

Progression of Chest X-ray Findings of
Silicosis Among Fluorspar Miners and
Prognostic Factors: Retrospective Cohort
Study in Mongolia

(蛍石鉱山労働者における珪肺症の胸部 X 線
所見の進行と予後因子: モンゴルにおける
後向きコホート研究)

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Ethical considerations and disclosures: The present study was conducted with the approval of the Ethical Committee of the Faculty of Medicine Kyoto University (R2631) and the Medical Science Ethical Committee of the Mongolian National University of Medical Sciences (2021/3-04). Based on the retrospective data, informed consent was waived.

Funding sources: None to disclose.

Conflict of interests: T.N. received consulting fees from Otsuka Pharmaceutical Co., Takeda Pharmaceutical Co., Johnson and Johnson K.K., I&H Co. Ltd., Konica Minolta, Inc., Cocokarafine Group Co. Ltd., NTT DATA, and a research grant from Kyoto University. All of them were outside the submitted work. The other authors have no conflicts of interest to declare.

Availability of data and materials:

The data sets were sourced from the Mongolian Occupational Safety and Health Center (OSHC). However, they are available from the corresponding author upon reasonable request.

Authors' contributions: D.K. performed the conception and design of the work. D.K. and I.D.

performed the data collection, analysis, and interpretation. D.K., B.N., and L.M. evaluated and interpreted the chest radiographs according to the International Labour Organisation International Classification of Radiographs of Pneumoconiosis (ILO ICRP). D.K. performed the drafting of the manuscript. Y.N., M.T., Y.T., and T.N. performed the critical revision of the article. T.N. supervised the study. All authors read and approved the final version of the manuscript.

The study adhered to the STROBE guidelines.

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Abstract

This study investigated the natural course of silicosis among fluorspar miners after the cessation of the dust environment, which has been unstudied until now. The findings of this study extend the overall understanding of silicosis's flow up after dust cessation and prognostic factors for the progression of silicosis.

Objective

This study aimed to delineate the natural progression of silicosis in fluorspar miners after the termination of dust exposure and identify its prognostic factors.

Methods

This retrospective cohort study, conducted from 2000 to 2019, included 67 former miners. Radiological images were evaluated by comparing the initial and most recent radiographs using the International Classification of Radiographs of Pneumoconiosis. Cox multivariate proportional hazard models were used to estimate the hazard ratios using follow-up time to analyze the multivariable study of associated prognostic factors.

Results

Among the participants, 50 (75%) exhibited progression over 2 to 16 years (median, 5.8 years). The Cox analysis highlighted older age as a likely precursor to the progression of significant opacities. Additionally, higher International Labour Organization category grades at onset were associated with disease progression.

Conclusions

Nearly three-quarters of the miners diagnosed with silicosis demonstrated radiological progression even after the termination of dust exposure. Advancement in age and the degree of initial radiological opacity were associated with progression.

Keywords: silicosis; dust; exposure; radiologic; progression; miners

Visual abstract

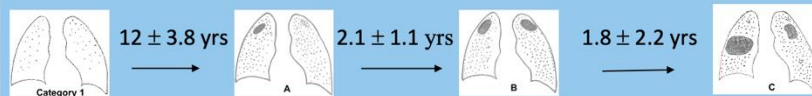
The prevention of silicosis and the importance of monitoring it over time

ILO International Classification of Radiographs of Pneumoconiosis was used for the evaluation of the chest radiographs.



Small opacities:
Categories 1 to 3
Large opacities:
A: < 50 mm
B: 10 mm > right
upper zone
C: area > right
upper zone

The former Mongolian fluorspar mine workers followed up 1-16 (median 4.6) years. The notable difference in progression time with the severity of ILO classification underscores the importance of early detection of silicosis and prompt cessation of dust exposure.



Approximately 75% of the miners diagnosed with silicosis demonstrated radiological progression even after the termination of dust exposure.

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LEARNING OUTCOMES

After reading this article, the reader will be able to:

- Gain a comprehensive understanding of the flow of silicosis among previously unstudied cohorts of underground fluorspar miners and workers in fluorspar concentrate-processing facilities
- Outline that occupational health strategy should focus on the primary prevention and early detection of silicosis by collaborating at each responsible level to eliminate dust exposure risk in the workplace.

INTRODUCTION

Silicosis is a persistent occupational disease resulting from inhaling dust containing free crystalline silica particles, primarily smaller than 5 μm , commonly found in rock, sand, and soil. Industries including mining, tunneling, quarrying, and manufacturing, spanning from glass and ceramics to dental prostheses and denim sandblasting, bear significant consequences.^{1–6}

Despite preventive measures, silicosis remains a widespread health and economic challenge worldwide, affecting developed and developing nations. The “Hawks Nest Tunnel disaster” in West Virginia stands as one of the most severe industrial accidents in United States history, claiming 764 lives to silicosis.⁷

A collaborative effort by the World Health Organization and the International Labour Organization (ILO) in 1995 aimed to eliminate global silicosis by 2030.^{8,9} Although silicosis rates have improved in the United States and Europe, significant problems persist, such as in parts of Appalachia and among engineered stone countertop workers.^{4,10} Moreover, there are concerns regarding the resurgence of crystalline silica exposure as a traditional occupational respiratory hazard.

Mongolia, situated in Central Asia, has a population of approximately 3.2 million as of 2022, with about half residing in the capital, Ulaanbaatar. Historically, cattle raising has been the primary industry; however, mining has emerged as the most significant economic sector, yielding copper, gold, coal, and other commodities. The surge in demand for natural mineral resources has propelled Mongolia's mining industry, profoundly impacting its economy. Presently, mining contributes to 22% of Mongolia's Gross Domestic Product (GDP) and constitutes over 90% of its exports. With approximately 60,000 workers employed in private joint venture mining firms, concerns regarding dust exposure and escalating rates of occupational lung disease have heightened.¹¹

Despite studies uncovering the factors contributing to the rapid progression of silicotic progressive massive fibrosis (PMF), a comprehensive understanding of the natural progression of silicosis remains elusive.^{12,13} Numerous studies have examined the progression of silicosis after cessation of exposure across various occupations, from slate pencil workers and iron ore miners to denim sandblasters and ceramic workers.^{5,6,14–22} Nonetheless, silicosis remains uncharted among fluorspar miners in Mongolia.

This novel study ventures into this unexplored domain and delves into the natural progression of silicosis in fluorspar miners and workers in fluorspar concentrate–processing facilities after

exposure cessation. Furthermore, our study aimed to determine whether prognostic factors are identifiable and underscores the importance of monitoring chest x-ray changes over time, particularly once exposure to crystalline silica dust is terminated.

MATERIALS AND METHODS

Study Design and Settings

Mongolia is bordered by Russia to the north and China to the south, and the majority of the land consists of plateaus, mountains, and steppes. There are substantial deposits of fluorspar in the southeastern region of Mongolia, leading to the establishment of various mining and fluorspar concentrate processing factories. Founded in 1981, the largest underground fluorspar mining company began operations in 1985. This company produces approximately 700,000 tons of metallurgical fluorspar annually, which is used in steelmaking and chemical production.

The mined fluorite ore undergoes extraction and surface transport, followed by sorting and processing into powdered form in the factory. Whereas most of the factory employees in the sorting section are women, all underground miners are men. The former fluorspar mine workers diagnosed with silicosis have been following up at the Occupational Safety and Health Centre (OSHC) of Mongolia.

Eligibility

Participants were included in this study if they had a documented history of silica exposure and chest radiography indicating a profusion rate of at least 1/0 as per the ILO International Classification of Radiographs of Pneumoconiosis. The exclusion criteria included those with initial chest radiographs revealing the largest opacity (category C) and those lacking two chest radiographs.

Data Collection

Patient medical reports from January 2000 to 2019 were sourced from the OSHC. After being diagnosed with silicosis, these individuals were no longer exposed to occupational dust. The patients' data included occupational history, age, smoking status, treatment history, and spirometry readings FVC (Forced vital capacity) and FEV₁ (Forced expiratory volume in the first second). From the OSHC archives, chest X-rays of each patient were analyzed by two radiologists and an

occupational health physician, all trained in the ILO International Classification of Radiographs of Pneumoconiosis methodology at OSHC, Mongolia, and two of them are certified readers of the Asian Intensive Reading of Pneumoconiosis (Air Pneumo). Disagreement between readers was resolved through consensus.

Radiological Assessment

Radiographs were read side by side and benchmarked against the ILO's standard 22 radiographs.^{23–}

²⁵ The profusion of small opacities is classified into four categories (0, 1, 2, 3), each of them containing 3 sub-categories total of 12 subcategories (0/-, 0/0, 0/1; 1/0, 1/1, 1/2; 2/1, 2/2, 2/3; 3/2, 3/3, 3/+). The study primarily focused on the radiographic progression of silicosis and evaluated the changes in profusion rates of small opacities of two or more subcategories (such as from 1/1 to 2/1 or 1/2 to 2/2), the emergence and increase in size of large opacities (A, B, and C categories), and progression timelines. Large opacities exceeding 10 mm were considered PMF. The development and growth of PMF in the lungs lead to consequences, such as deterioration of respiratory failure and complications of tuberculosis, as well as necrosis and cavities in lung fibrosis.

Statistical Analysis

Descriptive analysis was used to evaluate participant characteristics, radiograph intervals, and lung function metrics. Radiological progression was analyzed in patients with a minimum 1-year follow-up. The χ^2 , *t*-test, and Kruskal-Wallis tests were employed. Cox multivariate proportional hazard models were used to estimate the hazard ratios (HRs) using follow-up time to analyze associated prognostic factors. The level of significance of the study was set at $P < 0.05$. IBM SPSS Statistics 29 for Mac was the software used for the statistical analyses.

Ethical Consideration

The present study was conducted with the approval of the Ethical Committee of the Faculty of Medicine Kyoto University (R2631) and the Medical Science Ethical Committee of the Mongolian National University of Medical Sciences (2021/3-04). Based on the retrospective data, informed consent was waived.

RESULTS

Participants Characteristics

Among the 76 patients with confirmed silicosis between 1997 and 2019, 67 with serial chest radiographs of acceptable quality were included. Silicosis was diagnosed among men starting in 2007 and among women in the factory section in 2014, regularly (Fig. 1). The follow-up time was 1 to 16 (median, 4.6). During follow-up, six cases were excluded because serial chest radiography was not available, and three cases died for reasons unrelated to silicosis. All cases of silicosis were diagnosed among underground miners and factory workers.

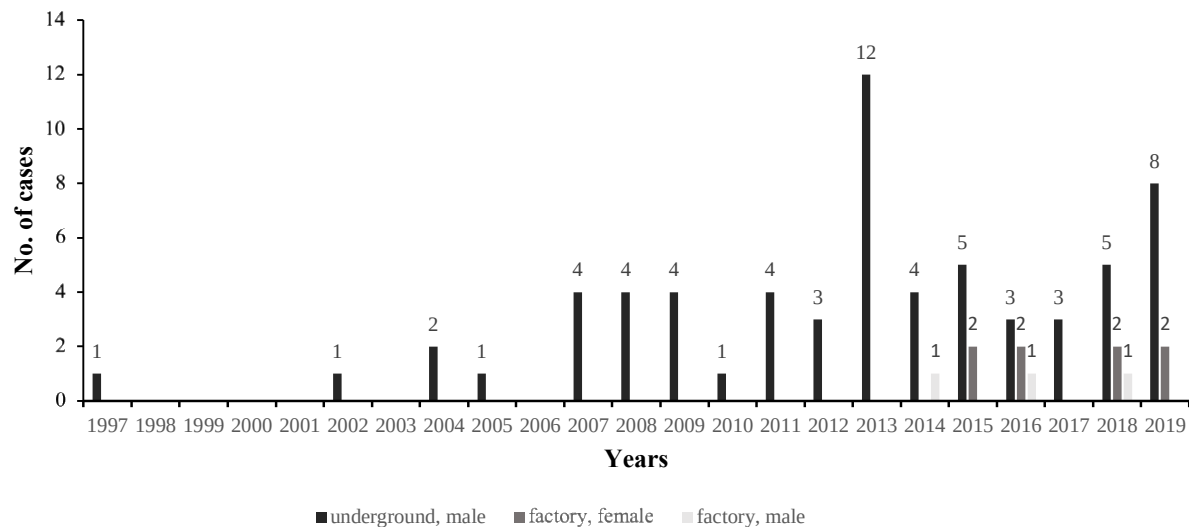


FIGURE 1 Cases of silicosis by year of diagnosis (1997-2019)

An underground mine is a closed space that plays a crucial role in wet technology and is an appropriate ventilation system. Silicosis was diagnosed among 33 (49%) perforators and 23 (34%) drillers in underground mines. Perforators drill spurs (diameter, 3.2–4.8 cm; depth, 1.5–2.2 m) with handheld drills to detail the location of underground fluorspar ores and access ore bodies in horizontal, inclined, and vertical directions in underground mines, along with its laying a road to the shaft. The next operation is for deep drillers to follow the fluorspar ore vein and drill four to six holes based on its width at 2.5-m intervals, using stationary drills from 4.5 to 12 m, preparing for the blasting. The sorting section of the processing factory is an open space that continuously spins a conveyor belt, from which fluorspar ores are sorted by hand. The diagnosed cases of

silicosis in the underground miners were all (56, 84%) men; the processing factory had eight (12%) women and three (4%) men.

The incidence of tuberculosis for underground workers was 9 (16%), whereas smoking was observed in 43 (76%) underground workers and 2 (18%) male factory workers. The mean duration of dust exposure was 12 (SD, 2.8), 21 (SD, 5.1), and 16 (SD, 3) years for underground mine workers, male processing factory workers, and female workers, respectively ($P = 0.001$). The mean age at the initial chest radiograph was 35 (SD, 3.4), 42 (SD, 7.5), and 40 (SD, 3.9) years for underground workers, male processing factory workers, and female workers, respectively ($P = 0.007$) (Table 1).

TABLE 1 Characteristics of the study participants (n=67)

Characteristics	Underground male n (%)	Factory male n (%)	Factory female n (%)
Workers	56 (83.5)	3 (4.5)	8 (11.9)
Anamnesis of tuberculosis (presence %)	9 (16.1)	0	0
Smoking (presence %)	43 (76.8)	2 (18.2)	0
	(mean $\pm$ SD)		
Age at the start work	21.5 $\pm$ 3.9	21 $\pm$ 2.6	24.7 $\pm$ 4.6
Duration of dust exposure	12.3 $\pm$ 2.8	21.6 $\pm$ 5.1	16.0 $\pm$ 3
Age at the initial radiography	35.4 $\pm$ 3.4	42.6 $\pm$ 7.5	39.8 $\pm$ 3.9
Age at the most recent radiography	42.4 $\pm$ 4.7	47.3 $\pm$ 5.5	43.7 $\pm$ 5.3
Forced Vital Capacity (FVC) (L)			
At the first visit	3.7 $\pm$ 0.7	2.5 $\pm$ 0.1	2.5 $\pm$ 0.7
At the most recent visit	3.4 $\pm$ 0.8	2.0 $\pm$ 0.1	2.4 $\pm$ 0.7
Forced Expiratory Volume in the first second (FEV ₁) (L)			
At the first visit	2.9 $\pm$ 0.6	4.0 $\pm$ 0.1	2.3 $\pm$ 0.6
At the most recent visit	2.6 $\pm$ 0.7	3.0 $\pm$ 0.8	2.1 $\pm$ 0.6

The duration of dust exposure was calculated for underground miners and classified by categories and cases of silicotuberculosis. The duration of dust exposure increased slightly with the severity of ILO classification. For category 1, the dust-exposed years were 11 (SD, 1.6); category 2, 12 (SD, 2.9); category 3, 13 (SD, 2.5); and large opacities were 14 (SD, 3.7); and the duration of dust exposure for cases associated with tuberculosis (silicotuberculosis) was 8 (SD, 1.1) years ($P = 0.07$).

Radiological Progression

Among the 67 participants who underwent serial chest radiography, 50 (75%) progressed through 2 to 16 years (median, 5.8 years), and 17 (25%) did not progress. The profusion of small opacities in initial category 1 was 10 (15%); category 2, 38 (56%); and category 3, 13 (19%), and large opacities were diagnosed in six participants (8%). Most cases of silicosis were diagnosed at the level of category 2 (56%). At the most recent visit, the chest x-ray film category was changed from the initial category to higher categories as follows: category 1, 1 (1%); category 2, 16 (24%); category 3, 21 (31%); and large opacities, 29 (43%) (Table 2). Among the 50 (75%) progressive cases, 42 showed radiographic progression in the major category. Figure 2 depicts the steps of radiological progression by year for each 42 patients. We calculated the mean duration of progression through overall major categories: from category 1 to categories 2 and 3, 3.1 and 5.10 years, respectively; from category 2 to category 3, 5.7 years; from category 3 to the large opacity, 5.1 years. The two- and three-step progressions from category 1 to the development of large opacity and from category 2 to large opacity were 12 and 6.6 years, respectively. The mean duration of progression among large opacities was calculated for 11 cases. The progression time between large opacities was short at 2.1 and 1.8 years, respectively ($P=0.05$) (Table 3).

TABLE 2 Chest radiography profusion rate by ILO classification at the initial and the most recent visits (n=67)

		Follow-up changes								
		Initial cases*	Lost follow-up	Initial visit	Small opacity category			Large opacity category (PMF)		
ILO classification		n (%)		n (%)	1	2	3	A	B	C
Small opacity category	1	12 (16)	2	10 (14.9)	1	2	3	3	..	1
	2	45 (60)	7	38 (56.7)	..	14	12	6	5	1
	3	13 (17)	..	13 (19.4)	..	..	6	4	3	..
Large opacity category (PMF)	A	4 (5)	..	4 (5.9)	..	..	..	..	3	1
	B	2 (2)	..	2 (3)	..	..	..	..	..	2
Total		76	9	67	1 (1.5)	16 (23.8)	21 (31.3)	13 (19.4)	11 (16.4)	5 (7.4)

*Nine cases (category 1, 2 cases; category 2, 7 cases) were excluded because only a single chest X-ray was available.

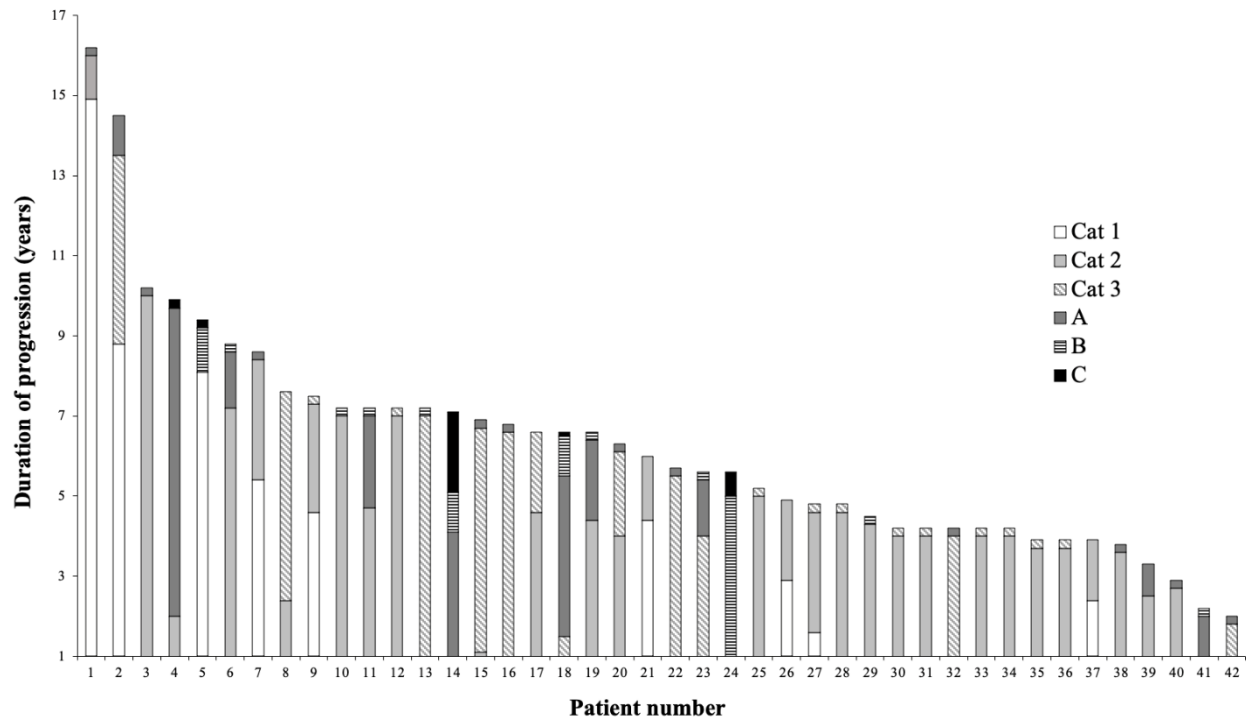


FIGURE 2 Duration of radiographic progression in each patient (n=42)

TABLE 3 The mean time of radiographic progression into a major category (n= 42)

ILO classification	N[‡]	Mean progression years (Year ± SD)	Ranges (Years)
Category 1 to 2	3	3.1 ± 1.0	2.4 - 4.4
Category 1 to 3	2	5.10 ± 1.3	4.6 - 7.1
Category 1 to large opacities	4	12 ± 3.8	8.4 - 15.10
Category 2 to category 3	11	5.7 ± 2.0	3.7 - 10.0
Category 2 to large opacities	12	6.6 ± 2.10	2.7 - 13.11
Category 3 to large opacities	7	5.1 ± 1.9	1.8 - 6.10
A large opacity to B large opacity [†]	7	2.1 ± 1.1	1.1 - 4.1
B large opacity to C large opacity [†]	4	1.8 ± 2.2	0.11 - 5.0

[†] calculated between the 2-step and 3-step into major progression

[‡] Among the 67 patients that had radiographic progression, 42 had radiographic progression in a major category

Figures 3 to 5 show the radiography changes between the initial and last visits of the radiological progression of silicosis in three different cases.



FIGURE 3 A 33-year-old underground perforator who worked 12 years was diagnosed with silicosis. The chest radiography progressed from the initial ILO 2/2 q/q category to the large opacity B category with a progression time of 7 years.

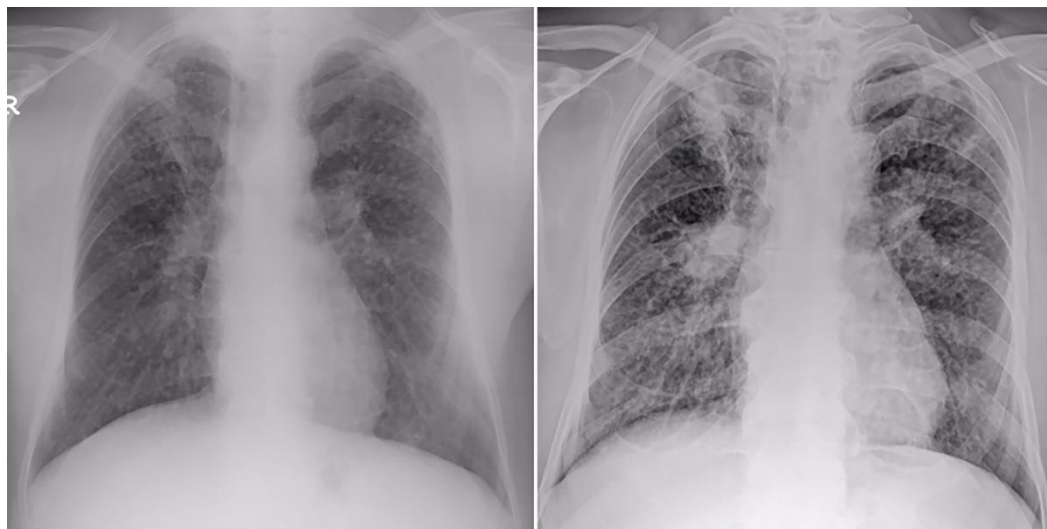


FIGURE 4 shows a 41-year-old factory worker with 16 years of dust exposure, and chest radiography progressed from the initial ILO 3/2 q/q category to the B large category with a progression time of 7 years.

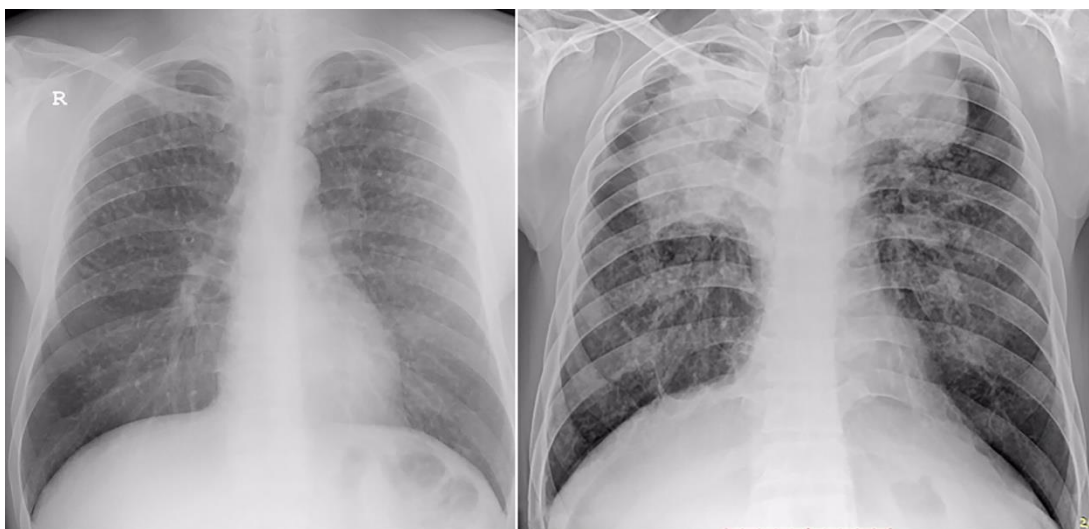


FIGURE 5 shows a 32-year-old underground perforator with 13 years of dust exposure whose small opacities 2/3 q/q progressed into the large opacity C category over a progression time of 6 years.

Cox Multivariate Proportional Hazard Models for Radiological Progression of Silicosis

Increasing age was significantly associated with the radiological progression of silicosis (HR, 1.14; 95% confidence interval [CI], 1.02–1.27; $P = 0.02$) and was two times more likely (HR, 2.07; 95% CI, 1.02–4.19; $P = 0.04$) in those with profusion category 3 on the initial chest radiograph than in those with profusion categories 1 and 2 (Table 4).

TABLE 4 Cox regression analysis for radiological progression of silicosis (n=67)

Variables	HR	95% CI	P value
Factory	reference		
Underground mine	1.62	0.52 to 5.03	0.39
Tuberculosis	0.44	0.16 to 1.18	0.10
Duration of dust exposure	0.95	0.83 to 1.09	0.52
Smoking	0.74	0.32 to 1.68	0.47
Age	1.14	1.02 to 1.27	0.02
ILO category 1 and 2 at the initial visit	reference		
ILO category 3 at the initial visit	2.07	1.02 to 4.19	0.04

This study analyzed prognostic factors associated with the development and increase in large opacities or PMF. Progression to PMF was significantly associated with the greater ILO category at the initial visit (HR, 6.66; 95% CI, 2.31–19.23; $P = 0.001$) (Table 5).

TABLE 5 Cox regression analysis for the large opacities (n=67)

Variables	HR	95% CI	P value
Factory	reference		
Underground mine	0.75	0.19 to 2.92	0.67
Tuberculosis	0.82	0.23 to 2.95	0.76
Duration of dust exposure	1.01	0.84 to 1.22	0.84
Age	1.14	0.98 to 1.32	0.08
Smoking	0.75	0.24 to 2.39	0.63
ILO category 1 and 2 at the initial visit	reference		
ILO category 3 at the initial visit	6.66	2.31 to 19.23	0.001

DISCUSSION

To the best of our knowledge, our study from Mongolia is the first to follow changes in the chest radiographs of fluorspar miners diagnosed with silicosis after silica exposure. Among all cases, 75% demonstrated radiological progression within a period spanning 2 to 16 years (median, 5.8 years) after cessation of dust exposure. The prevalence of large opacities increased from 9% to 43% during follow-up. The risk of progression of large opacities was six times higher in those with a higher profusion category on the initial chest radiograph than in those with lower profusion categories.

Previous reports indicate the radiological progression of silicosis across various work environments. The progression rates observed in this study were higher than those observed in granite, slate pencil, iron mine, tunnel, coal, and ceramic workers (24%–62%) and second only to the progression rate (82%) observed in denim jeans workers.^{5,6,14–22} These studies showed similar results related to the average progression time, which varied according to the initial ILO category.^{5,20,22} Our findings regarding the progression time between silicosis opacities are consistent with those of studies on ceramic workers in Turkey and tunnel workers in Japan. The

notable difference in progression time between the lower and higher ILO categories underscores the importance of early detection of silicosis and prompt cessation of dust exposure.

The prevailing misconception among the local Mongolian population is that only male underground miners develop silicosis. Although silicosis has been concerning among male miners, it has also been diagnosed in processing factory workers, including women, since 2014. In our study, the number of diagnosed cases of silicosis in female factory workers was eight (12%), and the duration of dust exposure and age at initial diagnosis was shorter than those of male factory workers. The patients in previous studies that evaluated the radiological progression of silicosis were all men. Studies including female miners discovered very few cases of silicosis in the mining industry; most cases were diagnosed in nonmining sectors such as ceramics and pottery.^{26,27} An autopsy study of deceased South African miners observed no differences in silicosis and tuberculosis prevalence between women and men.²⁶ A study of 642 female ceramic workers in Italy indicated nine cases of silicosis; the dust exposure years and age were correlated with the diagnosis.²⁷

Studies have shown that underground miners are at a higher risk of developing silicosis and pneumoconiosis than other workers.^{28–30} Our findings are consistent with those of studies involving miners from Kiruna and pyrophyllites in Japan.^{15,31} Although our observations regarding age at the start and diagnosis align with studies involving miners from Kiruna,¹⁵ our operational similarities and radiographic findings resonate with studies including pyrophyllites in Japan.³¹

Cox multivariate proportional hazard models have only indicated a greater likelihood of radiological progression with increasing age and radiological profusion rate on the initial chest radiograph.^{5,16,17,20,32} Our study showed a higher probability of progression by two times in those with category 3 at the initial visit. Therefore, the study on the granite quarry workers revealed a higher probability of radiological progression of silicosis by five times in category 3 at the initial visit and 20% increased odds of progression for every additional year of follow-up. The study on ceramic workers showed a higher probability of progression by 3.5 times in those with profusion categories 2 and 3 on the initial radiography and with the increased age.^{17,22} Most studies found evidence that silicosis is progressive over time, and a longer follow-up time is more likely to be associated with the progression of silicosis.^{5,14,17,18,20,22,32,33} There was no significant association with sex, history of tuberculosis, and workplace, which was along with other studies. Several

studies, including ours, have not revealed a significant association between smoking habits and silicosis progression.^{14,18,20,22}

The importance of early detection of silicosis among workers is proved in our study; category 3 at the initial visit had a higher probability of further development of PMF by six times. It is pertinent to note that the onset of large opacities is an ominous sign linked to heightened mortality and morbidity.^{12,21} The onset of large opacities is associated with increased mortality and morbidity. Exposure to silica dust, as is evident in several professions, is instrumental in the development of these opacities. Our findings align with this knowledge, highlighting the significant risk posed by early exposure, particularly in young workers, such as denim sandblasters and slate pencil workers.^{14,28,34}

Most cases were identified as ILO International Classification of Radiographs of Pneumoconiosis classification category 2 (n = 38, 56%). Even if detected early, workers are likely to be reluctant to change occupations, and clinical symptoms may be minor but persist for an extended period. Therefore, regular medical monitoring focused on early detection and preventive intervention is crucial, and raising awareness among workers and their employers is imperative.

This study has a few limitations. First, the absence of specific dust exposure data at workplaces necessitates the reliance on years of dust exposure as a proxy. Second, the accurate detection of the timing of silicosis onset through periodic physical examinations remains challenging. Therefore, the results of Cox regression require careful and conservative interpretation. Lastly, the number of cases may not have been sufficient to detect prognostic factors statistically. Despite these limitations, the present results will contribute to improving industrial hygiene not only in Mongolia but also in countries with similar conditions.

CONCLUSIONS

Approximately 75% of the miners diagnosed with silicosis demonstrated radiological progression, even after the termination of dust exposure. Progression to large opacities was frequently observed. Furthermore, advanced age and the degree of initial radiological opacity were associated with progression.

ACKNOWLEDGMENTS

The authors would like to thank the OSHC of Mongolia for kindly providing the archived data for occupational diseases for this study. They also thank the Department of Health Informatics team at the Graduate School of Medicine, Kyoto University, for the technical support and valuable comments.

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