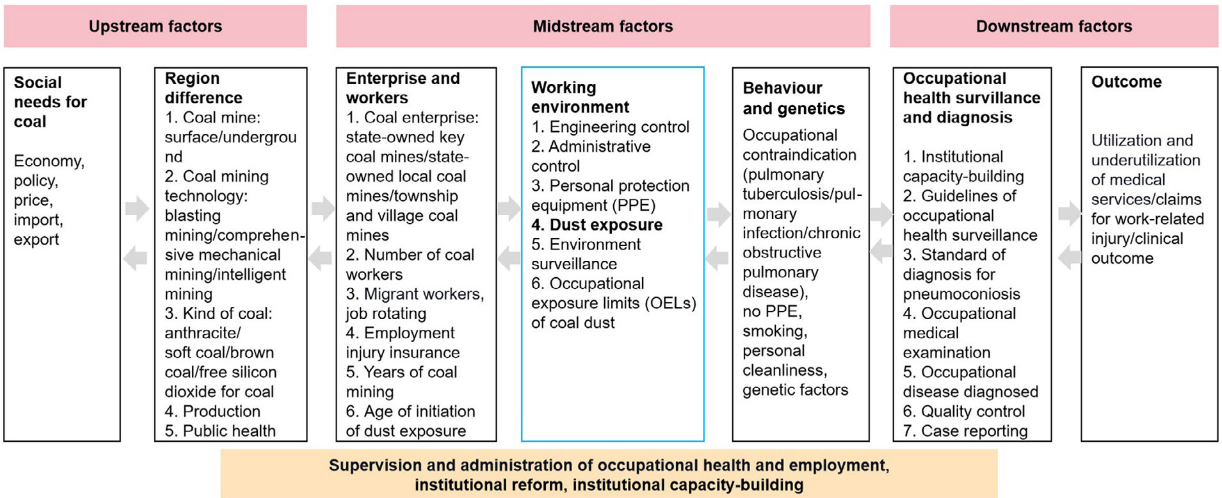

Fig. 7. Framework for social determinants and risk factors for pneumoconiosis among coal miners. The upstream influencing factors include the societal demand for coal, differences in coal mining area locations, coal mine quality and composition, coal mining technology, raw coal production, and regional public health level in coal-producing areas. The midstream influencing factors include enterprise nature (state-owned key coal mines, state-owned local coal mines, township and village coal mines), the number of coal workers, migrant workers, job rotating, purchases of work-related injury insurance, the duration of dust exposure, age of starting dust exposure, the national exposure limit regulations for dust, coal mining dust control technology and measures, management, personal protection, dust exposure, daily dust detection, and other work environment factors, coal workers' own health status, such as whether they have tuberculosis, chronic obstructive pulmonary disease, other lung infections, whether they correctly wear individual protective equipment, smoking, personal hygiene habits, and genetic factors. The downstream influencing factors include the coverage rate and capacity construction of regional occupational health monitoring institutions and diagnostic institutions, relevant standard requirements and quality control, whether workers can receive timely and effective physical examinations and diagnostic services, whether patients can obtain occupational disease reports after a diagnosis, and whether patients can obtain medical services and work-related injury compensation in a timely manner.

In this study, we found that in the past decade, coal production in China has mainly taken place from Shanxi, Inner Mongolia, Shaanxi, and Xinjiang, followed by Shandong, Henan, and Guizhou, but the number of patients and incidence rate were highest in Hunan, Chongqing, Sichuan, Hubei, and Beijing over the years, and their coal production and number of coal workers have not ranked in the front (Fig. 4). The regional distribution of China's raw coal production and the number of pneumoconiosis cases is inconsistent. It can be seen that the occurrence of coal miners' pneumoconiosis is also related to geographic regions and may be mainly affected by certain factors, such as the imbalance in local economic development, the scale of coal mining enterprises and coal mining technology, coal ranks, local policies, and imbalances in the number and capacity of occupational health examinations and occupational disease diagnoses institutions.[46] Sichuan, Chongqing, Hunan, and Hubei were dominated by small and medium-sized coal mines, while Shanxi, Inner Mongolia, Shandong, and Anhui were dominated by large coal mines. Large coal mining enterprises are characterized by their large scale, high level of modern mechanization, great importance given to dust prevention management, and high coal mining efficiency, while the coal mining technology and dust-proof technology in small and medium-sized coal mines are usually backward in their development with a lower efficiency of coal mining.

We know that the mineral type of coal, especially the content of free silica, has a great impact on pneumoconiosis. Different types of coal rank contain different mineral elements, and the high rank coals termed as anthracites are more brittle than medium and low rank coals, usually contain more free silica and produce more nano-sized coal dusts, causing severe lung diseases in coal miners.[47–49] The main production areas of anthracite in China are Shanxi, Henan, Hunan, Guizhou, and Sichuan, and Beijing Jingmei Group was once one of the six major anthracite coal bases in China.[50] The risk of pneumoconiosis caused by anthracite production is higher, which may be one of the reasons for the high incidence rate of coal miners' pneumoconiosis in Hunan, Sichuan, and Beijing. In this study, we found that the number of cases and incidence rate of pneumoconiosis increased during 2007–2016 in the western region of China, which matched the substantial increase in coal production, but there was only a small increase in the number of workers there. It reflected that the local health surveillance and diagnostic reporting network was strengthened and the occupational health supervision and management in coal mines was greatly reinforced during this period. But the proportion of pneumoconiosis cases in western regions in all cases of coal miners' pneumoconiosis in China during 1997–2006 and 2017–2020 clearly did not match the increase and the predominance of the raw coal production. The reason for this needs to be studied further.

It is reported that a total of 813 mine tunnel segments in China were turned into intelligent production facilities in 2021, an increase of 65% compared with that in 2020. Since 2016, the number of workers who need to work underground in coal mines has decreased by 370,000, which will undoubtedly reduce the occurrence of coal miners' pneumoconiosis.[51] According to the national coal energy program, Shanxi, Shaanxi, and Inner Mongolia will become the main supply sites of coal in China in the future.[52] Cases of coal miners' pneumoconiosis may increase, and the capacity of occupational health examination institutions, diagnostic institutions, and regulatory authorities in these areas needs to be further improved. The incidence of coal miners' pneumoconiosis will continue to decrease in the eastern and some central areas because of the general withdrawal from coal production.

In this study, we examined the causes of abnormal depression of the incidence of coal miners' pneumoconiosis during 1987–2008, which may be related to the revised diagnostic criteria and diagnostic system for pneumoconiosis that are stricter in addition to the lack of occupational health monitoring among migrant workers who account for the main body of coal workers. It is, thus, recommended to modify the diagnostic criteria for pneumoconiosis and use pulmonary function parameters as one of the main indicators for diagnosis. In this study, we found that the number of patients and incidence rate of coal miners' pneumoconiosis in China may be affected by a variety of social determinants and risk factors, including societal needs for coal mining, industrial policies, the number of coal workers, the employment systems of countries, regions and enterprises, coal production, the nature of enterprises, enterprise sizes, their determined coal mining techniques and prevention and control measures, occupational health examination coverage rates, pneumoconiosis diagnoses and reporting systems, occupational health supervision and management systems, and social security systems.

In summary, combined with an analysis of the relevant literature and work experience in the prevention and control of coal miners' pneumoconiosis, we tried to draw a pattern diagram in which the number of patients and incidence rate of pneumoconiosis are affected by a variety of social determinants, as shown in Fig. 7. According to the progressive and close relationship of the various influencing factors, it can be artificially divided into three types of influencing factors: upstream factors, midstream factors, and downstream factors. These factors all interact with each other and are directly influenced by national and local occupational health supervision and health promotion work, which are very complex and need to be further studied.

The prevention and treatment of coal miners' pneumoconiosis is an international public health problem that requires multi-sectoral cooperation and gradual solutions. It is required to formulate economic policies for sustainable development and fair public health policies at the national and societal levels, maintain effective hygiene supervision and public opinion supervision, while in some cases, enterprises should be required to adopt advanced coal mining technology and dust-control technology, and others need to require workers to abide by the operating procedures, strictly wear personal protective equipment, and eliminate smoking habits.

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Conflicts of interest

None.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.pccm.2023.03.002.

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