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RESPIRATORY PARAMETERS AT VARIED ALTITUDES IN INTERMITTENT MINING WORK

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Abstract
Objectives: Workers in the mining industry in altitude are subjected to several risk factors, e.g., airborne silica and low barometric pressure. The aim of this study has been to assess the risks for this work category, evaluating single risk factors as airborne silica, altitude and work shift, and relating them with cardiovascular and ventilatory parameters. **Material and Methods:** Healthy miners employed in a mining company, Chile, working at varied altitudes, and subjected to unusual work shifts, were evaluated. Cardiovascular and respiratory parameters were investigated. Exposure to airborne silica was evaluated and compared to currently binding exposure limits. **Results:** At varied altitudes and work shifts, alterations emerged in haemoglobin, ventilation and respiratory parameters, related to employment duration, due to compensatory mechanisms for hypoxia. Haemoglobin increased with altitude, saturation fell down under 90% in the highest mines. The multiple linear regression analysis showed a direct relationship, in the higher mine, between years of exposure to altitude and increased forced vital capacity percent (FVC%), and forced expiratory volume in 1 s (FEV_1). An inverse relationship emerged between forced vital capacity (FVC) and years of exposure to airborne silica. In the workplace Mina Subterrànea (MT-3600), statistically significant inverse relationship emerged between the Tiffeneau index and body weight. **Conclusions:** The working conditions in the mining industry in altitude appeared to be potentially pathogenic; further investigations should be realized integrating risk assessment protocols even in consideration of their undeniable unconventionality. Int J Occup Med Environ Health 2018;31(2):129–138

Key words:
Shift work, High altitude, Silica, Risk assessment, Mining, Mountain-top mining

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INTRODUCTION

Risk assessment in the mining industry is a challenge for the occupational physician and the industrial hygienist, who need to collaborate in the identification, evaluation and proper management of concurrent risk factors.

Apart from work accidents, maybe the most important risk factor in the mining industry is the exposure to airborne silica. Indeed, the main occupational disease contracted in the mining sector is silicosis, a pneumoconiosis caused by inhaling dust containing free crystalline silica (silicon dioxide) that degenerates in a dose-dependent progressive pulmonary fibrosis. Although silicosis is classified as a chronic restrictive bronchopneumopathy, in the early stages, obstructive airway disease is detectable [1].

The main productive activity in Chile consists in the mining industry, in particular copper mining. Only the state-owned Copper Corporation (Codelco) employs over 40 000 people among miners, clerical workers and professional staff.

The working conditions are peculiar. Copper extraction takes place mainly along the Andes Mountains, at altitudes ranging from 1500 m to more than 4000 m. As atmospheric pressure decreases with increasing altitude, these workplaces are characterized by a rarefied atmosphere. In literature, altitude is generally considered as a risk for workplaces above 3000 m [2] but several authors observed altitude sickness symptoms yet above 1500 m [3]. At low barometric pressure, in order to compensate for the low oxygen levels, a progressive time-dependent hyperventilation occurs; the exercise due to the mining work may accentuate the hyperventilation. As larger amounts of air per unit of time are inhaled, more airborne silica, if any, can be inhaled [4,5]. Electrocardiographic changes during exercise in hypoxic conditions were investigated [6] and altered sleep quality and nocturnal apnoeas were observed in Chilean miners working in altitude [7].

In addition, unusual work shifts are logistically required for miners, with schedules consisting of 12-h shifts, alternating day and night shifts. Unusual work shifts and night shifts are physically, mentally and emotionally stressful; they may cause obesity, diabetes [8,9] and sleep disorders [10]. In previous researches, acclimatization in Chilean mine workers exposed to altitude was investigated, reproducing working conditions through submaximal exercise, but without carefully considering the unusual work shifts [11,12].

The aim of this study has been to evaluate the current working conditions in mining industry in altitude and to assess the risks for this work category, evaluating the risk factors airborne silica, altitude and work shift, and relating them with cardiovascular, laboratory and ventilatory parameters.

MATERIAL AND METHODS

Database processing

We realized a cross-sectional study. The initial sample consisted of 1627 workers of Codelco Andina, Chile. Personal and job data were collected. Among recorded data: gender; date of birth; date of recruitment; the type of contract (open-ended, fixed-term, externally-funded, consultancy); task; work shift schedule; workplace (Mina Sur, Mina Subterrànea, Saladillo and Planta Filtro).

The following inclusion criteria were considered for sample selection: male workers; age between 20 and 58 years old; assignments with similar metabolic load; no evidence of chronic or acute respiratory, cardiovascular and hematological diseases in the last 30 days; no consequences of chronic respiratory diseases; no polycythemia, hypertension or obesity diagnosis; no obstructive sleep apnoea syndrome diagnosis; less than 10 packs-year smoking history for workers over 45 years.

The final sample consisted of 260 miners working at varied altitudes with the 4×4 work shift (two 12-h day shifts and two 12-h night shifts, followed by 4 rest days).

This study group was divided according to the workplace: 82 miners from Mina Sur (MS-4300), an open-cut mine located between 3700 m and 4300 m; 119 miners from Mina Subterrànea (MT-3600), an underground mine located between 3070 m and 3656 m; 59 miners from Saladillo and Planta Filtro (SPF-1500), mineral comminution plants located between 1535 m and 1570 m.

The subjects were informed in detail about the experimental procedures prior to the study and they gave their written consents. The experimental protocol was approved by the Accident and Occupational Diseases Safety Board of Codelco (Seguridad Accidentes del Trabajo y Enfermedades Profesionales en Codelco).

Data evaluation

In order to investigate possible compensation mechanisms and degree of acclimatization, the following parameters were evaluated and related to the altitude of workplaces: hemoglobin saturation, heart rate, respiratory rate, tidal volume, minute volume and spirometric parameters (forced vital capacity – FVC, forced expiratory volume in 1 s – FEV_1, Tiffeneau index – FEV_1/FVC, maximum midexpiratory flow – MMEF75/25).

Clinical measurements were performed within 1 year, excluding austral winter, both at high and moderate altitudes. Measurements at high altitude were realized in the dedicated infirmaries of the selected workplaces (MS-4300, MT-3600 and SPF-1500). Measurements at moderate altitude were realized in the health care facility "Clinica Rio Blanco" located at Los Andes, 800 m above sea level (LA-800).

Each miner of the study group was examined after, at least, a 10-min pause from any manual work, in 3 different situations: at high altitude during both day and night work shifts, and at moderate altitude during a rest day.

Heart rate and hemoglobin saturation were measured with a pulse oximeter, Fingertip Oximeter, model RMS-50D. Respiratory rate and minute volume were measured with a Wright/Haloscale Respirometer. Spirometric measurements were realized with a Jager Masterscreen Pneumo spirometer. Each parameter was measured in triplicate during the first or the second day of the selected shift. The overall time required for the complete test varied between 20 min and 30 min per subject.

In addition, exposure to airborne crystalline silica was evaluated. Exposure values ranged 0.006–0.175 mg/m^3: several exposures did not respect the threshold limit value – time weighted average (TLV-TWA) (0.025 mg/m^3) [13] especially in the underground site. In MT-3600, TLV-TWA was exceeded in 18 out of 37 measurements. In MS-4300, TLV-TWA was exceeded in 1 out of 15 measurements. Besides, the eventual respect of TLV seems to be only formal, in consideration of unusual altitude and work shifts.

In a dedicated work by the same authors, exposure limits corrected for and to be employed at high altitude will be proposed and risk evaluation for contemporary exposition to airborne silica and low barometric pressure (high altitude) will be discussed.

Statistical analysis

Arithmetic mean and standard deviation for all measured parameters were calculated, and compared by ANOVA test. Results were compared by Wilcoxon and Kruskal-Wallis tests. Shapiro-Wilk test was applied to verify data normality. Finally, data was re-analyzed by means of multiple linear regression methods by using the Tiffenau index and respiratory parameters as dependent variables, and years of exposure to altitude and silica, body weight and age as independent variables. Data was processed with IBM SPSS Advanced Statistics 20.0 software. The sample is described in the Table 1.

RESULTS

The effect of altitude on hemoglobin

In order to evaluate the degree of acclimatization of Chilean miners working at varied altitudes, hemoglobin levels were measured and related to altitude. Ninety-nine percent of hemoglobin levels measured in the study group resulted as non-pathological; no evidence of polycythemia emerged. Hemoglobin levels (expressed in g/dl) sorted by

Table 1. Descriptive analysis of the investigated sample (N = 260) – healthy miners employed in a mining company, Chile, working at varied altitudes, and subjected to unusual work shifts

Respondents characteristics	M±SD	Me
Age [years]	40.70±7.600	40.00
Body height [m]	1.71±0.050	1.71
Body weight [kg]	67.50±4.750	67.00
Respiratory parameters [l]		
tidal volume	0.54±0.037	0.54
minute volume	7.56±0.520	7.53
Exposure [years]		
to silica	7.69±6.570	18.49
to altitude	8.78±6.460	18.49

M – mean; SD – standard deviation; Me – median.

workplace (different altitudes) were compared (Figure 1). Hemoglobin increased with altitude, with the highest values at MS-4300 and the lowest values in the mineral comminution plants (SPF-1500).

The effect of altitude on respiratory parameters

The measured forced vital capacity (FVC) levels appeared to be normal. Forced vital capacity levels (expressed in terms of percentage share of predicted), respiratory rate levels (expressed in breaths per minute), tidal volume levels (expressed in liters), minute volume levels (expressed in liters) sorted by workplace during day shift, night shift and at rest were compared by ANOVA test according to different work shifts and workplaces, but no significance emerged.

M – mean; SD – standard deviation.
MS-4300 – Mina Sur; MT-3600 – Mina Subterrànea;
SPF-1500 – Saladillo and Planta Filtro.

Fig. 1. Hemoglobin levels in miners (N = 260) employed in a mining company, Chile, by workplace (altitude)

The effect of altitude on heart rate

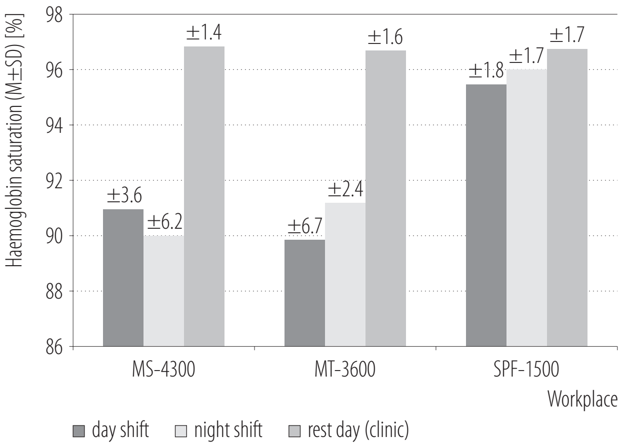
Heart rate levels (expressed in beats per minute) sorted by workplace during day and night shifts and at rest were compared according to different work shifts and workplaces (Figure 2). ANOVA test showed, within the groups divided by workplace, significant differences in heart rate variability between work shifts, as reported in the Table 2.

The effect of altitude on hemoglobin saturation

Hemoglobin oxygen saturation levels (SO_2) (expressed in terms of percentage share) sorted by workplace were compared according to different work shifts and workplaces (Figure 3). Hemoglobin saturation levels higher than 95% were observed only at SPF-1500. ANOVA test showed, within the groups divided both by workplace and by work shift, significant differences in SO_2 variability between work shifts, as reported in the Tables 3 and 4.

Abbreviations as in Figure 1.

Fig. 2. Heart rate values in miners (N = 260) employed in a mining company, Chile, by work shift and workplace (altitude)



Abbreviations as in Figure 1.

Fig. 3. Haemoglobin saturation in miners (N = 260) employed in a mining company, Chile, by work shift and workplace (altitude)

Conformation and analysis of subgroups with varied ventilation in altitude

In order to identify the main risk factors in the described working conditions, available data was statistically processed. The study group stratified by workplace was divided by comparing minute volume at high and moderate altitudes. The subgroup "higher minute volume (HMV)" identified subjects with increased pulmonary ventila-

Table 2. ANOVA test on heart rate values of the miners employed in a mining company, Chile, by workplace and work shift

Workplace	Respondents (N = 260) [n]	Heart rate [beats/min]		$df_{between}$	df_{within}	F	p
		M	variance				
MS-4300	82			2	221	3.03	0.000
day shift		76.80	145.60				
night shift		76.46	101.50				
rest day (clinic)		66.41	108.22				
MT-3600	119			2	306	3.02	0.000
day shift		77.09	176.62				
night shift		76.23	128.01				
rest day (clinic)		67.17	108.76				
SPF-1500	59			2	106	3.08	0.0006
day shift		74.65	113.92				
night shift		79.29	99.97				
rest day (clinic)		68.20	127.40				

MS-4300 – Mina Sur; MT-3600 – Mina Subterrànea; SPF-1500 – Saladillo and Planta Filtro.
M – mean; df – degrees of freedom, between or within group; F – F statistic.

Table 3. ANOVA test on hemoglobin saturation values of the miners employed in a mining company, Chile, by workplace

Workplace	Respondents (N = 260) [n]	Hemoglobin saturation [%]		$df_{between}$	df_{within}	F	p
		M	variance				
MS-4300	82			2	221	3.03	0.000
day shift		90.95	12.84				
night shift		90.01	38.19				
rest day (clinic)		96.84	2.05				
MT-3600	119			2	306	3.02	0.000
day shift		89.84	44.17				
night shift		91.18	5.88				
rest day (clinic)		96.69	2.51				
SPF-1500	59			2	106	3.08	0.003
day shift		95.48	3.32				
night shift		96.00	2.75				
rest day (clinic)		96.74	2.82				

Abbreviations as in Table 2.

Table 4. ANOVA test on hemoglobin saturation values of the miners employed in a mining company, Chile, by work shift

Work shift and workplace	Respondents (N = 260) [n]	Hemoglobin saturation [%]		$df_{between}$	df_{within}	F	p
		M	variance				
Day shift	260			2	238	3.03	0.000
MS-4300		90.95	12.84				
MT-3600		89.84	44.17				
SPF-1500		95.48	3.32				
Night shift	260			2	168	3.05	0.000
MS-4300		90.01	38.19				
MT-3600		91.18	5.88				
SPF-1500		96.00	2.75				
Rest day (clinic)	260			2	227	3.04	0.81
MS-4300		96.84	2.05				
MT-3600		96.69	2.51				
SPF-1500		96.74	2.82				

Abbreviations as in Table 2.

tion at high altitude; the subgroup "lower minute volume (LMV)" identified subjects with reduced pulmonary ventilation at high altitude. Average years of exposure to altitude, minute volume, heart rate and hemoglobin saturation in the identified subgroups are described in the Table 5.

In the subgroup with increased ventilation at high altitude, average minute volume increased by 14% at 1500 m and

Table 5. Characteristics of miners (N = 260), employed in a mining company, Chile, with different ventilation in altitude

Characteristics	MS-4300		MT-3600		SPF-1500	
	HMV	LMV	HMV	LMV	HMV	LMV
Respondents [%]	52.0	48.0	51.0	49.0	50.0	50.0
Age [years]	40.1	41.1	40.9	39.5	42.0	42.0
Exposure to altitude [years]	10.3	8.4	10.3	8.6	5.7	5.9
Minute volume [l]						
day shift	13.8	11.6	15.0	12.2	13.0	12.8
night shift	14.3	12.5	14.5	12.7	12.1	14.0
rest day (clinic)	11.7	14.5	12.3	15.0	11.0	16.7
Heart rate [beats/min]						
day shift	78.7	75.0	80.2	72.9	75.7	75.2
night shift	78.4	75.7	76.5	75.8	72.4	85.3
rest day (clinic)	67.0	65.8	65.3	69.1	65.8	71.2
Hemoglobin saturation [%]						
day shift	91.7	90.0	91.3	89.8	95.8	94.9
night shift	90.2	89.6	91.7	90.9	95.6	96.6
rest day (clinic)	97.0	96.7	96.9	96.5	96.8	96.6
Respondents with hemoglobin saturation < 90% [n]						
day shift	11	18	10	14	0	1
night shift	11	11	4	8	0	0
rest day (clinic)	0	0	0	0	0	0

HMV – higher minute volume at different altitudes; LMV – lower minute volume at different altitudes.
Other abbreviations as in Table 2.

by 20% above 3000 m, compared to minute volume levels recorded at 800 m.

In the highest workplace, MS-4300, hemoglobin saturation was below 90% for 28% of HMV subjects and for 50% (day shift), and 30% (night shift) of LMV subjects. In the underground mine, MT-3600, hemoglobin saturation was below 90% for 18% (day shift) and 7% (night shift) of HMV subjects and for 26% (day shift) and 15% (night shift) of LMV subjects.

Relationship between respiratory parameters and years of exposure to altitude, and airborne silica.

A multiple linear regression analysis was carried out, in which the respiratory parameters composed the dependent variables and years of exposure to altitude and airborne crystalline silica composed the independent variables. Statistically significant results are presented in the Table 6.

A direct relationship emerged, in the higher mine, between years of exposure to altitude and increased FVC%, and FEV_1. An inverse relationship emerged between FVC and years of exposure to airborne silica.

Relationship between Tiffeneau index and age, and body weight

A multiple linear regression analysis was carried out, in which the Tiffeneau index composed the dependent variable and age and body weight composed the independent

Table 6. Relationship between respiratory parameters and years of exposure to altitude, and airborne silica in study of miners (N = 260) employed in a mining company, Chile

Exposure	MS-4300			MT-3600			SPF-1500		
	β	t	p	β	t	p	β	t	p
Altitude									
FEV_1/FVC	–0.044	–0.214	0.832	0.103	0.405	0.687	0.475	0.273	0.796
FVC	0.197	0.923	0.361	0.478	1.958	0.054	2.779	2.612	0.083
FEV_1	0.580	3.109	0.003	0.374	1.506	0.136	2.894	2.673	0.044
FVC%	0.588	2.997	0.004	0.286	1.181	0.241	2.267	1.620	0.166
Silica									
FEV_1/FVC	0.362	1.759	0.085	–0.011	–0.043	0.966	–0.254	–0.146	0.890
FVC	–0.315	–1.477	0.146	–0.643	–2.635	0.010	–2.627	–2.044	0.096
FEV_1	–0.087	–0.468	0.642	–0.146	–0.587	0.559	–2.466	–2.277	0.072
FVC%	–0.243	–1.241	0.221	0.047	0.195	0.846	–1.932	–1.380	0.226

FEV_1/FVC – Tiffeneau index; FVC – forced vital capacity; FEV_1 – forced expiratory volume in 1 s; FVC% – forced vital capacity percent.
β – regression coefficient.
Other abbreviations as in Table 2.

variables. In the workplace MT-3600, statistically significant inverse relationship emerged between the Tiffeneau index and body weight (β = –0.296, t = –2.616, p = 0.011).

DISCUSSION

According to collected data, hemoglobin values increased with altitude as a consequence of oxygen saturation decreasing. Above 3000 m (MS-4300 and MT-3600), higher percentage shares of low hemoglobin saturation were recorded among miners with reduced pulmonary ventilation at high altitude, both during day and night shift. It is well known that when hemoglobin saturation falls below 90%, oxygen delivery to tissue, including vital organs, is likely to be inadequate in healthy adults. Without adaptation mechanisms to hypoxia, diseases as acute mountain sickness (AMS), high-altitude pulmonary edema (HAPE), high-altitude cerebral edema (HACE) or, chronic mountain sickness (CMS) may occur [14].

Since data was not available yet, the effect of altitude on blood count was not evaluated. Further investigations will be realized to study the afore mentioned relationship, evaluating the presence of eventual polycythemia and compensation mechanisms to hypoxia, by means of a complete blood count and blood-gas analysis at the end of the shift to examine desaturation in detail.

By analyzing respiratory parameters, interesting alterations emerged.

Average minute volume values measured in Chilean miners ranged from 11.6 l to 16.7 l of air, levels quite higher than the normal minute ventilation values for healthy subjects at rest, from 6 l up to 9 l [15] probably due to acclimatization to high altitude and tidal volume and respiratory rate values resulted as altered but no statistically significant differences emerged between groups.

Minute volume values being equal, elevated respiratory rates increase energy demand and consumption by respiratory muscles, with consequent fatigue and labored (fast and shallow) breathing, lower alveolar ventilation and lower saturation [16], as emerged from our results. This physiological process is exacerbated by altitude and work load, during both night and day shifts, while at rest SO_2 resulted normal. Moreover, as hemoglobin oxygen saturation levels fell below 90%, especially at higher altitude levels during both day and night work shifts, it would be appropriate to consider whether to provide workers with an oxygen support during the work shifts. It would be an interesting object of study, to develop a strategy to provide oxygen support without interfere with physical activity, possibly with oxygen conditioning.

Another significant finding emerged from our study: the relationship ventilator compensation/silica exposure time. In result of the multiple linear regression analysis, direct relationship emerged between length of exposure and FEV_1, and FVC, on the other hand, negative correlation emerged between FVC and years of exposure to airborne silica.

Physiologically, the decreased pressure of inspired oxygen is compensated, but toxicological implications emerge. In workplaces characterized by poor air quality, increasing pulmonary ventilation involves larger amount of polluted air to be inhaled and, in particular, larger amount of airborne silica to be inhaled. Thus, at high altitude, higher doses of airborne crystalline silica may be assumed.

In addition, the current TLV levels for silica-containing dusts do not take into account any pulmonary ventilation normalization, therefore they are inadequate to protect exposed workers. A customized algorithm should be compiled.

Finally, we investigated the effects of shift work, and especially night work. We focused on major effects suggested by literature, i.e., the metabolic and respiratory ones [8,17,18]. Thus, the relationship between the index of chronic obstructive pulmonary disease (the Tiffenau index) and body weight was studied. Several risk factors, related to obesity and metabolic disorders, may be identified for the investigated job category: shift work and night shifts with irregular shifts [8] and alterations in lung function [17,18]. In Tables 3 and 4, it may be observed that in the highest mine, the lowest oxygen saturation levels occurred during the night shift. It is well known that altitude may affect sleep quality and altitude exposure may exacerbate obstructive sleep apnoea syndrome [11], but the decrease in SO_2 during the night shift deserves further investigation. Probably, it may be attributable to an increased metabolic request due to both altitude and the shift performed during the night, that requires more energy [11]. Unfortunately, we did not have the possibility to perform polysomnography, deepening the study of obstructive lung damage due to exposure to unusual shift. In addition, eventual metabolic alterations may be combined to other changes in the cardiovascular system due to altitude [19]; as a result, further studies are needed.

This study is a preliminary research: the first approach focused mainly on respiratory parameters, further studies will include hematological parameters (e.g., blood count or arterial blood gas analysis) in order to evaluate alterations and compensation mechanisms.

CONCLUSIONS

The working conditions in the mining industry in altitude have appeared to be potentially pathogenic. Acclimatization and compensation mechanisms observed, with increased pulmonary ventilation, imply increased airborne silica inhaling. In order to prevent silica relate diseases, further investigations should be realized to integrate and correct risk assessment protocols.

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